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# Solar Cell Parameters Extraction Using Rao-3 algorithm

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**Abstract -** The extraction of solar cell parameters is a subject of significant interest, as it plays a crucial role in predicting the performance and behavior of solar cells, as well as in evaluating their efficiency. This paper presents a simple, efficient, and reliable metaheuristic optimization technique, i.e. the Rao-3 algorithm, for extracting five key electrical parameters of a solar cell from a single illuminated current–voltage (*I–V*) characteristic. An interactive numerical simulation has been developed using LabVIEW as the programming platform to implement the algorithm. The consistency and accuracy of the Rao-3 algorithm have been validated by applying it to reported *I–V* data of various types of solar cells, including silicon, plastic, and CIGS cells. The parameter values obtained through this approach show excellent agreement with those reported in the literature. Furthermore, the self-developed program has been tested on experimentally measured *I–V* characteristics of a monocrystalline silicon solar cell. The results indicate that the Rao-3 algorithm consistently converges to stable and repeatable parameter values. This study demonstrates that the proposed program, based on the Rao-3 algorithm, can be effectively applied to a wide range of solar cells and modules for parameter extraction from a single illuminated *I–V* curve, using only a few control variables.

***Key Words***: Solar Cells, Parameters extraction, Rao-3 algorithm, I-V characteristics.

## 1. INTRODUCTION

Solar cells, also known as photovoltaic (PV) cells, are semiconductor devices that convert sunlight directly into electricity. Solar energy is a promising alternative to conventional energy sources due to its abundance, environmental friendliness, and safety [1]. The performance and efficiency of solar cells are strongly influenced by several key physical parameters, including the reverse saturation current ($I_o$), photocurrent ($I_{ph}$), diode ideality factor (n), series resistance ($R_s$), and shunt resistance ($R_{sh}$). Accurate extraction of these parameters is essential not only to evaluate the performance of a cell but also to enhance the design, fabrication process and quality control of the cell. Incorrect values of parameters directly affect the energy conversion efficiency [1]. As a result, the extraction of solar cell parameters remains a critical area of research in photovoltaic technology. In the present work, the single-diode equivalent circuit model of a solar cell is employed to extract these five parameters. The current–voltage (I–V) relationship of a solar cell based on the single-diode model is given by,

$$I = I_{ph} - I_o[e^{\frac{q(V+IR_s)}{nk_BT}} - 1] - \frac{V+IR_s}{R_{sh}} \qquad (1)$$

From Eq. (1), it is noticeably observed that the direct parameter estimation from experimental *I-V* characteristic data is restricted due to non-linear and transcendental nature of the I-V relation of a solar cell.

Over the years, various approaches have been developed for extracting solar cell parameters. These methods generally fall into two categories: analytical [2–3] and numerical [4–5]. Analytical techniques determine parameters using specific points from the experimental *I–V* characteristics, such as short-circuit current, open-circuit voltage, current and voltage at the maximum power point, and the slopes at axis intersections. However, the accuracy of these methods is highly sensitive to the correctness of the selected data points, any errors in these values can lead to significant inaccuracies in the extracted parameters. On the other hand, numerical methods apply mathematical algorithms, such as curve-fitting techniques, to match the entire *I–V* curve in order to estimate the parameters. The reliability of these techniques depends on factors such as the choice of fitting algorithm, the objective function, the fitting criteria, and the initial guess of parameter values [4]. Moreover, numerical methods often lack global convergence guarantees, as their performance can be highly dependent on initial conditions, including the number of iterations and tolerance thresholds.

