Energy Conversion and Management 157 (2018) 460–479

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Parameter extraction of solar cell models using improved shuffled complex evolution algorithm

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ARTICLE INFO

Keywords:
Solar cell
Single diode model
Double diode model
Parameter extraction
Shuffled complex evolution

ABSTRACT

Fast and accurate parameter extraction of solar cell models is always desired for simulation, evaluation and maximum energy harvesting of PV systems. This paper proposes an improved shuffled complex evolution (ISCE) algorithm for parameter extraction of different PV models, including single diode model, double diode model and single diode solar module model. The novelty of proposed ISCE algorithm lies primary in the improved competitive complex evolution strategy, where three amendments are proposed to overcome the shortcomings of original SCE algorithm. (1) The expansion step and outside contraction step are inserted into to improve the probability of producing better solution. (2) The reflecting-absorbing bound- handling method is employed to enhance the chance of global search and avoid being trapped in local minima. (3) The main diagonal of simplex is adopted to overcome local roughness and drive the global search in an efficient manner. In order to test the parameter extraction performance of proposed ISCE and compare it with some state-of-the-art algorithms, the standard datasets and practical measured datasets of one solar cell and three solar modules are selected for parameter extraction of different PV models. Comparison results indicate that the proposed ISCE algorithm always exhibits the highest computational efficiency to get the most accurate parameter values among all compared algorithms. More importantly, the proposed ISCE algorithm generally promises better convergence speed and robustness than the best reported algorithms. Due to these superiorities, the proposed ISCE algorithm is quite promising and envisaged to be an accurate, efficient and reliable alternative for solving the parameter extraction problem of solar cell models.

1. Introduction

To cope with the increasing energy shortage and environment pollution, a large number of efforts have been made to accelerate energy structure adjustment and intensify the research of renewable energy. Among renewable energy technologies, solar photovoltaic is envisaged to be the most feasible candidate to meet the increasing energy demands. With the advancement of PV technology, accurate modeling and parameter extraction that closely representing the nonlinear current–voltage (*I–V*) characteristics of solar cells have drawn considerable attention in simulation, evaluation and maximum energy harvesting of PV systems [1–3]. Over the past decades, despite various models have been developed to describe the behavior of solar cells, only two lumped parameter equivalent circuit models are used practically: single diode model (SDM) and double diode model (DDM) [3–8]. There are five parameters in SDM and seven parameters in DDM need to be extracted as accurately as possible. An accurate knowledge of these parameters is of vital importance not only for performance evaluation and quality control of solar cell, but also play a important role in tracking the maximum power point (MPP) of PV systems [9–17]. Unfortunately, both SDM and DDM are implicit transcendental equations and have the shortcoming of being explicitly unsolvable using common elementary functions [18]. This inherent implicit nature hampers not only solar cell parameter extraction [19] but also PV system simulation [1]. Therefore, it is imperative to develop reliable and efficient method to accurately extract these parameters from the measured *I–V* data of solar cells.

For determining the model parameters of SDM and DDM, dozens of techniques have been developed in literature. These techniques can be generally classified into analytical methods and numerical methods. Apart from appropriate simplifying assumptions, analytical methods depend heavily upon the correctness of several key points on *I–V* curve, i.e., short-circuit current, open-circuit voltage, MPP and curve slopes at the axis intersections. Therefore, in essence, analytical methods “take a part for the whole”, that is, take the selected points to generalize all measured *I–V* data. If one or more of the selected points are incorrectly assigned, the errors for the extracted parameters can be very significant

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https://doi.org/10.1016/j.enconman.2017.12.033
Received 17 August 2017; Received in revised form 4 December 2017; Accepted 9 December 2017
0196-8904/

