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Parameter estimation of photovoltaic cells using an improved chaotic whale optimization algorithm

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H I G H L I G H T S

- We modify the whale algorithm using chaotic maps.
- We apply a chaotic algorithm to estimate parameter of photovoltaic cells.
- We perform a study of chaos in whale algorithm.
- Several comparisons and metrics support the experimental results.
- We test the method with data from real solar cells.

A R T I C L E I N F O

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A B S T R A C T

The using of solar energy has been increased since it is a clean source of energy. In this way, the design of photovoltaic cells has attracted the attention of researchers over the world. There are two main problems in this field: having a useful model to characterize the solar cells and the absence of data about photovoltaic cells. This situation even affects the performance of the photovoltaic modules (panels). The characteristics of the current vs. voltage are used to describe the behavior of solar cells. Considering such values, the design problem involves the solution of the complex non-linear and multi-modal objective functions. Different algorithms have been proposed to identify the parameters of the photovoltaic cells and panels. Most of them commonly fail in finding the optimal solutions. This paper proposes the Chaotic Whale Optimization Algorithm (CWOA) for the parameters estimation of solar cells. The main advantage of the proposed approach is using the chaotic maps to compute and automatically adapt the internal parameters of the optimization algorithm. This situation is beneficial in complex problems, because along the iterative process, the proposed algorithm improves their capabilities to search for the best solution. The modified method is able to optimize complex and multimodal objective functions. For example, the function for the estimation of parameters of solar cells. To illustrate the capabilities of the proposed algorithm in the solar cell design, it is compared with other optimization methods over different datasets. Moreover, the experimental results support the improved performance of the proposed approach regarding accuracy and robustness.

1. Introduction

The air pollution is a situation that affects all the countries in the world. Along decades, fossil fuels have been used as energy sources. However, their using has affected the cities of several countries. Nowadays, the effects of the abuse on using this kind of energy sources are reflected in the global warmness. As a result, many nations put more attention to renewable energies. One of the

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most efficient renewable sources is the solar energy that is currently explored, and it is used to contribute in the rising demands for energy supplies. According to [1], the solar photovoltaic (PV) power generation technology had a new record in the world in 2015, increasing their capacities 25% up to 2014. Moreover, PV is an emission-free distributed generation system that is able to directly convert solar energy to electricity and supply power for specific purposes. Solar energy has several advantages compared with other typical sources. However, it has some disadvantages that represent open research problems. The main drawbacks of PV energy are the high initial investment and the low efficiency of the solar cells [2]. In the same way, since PV modules are outdoors, the energy is affected by weather. This fact also implies to a high cost of the maintenance and the replacement of modules [3,4].

The efficacy of the solar cells (SC) system is affected by weather and its design [3,4]. Considering such situations, an accurate design of PV cells is a crucial and challenging task in this field. There are two basic steps for modeling the PV cells: (1) the mathematical model formulation and (2) The estimation accuracy of PV cells parameter values. On the mathematical model, there are characteristics of the Current vs. Voltage (*I-V*) that dominates the SC behavior. Several mathematical approaches have been developed to describe the nonlinearity performance of the PV systems [5–12]. In practical terms, the single diode (SD) model and double diode (DD) model are equivalent electronic circuits that are extremely used to define a solar cell. The SD model that has five unknown parameters and the DD model which is required to find seven unknown parameters [13,14]. Regardless of the selected model, it is necessary to estimate or identify the photo-generated current, the diode saturation current, the series resistance, and the diode ideality factor. Such parameters directly affect the performance of the SC and photovoltaic panels. The biggest problem could be established as determining the optimal values of parameters which are applied to the selected model and approximate the results of the experimental data from the real SC [13].

The problem of identifying the PV cells parameters should be defined from an optimization point of view. In other words, it is necessary to specify an objective function based on the characteristics of the *I-V* of the SC. Considering the data is commonly obtained from the measurements, it has a certain degree of noise. The resultant search space produced by the objective function is high multimodal and complex to be solved by the classical algorithms that involve gradient operators [15–17].

