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Parameter extraction of solar photovoltaic models using an improved whale optimization algorithm

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ABSTRACT

Parameter extraction of solar photovoltaic (PV) models is a typical complex nonlinear multivariable strongly coupled optimization problem. In this paper, an improved whale optimization algorithm (WOA), referred to as IWOA, is proposed to accurately extract the parameters of different PV models. The original WOA has good local exploitation ability, but it is likely to stagnate and suffer from premature convergence when dealing with complex multimodal problems. To conquer this concerning shortcoming, IWOA develops two prey searching strategies to effectively balance the local exploitation and global exploration, and thereby enhance the performance of WOA. Three benchmark test PV models including single diode, double diode and PV module models, and two practical PV power station models with more modules in the Guizhou Power Grid of China are employed to verify the performance of IWOA. The experimental and comparison results comprehensively demonstrate that IWOA is significantly better than the original WOA and three advanced variants of WOA, and is also highly competitive with the reported results of some recently-developed parameter extraction methods.

1. Introduction

Solar energy has gained the highest attention (highest growth rate) worldwide in the last years due to its potential availability, good visibility, and safe use for small and large scales by residential, commercial, and utility-scale users [1]. China, for example, added about 42 GW of solar photovoltaic (PV) power capacity in the first nine months of 2017, and the total PV installed capacity has risen to 119 GW [2]. In such a context, the PV system, which directly converts solar energy into electricity, has attracted increasing attention in recent years. In order to study the dynamic conversion behavior of a PV system, one first needs to know how to model its basic device, i.e., the PV cell. Many approaches have been developed to model PV cells and the most popular one is the use of equivalent circuit models [3]. Among which the widely used circuit models are the single diode model and double diode model. After selecting an appropriate model structure, the accuracy of the parameters associated with the structure is crucial for modeling, sizing, performance evaluation, control, efficiency computations and maximum power point tracking of solar PV systems [4,5]. However, these model parameters, in general, are unavailable and changeable due to the following two reasons. On one hand, the manufacturers usually provide only the open circuit voltage, short circuit current, maximum power point current, and voltage under standard test condition (STC). But the actual environmental conditions are always changing and are far from the STC. On the other hand, the value of these parameters changes over time due to the PV degradation [6]. Therefore, how to achieve or extract accurate parameters is of high importance and significance, and has been highly attracted by researchers [4].

In order to handle this complex yet important problem, a good number of methods have been proposed. These methods can be divided into two types: analytical methods [7–15] and optimization methods. The former, mainly based on the key data points provided by the manufacturers, utilizes mathematical equations to derive the model parameters. However, we know that the value of these points is achieved under the STC and thereby they are not enough to predict accurate current–voltage (*I-V*) characteristic curves under varying insolation and temperature levels [16]. With regard to the optimization methods, they can be further categorized into deterministic and heuristic methods from the algorithmic perspective. Both methods transform the parameter extraction problem into an optimization problem and then use some reference points of a given *I-V* characteristic curve to extract the parameters. The deterministic methods, including the least squares (Newton-based method) [17], Lambert W-functions [18], iterative curve fitting [19], impose various restrictions such as

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Nomenclature

a	parameter linearly decreased from 2 to 0
A, C	coefficients
b	constant
D	dimension of individual vector
I_d	diode current (A)
I_L	output current (A)
I_{ph}	photo generated current (A)
I_{sd}, I_{sd1}, I_{sd2}	saturation currents (A)
I_{sh}	shunt resistor current (A)
k	Boltzmann constant ($1.3806503 \times 10^{-23}$ J/K)
l, p	random real numbers in (0, 1)
n, n_1, n_2	diode ideality factors
N	number of experimental data
N_p	number of cells connected in parallel
N_s	number of cells connected in series
ps	size of population
q	electron charge ($1.60217646 \times 10^{-19}$ C)
R_s	series resistance (Ω)
R_{sh}	shunt resistance (Ω)
t	current iteration
T	cell temperature (K)
VL	output voltage (V)
Vt	diode thermal voltage (V)
x	extracted parameters vector
$x_{i,d}$	dth parameter of ith individual vector
Xi	ith individual vector
Xg	best position found so far
X_r, X_{r1}, X_{r2}	random individual vectors
I-V	current–voltage
P-V	power–voltage
PV	photovoltaic
RMSE	root mean square error
Min	minimum RMSE
Max	maximum RMSE
Mean	mean RMSE
Std Dev	standard deviation
WOA	whale optimization algorithm
CWOA	chaotic WOA
IWOA	improved WOA
LWOA	Lévy flight trajectory-based WOA
PSO-WOA	hybrid particle swarm optimization-WOA
STC	standard test condition