In the past decade, evolutionary algorithms (EAs) have gained significant attention in the field of solar cell parameter extraction due to their robustness and global search capabilities [6]. Among these, the Genetic Algorithm (GA) has been widely used for parameter estimation in solar cells [7, 8]. GA has demonstrated superior performance compared to traditional methods such as quasi-Newton methods and curve-fitting techniques. However, GA requires several algorithm-specific parameters, such as crossover and mutation rates, whose appropriate selection is problem-dependent and often challenging. More recently, Particle Swarm Optimization (PSO) has been explored as an alternative for solar cell parameter extraction [9–11]. While PSO has shown promise and is considered a more efficient alternative to GA in some cases, it still has notable limitations. These include: (1) inconsistency in the extracted parameter values and (2) the requirement for a large number of iterations to reach global convergence [11]. Furthermore, PSO relies on key parameters such as acceleration constants (c1 and c2) and inertia weight, which govern the balance between individual and social components of the particle's movement. Improper tuning of these parameters can cause the search process to become trapped in local optima rather than reaching the global optimum [12]. In general, all evolutionary and swarm intelligence algorithms are nature-inspired and population-based, requiring common control parameters such as population size and number of iterations. In addition, they involve algorithm-specific parameters that significantly influence their performance. The improper selection or tuning of these parameters can adversely affect the convergence behavior and the accuracy of the optimal solution.

In recent years, several new classes of global optimization algorithms have been developed inherently parameter-less

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algorithm to address a wide range of optimization problems. Notable among these are the Teaching-Learning-Based Optimization (TLBO) algorithm [13, 14], the Jaya algorithm [15], and the Rao algorithms [16]. These methods require only common control parameters, such as the number of iterations and population size, similar to conventional population-based algorithms, but they eliminate the need for algorithm-specific parameter tuning. To the best of our knowledge, the Rao-3 algorithm has not yet been investigated for the problem of solar cell parameter extraction in the existing literature. Therefore, this study aims to evaluate the effectiveness of the Rao-3 algorithm in accurately extracting five key solar cell parameters from both synthetic and experimentally obtained I–V characteristic data. The algorithm has been implemented via an interactive numerical program developed using the trial version of LabVIEW (Laboratory Virtual Instrument Engineering Workbench) as the programming environment.

## 2. Implementation of Rao-3 algorithm for Solar Cell Parameters Extraction

The Rao-3 algorithm operates by identifying the best and worst candidate solutions during the optimization process and updating the population through randomized interactions based on these two extremes. At each iteration, candidate solutions are modified accordingly. In this study, the best candidate is defined as the one with the minimum fitness value, while the worst candidate has the maximum fitness value among all candidates in the population. A detailed explanation of the Rao-3 algorithm's working mechanism can be found in the literature [16].

The implementation of the solar cell parameter extraction problem begins with inputting the *I–V* data of the solar cell. Initially, the program reads user-defined parameters such as the number of iterations and population size. In this work, five key parameters of the solar cell such as the reverse saturation current ($I_o$), photocurrent ($I_{ph}$), diode ideality factor (n), series resistance ($R_s$), and shunt resistance ($R_{sh}$) are considered as design variables in the optimization process. The performance of each candidate solution is evaluated at every iteration using a defined fitness function. In our implementation, the fitness function is expressed as,

$$F(X) = \frac{\left\{ \sum_{k=1}^{p} [I^{exp}(V_k) - I^{cal}(V_k, X)]^{2} \right\}}{p} \qquad (2)$$

Where, $I^{exp}(V_k)$ is the experimental value of current (I) at voltage $V_k$, $I^{cal}(V_k, X)$ is the calculated values of current, which can be obtained by Eq. (1), for given set of parameters (i.e. $X_i = I_{oi}, I_{ph}, n_i, R_{si}$ *and* $R_{shi}$) at voltage $V_k$, $p$ is the total number of voltage steps in the I-V characteristic. Theoretically, the fitness function should reach zero when the exact values of all solar cell parameters are identified. However, in practice, a small but finite deviation between the experimental and calculated *I–V* values is expected. Therefore, a lower fitness function value indicates a better match between the fitted and experimental *I–V* characteristics. During each iteration, the best and worst candidate solutions are determined from the population based on their fitness values. These are then used in the Rao-3 update equation [16] to modify each candidate solution, progressively guiding the population toward the optimal set of solar cell parameters. A detailed flowchart illustrating the Rao-3 algorithm in the context of solar cell parameter extraction is presented in Fig. 1, while Table 1 outlines the terminology of the Rao-3 algorithm as applied to this specific problem.