Nomenclature

A	complex
B	simplex
CCE	competitive complex evolution
dim	problem dimension
D	population
DDM	double diode model
e	electronic charge ($1.60217646 \times 10^{-19}$ C)
$f_M(V, I, X)$	error function
F	objective function
g	centroid of simplex
H	smallest hypercube
I	terminal current (A)
I_0, I_{01}, I_{02}, I_{0m}	diode reverse saturation currents (A)
I_D, I_{D1}, I_{D2}	diode currents (A)
I_{ph}, I_{phm}	photocurrent (A)
IAE	individual absolute error
ISCE	improved shuffled complex evolution
k	Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K)
KCL	Kirchhoff's current law
L	relative positions of simplex
LB	lower bound
m	complex size
MPP	maximum power point
Max_NFEs	maximum number of function evaluations
n, n_1, n_2, n_m	diode ideality factors
N	number of experimental I–V data
N_s	number of cells in series
N_p	the strings of cells connected in parallel
$NFEs$	number of function evaluations
p	number of complexes
P	probability or power
q	simplex size
R_s, R_{sm}	series resistance (Ω)
R_{sh}, R_{shm}	shunt resistance (Ω)
$RMSE_{cal}$	calculated root mean square error
$RMSE_{sim}$	simulated root mean square error
s	population size
SCE	shuffled complex evolution
SDM	single diode model
SMM	solar module model
thV	threshold value of RMSEcal
T	cell temperature (K)
UB	upper bound
V	terminal voltage (V)
Vth	thermal voltage (V)
x	Sample point
X	unknown parameter vector
u_d	main diagonal of simplex
u_e	extension point
u_{ic}	inside contraction point
u_{oc}	outside contraction point
u_q	the worst vertex of simplex
u_r	reflection point
u_z	random point within H
α	number of iteration for each simplex
β	number of offspring

[20]. Consequently, analytical methods are usually uncertain and offer unsatisfied results in most cases. On the contrary, numerical methods take all measured I–V data into consideration for extracting solar cell parameters at a higher confidence level. Hence, with developments in mathematics and computer science, numerical methods have prevailed in solving the problem of solar cell parameter extraction. In recent years, various deterministic methods [21–27], traditional evolutionary algorithms [28–40] and bionics evolutionary algorithms [41–59] have been applied in this field. Deterministic methods are sensitive to initial values and prone to be trapped in local minima. Although evolutionary algorithms give higher accuracy and better computational efficiency than deterministic methods, their performance depends strongly on the proper tuning of control parameters. Any improper choice can result in slow convergence and premature termination of iterations. Therefore, searching for accurate and efficient numerical algorithm to solve the problem of solar cell parameter extraction is still ongoing.

The shuffled complex evolution (SCE) is an effective and efficient global optimization algorithm developed by Duan [60] at the University of Arizona. In principle, SCE algorithm is a synthesis of four concepts that have proved successful for global optimization: controlled random search, competition evolution, complex shuffling, and the reflection step and inside contraction step of Nelder-Mead simplex algorithm [61]. The first three concepts ensure SCE algorithm flexible and robust to share the information gained independently by each complex, and thus intensify the global searching ability and avoid being trapped in local minima. As the most popular direct-search method, the deterministic Nelder-Mead simplex algorithm is powerful in local search, which can better guide the directions of global optimization. From these points of view, SCE algorithm combines the strengths of population-based stochastic evolution and deterministic direct-search to accomplish the global minimization. To sum up, the attractive features of SCE algorithm are as follows: (1) Simple to understand and easy to program; (2) Free from derivatives and lower sensitivity to initial value; (3) Powerful global search ability and high probabilistic convergence to global optimum. Given these advantages, SCE algorithm and its variants [62–66] have successfully been applied in many engineering problems, especially for hydrological model calibration. However, an exhaustive examination of the literature reveals that there is less work on the application of SCE algorithm for solving the parameter extraction problem of solar cell models. The reason behind this is that SCE algorithm has slow convergence rate when coping with the complex problems involving numerous local minima.

In light of the preceding discussion, the main contribution of this paper is to propose an improved shuffled complex evolution (ISCE) algorithm that is perfectly well capable of solving the parameter extraction problem of SDM and DDM. The main idea of proposed ISCE algorithm is to reduce the randomness and improve the probability of producing better solution, and thus to ensure the population evolving continuously toward the global optimum. To this end, three amendments are proposed to overcome the shortcomings of original SCE algorithm. The other contribution of this paper is to test the parameter extraction performance of proposed ISCE algorithm and compare it with some reported state-of-the-art algorithms. To be objective and reproducible, the standard datasets and practical measured datasets of one solar cell and three solar modules are selected for parameter extraction of different PV models. The parameter extraction results of proposed ISCE algorithm is indirectly compared with some state-of-the-art algorithms and directly compared with the best reported EHA-NMS [25] and R_{cr}-IJADE [35] algorithms in detail. Accuracy, convergence speed and robustness are chosen as the performance criteria to evaluate the parameter extraction results of them. Comparison results demonstrate that the proposed ISCE algorithm consistently exhibits better performance than reported algorithms in most cases.

The rest of this paper is organized as follows. Section 2 describes the PV models used in this work together with the objective function to be optimized for parameters extraction. Section 3 introduces the original SCE algorithm and its shortcomings. Section 4 presents the proposed ISCE algorithm in detail. Section 5 elaborates and compares the