continuity, convexity, and differentiability on the objective functions. In addition, they are sensitive to the initial condition and gradient information and thereby are easily trapped into local optima when dealing with complex multimodal problems. These limitations make the deterministic methods encounter many difficulties and challenges when solving the nonlinear multimodal parameter extraction problem. Alternatively, the heuristic methods have no strict requirements on the form of optimization problems and can avoid the influences of the initial condition sensitivity and gradient information. Consequently, they have received considerable attention recently. The successfully implemented heuristic methods for the parameter extraction of PV models include genetic algorithm (GA) [20,21], particle swarm optimization (PSO) [22–24], differential evolution (DE) [25–28], artificial bee colony (ABC) [29], biogeography-based optimization (BBO) [30], harmony search (HS) [31], bacterial foraging algorithm (BFA) [32,33], teaching–learning-based optimization (TLBO) [34–36], water cycle algorithm (WCA) [37,38], flower pollination algorithm (FPA) [39], bird mating optimizer (BMO) [40], multi-verse optimizer (MVO) [41], asexual reproduction optimization (ARO) [42], fireworks algorithm (FWA) [43], cat swarm optimization (CSO) [44], ant lion optimizer (ALO) [45], moth-flame optimization (MFO) [46], hybrid methods [47–52], etc.

Whale optimization algorithm (WOA), proposed in 2016 [53], is a very young yet powerful population-based heuristic method inspired by the special spiral bubble-net hunting behavior of humpback whales. It has already proven a worthy optimization method compared with other popular population-based methods such as GA, PSO, and DE. Owing to its simplicity and efficiency, WOA has been successfully applied to various fields, such as reactive power dispatch [54], neural network [55], image segmentation [56], and feature selection [57], wind speed forecasting [58].

However, similar to other population-based methods, WOA also faces up to some challenges. One typical issue in point is that, it converges fast in the very beginning of the evolutionary process, but it is easily trapped into local search later and thereby suffers from prematurity when solving multimodal problems. The main reason is that, for a population-based method, it is well known that both the global exploration and local exploitation are indispensable. However, they are usually in conflict in practice. In such a context, it is important to balance them, especially in dealing with complex multimodal problems. With regard to the original WOA, it is good at exploiting the local search space, but lacks enough global exploration ability to jump out of local optima. In order to remedy the drawback mentioned, an improved WOA variant, referred to as IWOA, is proposed in this paper. IWOA, which develops two prey searching strategies to enhance the performance of WOA, is able to effectively balance the local exploitation and global exploration. The experimental and comparison results comprehensively demonstrate that IWOA is able to conquer premature convergence and to accelerate the global searching process simultaneously.

The main contributions of this work are as follows:

(1) An improved WOA method, IWOA, is proposed for the parameter extraction of PV models. IWOA, based on the deep analysis of the drawback of the original WOA, employs two proposed prey searching strategies to effectively balance the exploitation and exploration.
(2) IWOA is applied to three benchmark test PV models and two practical PV power station models with more modules in the Guizhou Power Grid of China. Multiple performance aspects including solution quality, convergence speed, robustness, and statistics are evaluated to comprehensively verify the effectiveness of IWOA.
(3) The performance of IWOA is extensively compared with the original WOA and three advanced variants of WOA, as well as those reported results of some recently-proposed parameter extraction methods. The comparison results consistently demonstrate that IWOA is highly competitive and can be used as an effective alternative to solve the parameter extraction problem of PV models.

The remainder of this paper is organized as follows. Section 2 presents the original WOA and the proposed IWOA. Section 3 briefly introduces the PV models and the mathematical formulation of parameter extraction problem. In Section 4, experimental results and comparisons are provided. Finally, Section 5 is devoted to conclusions and future work.

2. Improved whale optimization algorithm

2.1. Whale optimization algorithm (WOA)

WOA [53] is a very young yet powerful population-based algorithm inspired by the special spiral bubble-net hunting behavior of humpback