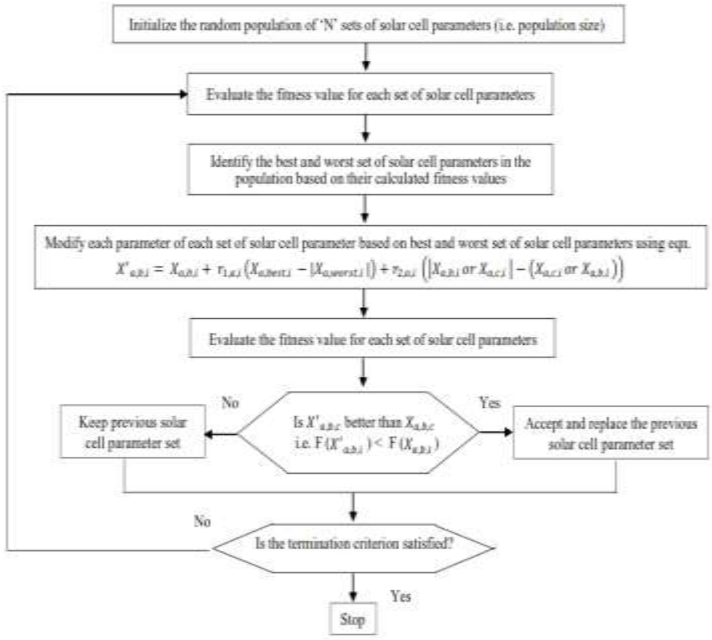


Fig. 1. Flow chart of Rao-3 algorithm for the extraction of solar cell parameters.

| Rao-3 algorithm terms | Equivalent Solar cell parameters |
|---|---|
| Initial population | Number of randomly generated sets of solar cell parameters |
| Design variable | An individual parameter of the solar cell |
| Best solution | Best parameters set with minimum value of fitness function in the entire population |
| Worst solution | Worst parameters set with maximum value of fitness function in the entire population |
| Search space | Range of minimum and maximum possible value of solar cell parameters to be extracted |

Table 1. Rao-3 algorithm terminology in the context of solar cell parameters extraction problem.

## 3. Results and Discussion

To verify the accuracy, consistency, and robustness of the Rao-3 algorithm, it was applied to *I–V* characteristics synthesized from the reported data of various types of solar cells, including Silicon, Plastic, and Dye-sensitized solar cell (DSSC). These synthetic *I–V* curves were generated using the single-diode model based on parameter values reported in the literature. The algorithm was used to extract five key solar cell parameters such as $I_o$, $I_{ph}$, n, $R_s$, and $R_{sh}$. The reliability and stability of the developed program based on the Rao-3 algorithm were evaluated by repeatedly executing the algorithm multiple times for each solar cell type and comparing both the extracted parameter values and the shape of the resulting *I–V* curves. Following this validation, the algorithm was also applied to experimentally measured *I–V* characteristics of a

 

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monocrystalline silicon solar cell obtained in our laboratory. For all simulations, both the population size (i.e., the number of parameter sets) and the number of iterations were fixed at 1000 to ensure consistent and optimal extraction of the five solar cell parameters.

## 3.1 Silicon Solar Cell

Initially, Rao-3 algorithm is applied to extract the parameters of a 57 mm-diameter commercial silicon solar cell from R.T.C. France [17]. The synthetic *I-V* characteristic is generated using the parameters values as reported in several literatures [17]. Fig. 2 shows the synthetic (black square) and Rao-3 algorithm fitted *I-V* characteristics (red dot). It is clearly seen that the *I-V* characteristics exactly overrides on the fitted curve. The parameters calculated by our program and those reported by different method in previous work are shown in the Table. 2. Here, it can be seen that the values obtained by Rao-3 algorithm match with the reported values [17] up to 5 significant digits.

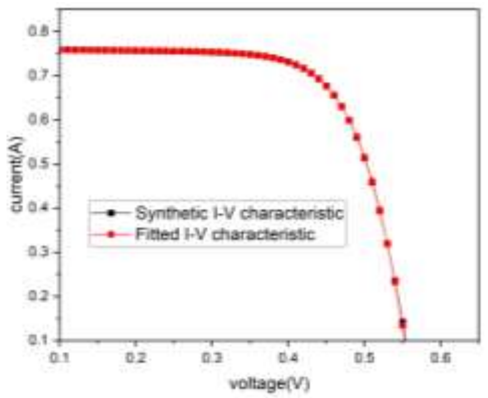


Fig.2. Synthetic and fitted *I-V* characteristics for Si solar cell.