The deterministic approaches are the most conventional or classic methodologies to estimate the PV parameters. For example, the least squares (Newton-based approach) [18], Lambert W-functions [19,20], the iterative curve fitting [21] and tabular method [22]. There exist some interesting studies that analyze different methods [23,24]. The using of the deterministic techniques implies to several model restrictions such as differentiability and convexity to be correctly applied [23]. Therefore, their outputs are affected by the initial solutions, which lead to local optima. For example, the application of the Newton-Rapson method [25] to the DD model, which presents a large deviation among the real, and the estimated of the current and voltage values [26]. The stochastic methods are an alternative efficient solution that avoids the situation presented by deterministic algorithms. In this group, they included the heuristic and the metaheuristic approaches that can solve complex problems considering simple initial conditions. In specifically, the results of metaheuristic algorithms are better than those which are based on deterministic methods considering robustness and accuracy [13,27–33]. In the related literature, they are exist several implementations to solve the solar cells parameter identification problem. Such methods include Genetic Algorithms (GA) [28,34], Particle Swarm Optimization (PSO) [10,35], Simulated Annealing (SA) [29], Harmony Search (HS) [13], Bacterial Foraging Algorithm (BFA) [30], Simplified Teaching-Learning Based Optimization (STBLO) [36] and Cat Swarm Optimization (CSO) [37]. Although heuristic methods present a higher probability of obtaining a global solution in comparison with deterministic ones, they have critical limits [27]. For example, the No Free Lunch (NFL) theorem that has been logically proved, states that not all the optimization algorithms can be used to solve all the problems [38]. Meanwhile, a considerable amount of metaheuristic methods have several parameters that should be experimentally tuned. This fact affects their efficacy and accuracy. On the other hand, depending on the search surface, the algorithms could be trapped into local optimal values, and their performance is degraded along the iterations. On the other hand, the design and the operators of each algorithm make it able to optimize some problems better. For example, in the case of the classical PSO and GA, they maintain a trend that concentrates toward local optima, since their elitist mechanism forces premature convergence [39,40]. Such a behavior becomes worse when the optimization algorithm faces multi-modal functions [41,42]. Since the SA and HS use only one search agent, they are very sensitive to the initialization. The use of only one search element affects the probability of localizing the global optimal in multimodal search spaces in comparison with GA or PSO [43,44]. Therefore, HS, GA, SA, and PSO present a deficient performance in the application over noisy and multi-modal objective functions. Considering these circumstances most of the stochastic approaches presents a bad performance for this problem [45]. In the problem of parameter estimation of SC, the use of accurate optimization approaches affects the SC system design that is reflected on the cost reduction [14,22]. However, metaheuristic approaches are a good alternative since they can achieve optimal solutions using processes that are not computationally expensive.

In the context of the metaheuristic methods, the Whale Optimization Algorithm (WOA) [46] was recently proposed as an alternative one for the global optimization problems. The WOA is inspired by the hunting behavior of the humpback whales. The WOA generates a random group of initial solutions, in the optimization process, each candidate solution takes a new position in the search space considering as a reference, the best element of the group. Some internal parameters are used to generate the whale's behavior. According to the authors, the values of such parameters is adaptive in the iterative process, and they guarantee a good relationship between the exploration and the exploitation. The main advantage of WOA is the simulation of the mechanism to chase the prey using the randomness of the best search agents and the using of spiral to mimics the bubble-net attraction process of humpback whales [46]. This mechanism differs the WOA from the other similar approaches. On the other hand, the WOA possesses few parameters to set and also the most important parameters are self-tuning along the iterative process. Considering these facts, WOA has two main drawbacks, (1) its adaptive parameter depending on the random distribution and (2) like another metaheuristic (evolutionary and swarm) algorithms, it has a premature convergence. It happens especially in problems that possess high multimodal search spaces. The WOA has been tested over different benchmark functions and engineering design benchmark problems [46].

Recently, the chaos theory has more attention improving the performance of metaheuristic algorithms [47]. It is described as erratic behavior in nonlinear systems through using the chaotic maps. These maps are treated as particles which travel in a limited range of nonlinear and dynamic system without definite regularity traveling path of these particles. The chaotic sequence with high randomness improves the diversity of solutions and its convergence, these features have been tested after several studies in the related literature [47].