Fig. 3 shows the variation of the fitness functions as well as that of individual solar cell parameters as the iteration progresses for Silicon solar cell. Here, it can be seen that the fitness value decreases steadily and consistently as program proceeds. The fitness function is the measure the quality of fitting between the synthetic I-V curve and the I-V curve generated by Rao-3 algorithm. Thus, the reducing fitness function indicates that this matching is gradually improving iteration by iteration. After iterations, the value of fitness function becomes very small and the change is not visible in the graph. However, the values from the data indicates that consistent enhancement in the fitness until saturates at about 500 iterations. The $R_s$, $R_{sh}$, and $I_o$ fluctuate significantly during initial iterations and their values become stable after about 500 iterations and then change in the value is slow and smooth as shown in fig.3. The value of $n$ drops rapidly at first and then quickly stabilizes. In contrast, the $I_{ph}$ values change gradually and steadily before leveling off around the 200 iterations. Overall, the algorithm requires approximately 500 iterations to fully converge to a stable solution.

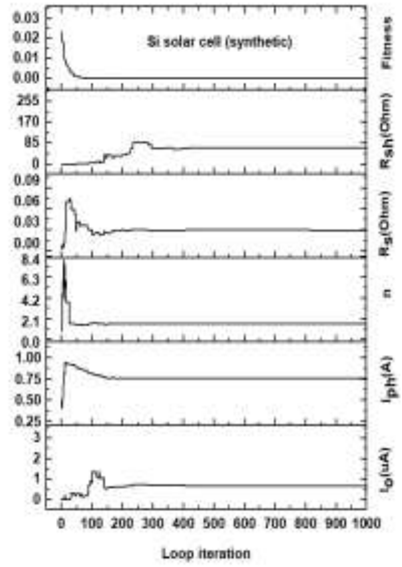


Fig.3 Variation in the values of fitness function and parameters as a function of loop iteration for synthetic *I-V* characteristic of Si solar cell.

| Type of Solar Cell | Io (μA) | Iph (A) | n | Rs (Ω) | Rsh (Ω) |
|---|---|---|---|---|---|
| **Silicon Solar Cell (Synthetic)** | | | | | |
| Reported values [17] | 0.3223 | 0.7608 | 1.4837 | 0.0364 | 53.76 |
| Rao-3 algorithm | 0.2989 | 0.7607 | 1.4786 | 0.0390 | 53.98 |
| **Plastic Solar Cell (Synthetic)** | | | | | |
| Reported values [18] | 0.0136 | 0.00794 | 2.31 | 8.59 | 197.24 |
| Rao-3 algorithm | 0.0137 | 0.00793 | 2.31 | 8.57 | 197.28 |
| **DSSC (Synthetic)** | | | | | |
| Reported values[19] | 0.035 | 0.00206 | 2.5 | 43.8 | 3736 |
| Rao-3 algorithm | 0.035 | 0.00205 | 2.5 | 43.8 | 3778 |
| **Monocrystalline Silicon Solar Cell (Experimental)** | | | | | |
| Rao-3 algorithm | 0.3778 | 0.1684 | 1.6157 | 0.018 | 37.70 |

Table. 2: Comparison of solar cell parameters obtained by the Rao-3 algorithm with reported values

## 3.2 Plastic and Dye-Sensitized Solar Cell

To further check the success of the Rao-3 algorithm over a diverse world of solar cell technologies, it is applied to the extraction of the parameters values of a plastic solar cell and a CIGS solar cell. The synthetic and fitted by Rao-3 algorithm *I-V* characteristics for Plastic and Dye-Sensitized Solar Cells are shown in Fig. 4 and Fig. 5, respectively. From the figs, it is clearly seen that the I-V characteristics exactly match with the fitted curves. Hence, we can say that the developed programme based on the Rao-3 algorithm also successfully works in the case of Plastic Solar Cells and Dye-Sensitized Solar Cells.

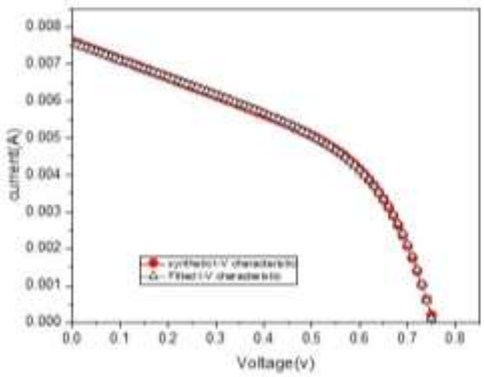


Fig.4. Synthetic and fitted *I–V* characteristics for Plastic Solar Cell

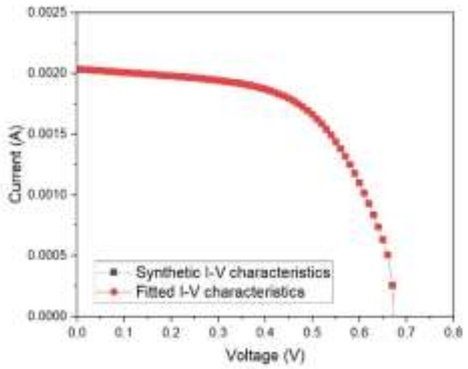


Fig.5. Synthetic and fitted *I–V* characteristics for Dye-sensitized Solar Cell.

### 3.3 Monocrystalline Silicon Solar cell

After validating the reliability of the developed program based on the Rao-3 algorithm on synthetic *I-V* characteristics, we utilized it to obtain the five electrical parameters from experimentally measured *I-V* characteristics of a monocryalline Si solar cell in our laboratory. The Rao-3 algorithm is also employed to extract the parameters of a monocrystalline Si solar cell with an active area of 4×4 cm$^2$ (Make: Bharat Electronic Limited, India). The *I-V* characteristics were measured using a solar simulator (make: NCPRE, IIT, Bombay, India) under an irradiance of 900 W/m$^2$ at a temperature of 45 °C in our laboratory. The experimental I-V and Rao-3 fitted *I-V* characteristics for the cell are shown in fig. 6

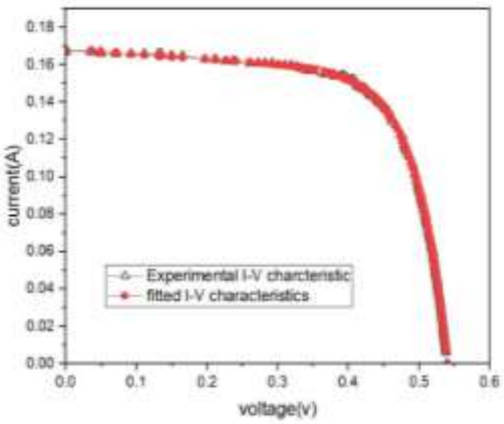


Fig. 6 Experimental and Rao-3 fitted *I-V* characteristics for monocrystalline Si solar cell.

## 4. CONCLUSIONS

We have successfully demonstrated the application of the Rao-3 algorithm for extracting all key solar cell parameters from a single illuminated *I–V* characteristic, based on the single-diode model. Initially, the effectiveness and validity of the algorithm were verified using synthetic *I–V* data generated from known parameter values. The results show that the parameters estimated by the Rao-3 algorithm closely match the reference values reported in the literature, confirming its accuracy. Moreover, the algorithm exhibited a high degree of repeatability in converging to the global optimum solution. Following this validation, the algorithm was applied to experimentally measured *I–V* characteristics of a monocrystalline silicon solar cell to estimate unknown parameter values. The findings confirm that the Rao-3 algorithm is a highly effective and reliable tool for extracting all five essential solar cell parameters $I_0$, $I_{ph}$, n, $R_s$, and $R_{sh}$ from a single *I–V* curve measured under illumination. The limitations typically associated with conventional numerical methods and other computational optimization techniques in solar cell parameter extraction can be significantly mitigated by adopting the Rao-3 algorithm

## REFERENCES

1. Chegaar M, Azzouzi G, Mialhe P.: Simple parameter extraction method for illuminated solar cells. Solid-State Electron. Vol. 50 (2206) 1234–7
2. Chan DSH, Phang JCH.: Analytical methods for the extraction of the solar cell single- and double-diode model parameters from I-V characteristics. Electron Dev IEEE Trans. 34(2) (1987) 286 - 293
3. De Soto W, Klein SA, Beckman WA.: Improvement and validation of a model for photovoltaic array performance. Sol Energy. Vol. 80 (2006) 78-88.
4. Gottschalg R, Rommel M, Infield DG, Kearney MJ.: The influence of the measurement environment on the accuracy of the extraction of the physical parameters of solar cells. Meas Sci Technol. Vol. 10 (1999) 796-804.
5. Liu C-C, Chen C-Y, Weng C-Y, Wang C-C, Jenq F-L, Cheng P-J, et al. Physical parameters extraction from current–voltage characteristic for diodes using multiple nonlinear regression analysis. Solid-State Electron. Vol. 52(8) (2008) 39–43.
6. Ishaque K, Salam Z, Taheri H, Shamsudin A. A critical evaluation of EA computational methods for Photovoltaic cell parameter extraction based on two diode model. Sol Energy. Vol. 85 (2011) 1768–79.
7. Jervase JA, Bourdoucen H, Al-Lawati A. Solar cell parameter extraction using genetic algorithm. Meas Sci Technol 2001; 12: 1922-25.
8. Zagrouba M, Sellami A, Bouaicha M, Ksouri M. Identification of PV solar cells and modules parameters using the genetic algorithms.: Application to maximum power extraction. J. Solar Energy. Vol. 84 (2010) 860-66.
9. Macabebe EQB, Sheppard CJ, van Dyk EE. Parameter extraction from I–V characteristics of PV devices.: Sol Energy. Vol. 85 (2011)12–8.
10. Munji M K, Okullo W, van Dyk E E, Vorster F J. Local device parameter extraction of a concentrator photovoltaic cell under solar spot illumination.: Solar Energy Materials and Solar Cells. Vol. 94 (2010) 2129-36.
11. Ye M, Wang X, Xu Y. Parameter extraction of solar cells using particle swarm optimization. J Appl. Phys.: Vol. 105 (2009) 094502.
12. Alhajri M F, El-Naggar K M, AlRashidi M R, Al-Othman A K. Optimal extraction of solar cell parameters using pattern search.: Renewable Energy.: Vol. 44 (2012) 238-45.
13. Rao RV, Savsani VJ, Vakharia DP. Teaching-Learning-based optimization: A novel method for constrained mechanical design

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optimization problems.: Computer aided-design. Vol. 43 (2011) 303-315.

14. Sanjaykumar J. Patel, Ashish K. Panchal, Vipul Kheraj: Extraction of solar cell parameters from a single current–voltage characteristic using teaching learning based optimization algo-rithm.: Applied Energy. Vol. 119 (2014) 384–393
15. Rao RV, Jaya: A simple and new optimization algorithm for solving constrained and uncon-strained optimization problems.: Int. J. Ind. Eng. Comput. Vol. 7 (2016) 19–34
16. Rao RV, Rao algorithms: Three metaphor-less simple algorithms for solving optimization problems.: Int. J. Ind. Eng. Comput. Vol. 11 (2020) 107-130
17. Easwarakhanthan T, Bottin J, Bouhouch I, Boutrit C. Nonlinear minimization algorithm for determining the solar cell parameters with microcomputers.: Int. J. Sol Energy. Vol. 4 (1986) 1-12.
18. Ortiz-Conde A, Garcia Sanchez FJ, Muci J. New method to extract the model parameters of solar cells from the explicit analytic solutions of their illuminated I-V characteristics.: Sol Energy Mater Sol Cells. Vol. 90 (2006) 352-61.
19. Murayama M, Mori T. Equivalent circuit analysis of dye-sensitized solar cell by using one diode model: effect of carboxylic acid treatment of $TiO_2$ electrode.: Jpn J Appl Phys Vol. 45 (2006) 542–5.

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