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# An improved explicit double-diode model of solar cells: Fitness verification and parameter extraction

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ABSTRACT

Accurate simulation of photovoltaic characteristics is now a mandatory obligation before validating an experiment; hence, accurate model and parameters of solar cells are indispensable. This paper presents an improved explicit double-diode model based on the Lambert W function (EDDM-LW), and then compares the fitness and parameter extraction performance. By defining two new parameters ($\kappa$ and $\tau$) to separate the exponential function in double-diode model (DDM) and using the Lambert W function, the explicit expression for *I-V* characteristics is proposed. In contrast to exiting works, the new parameters can readily be computed by the electrical characteristics of the standard test condition without an implicit characteristic. To verify the accuracy of the proposed model, the fitness difference is first investigated with a solar cell and three different types of solar modules. The results indicate that under the same parameter values, EDDM-LW achieves the lowest root mean square error value and exhibits better fitness in representing the *I-V* characteristics. In addition, the optimal parameters are extracted by an improved teaching-learning-based optimization algorithm. The experimental results show that the optimal parameter values extracted from EDDM-LW are more accurate than those extracted from DDM. Based on these observations, EDDM-LW can be deemed a useful and practical model for the simulation, evaluation, and optimization of the photovoltaic system.

## 1. Introduction

Because of a decrease in conventional energy resources and an increase in environmental pollution, solar energy has increasingly received more international support and attention as a type of green energy. In addition, research has focused on improving the quality of solar cells and the efficiency of photovoltaic (PV) generation systems [1]. To predict the behavior of the PV system and optimally utilize the available solar energy, an efficient and accurate simulation model is indispensable [2]. With such a model, the characteristics of solar cells can be precisely emulated; that is, the calculated values fit the measured *I-V* data under all conditions, which is useful for production process improvement, simulation [3], evaluation and maximum energy harvesting of the PV system [4].

Over the years, many models have been published in the literature, and two equivalent circuit models are commonly used: single-diode model (SDM) [5] and double-diode model (DDM) [6]. DDM considers the composite effect of the neutral region and the space charge regions of the junction. Therefore, it can characterize the solar cells more accurately [7]. However, DDM is an implicit nonlinear transcendental equation and has seven unknown parameters. The inherent nature of this model hampers not only solar cell parameter extraction but also PV system simulation [8]. Therefore, many scholars have proposed various methods to extract the optimal parameters for the accurate simulation of PV characteristics, all of which can be divided into analytical methods [9] and metaheuristic algorithms [10].

Because of the complexity of DDM, the analytical methods usually solve the problem by reducing the number of parameters or assuming the parameter dimension. Ishaque et al. [11] assumed that the values of both saturation currents are equal ($I_{o1} = I_{o2}$), while one of the diode ideality factors was assigned as 1, thereby decreasing the number of parameters to five. However, equating the two currents does not make any physical sense. Babu et al. [12] and Hejri et al. [13] simplified the model by neglecting the parallel resistance or series resistance. However, these parameters greatly affect the model accuracy, especially in the vicinity of the open circuit voltage. The analytical method is simple and fast. However, the subjective hypothesis and omitted parameters affect the model's accuracy.

Metaheuristic algorithms impose no restrictions on the problem formulation; thus, numerous metaheuristic algorithms or their variants have been applied to the parameters identification of solar cells. Some of the optimization techniques are as follows: simulated annealing (SA)

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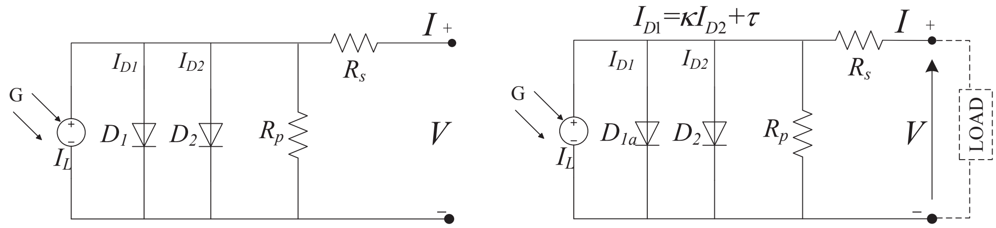

(a) Double-diode model [31] (b) The improved double-diode model

**Fig. 1.** Equivalent circuit of a solar cell under illumination.

[14], differential evolution (DE) [15], penalty-based differential evolution (P-DE) [16], artificial bee swarm optimization (ABSO) [17], flower pollination algorithm (FPA) [18], bird mating optimization (BMO) [19], partial swarm optimization (PSO) [20], artificial bee colony (ABC) [21], chaotic asexual reproduction optimization (CARO) [22], simplified swarm optimization (SSO) [23], and so on. However, DDM is an implicit nonlinear transcendental equation. In the calculation process, the measured current value is used as the original data to solve for the calculated current value. The implicit coupling relationship reduces the calculation accuracy.

Inspired by the superiority of the exact explicit single-diode model with more accurate *I-V* characteristics [24], maximum power point tracking (MPPT) [25], and efficient model parameter extraction [26], in recent years, the exact explicit expressions of DDM with two Lambert W function have been developed. Lugo-Munoz et al. [27] proposed a nonequivalent-$R_s$-connected two-diode model, which split the series resistance into two parts ($R_{s1a}$, $R_{s1a}$) and connected them to the diodes directly, thereby establishing an alternative model. Ortiz-Conde et al. [28] proposed another alternative model of DDM. The circuit was substituted by two equivalent resistances ($a_1R_{TH}$, $a_2R_{TH}$) in series with each of the two diodes. However, these alternative models are only approximations of DDM, because they are not exactly analogous for all possible arbitrary sets of parameters. Moreover, the extra parameters of these alternative models make parameter extraction even more difficult. Thus, some explicit expressions which maintain the original parameters and loyal to DDM have been developed.

Lun et al. [29] proposed a new explicit double-diode modeling method based on the assumption that both diode ideality factors were equal ($n_1 = n_2$). However, the relationship has no physical basis and is not always reliable. Dehghanzadeh et al. [30] proposed an approximate explicit double-diode model. A piecewise linear model was employed to approximate the two diodes. Unfortunately, the new parameter ($a$) cannot be generally defined by a mathematical function, which also results in parameter extraction difficulty. Gao et al. [31] proposed a Lambert W function based on the exact representation (LBER) for DDM. In this work, a vector $r$ was defined as the Lambert W function coefficient, which was denoted by the ratio of the diffusion current to the sum of the diffusion and recombination currents. LBER is derived without an approximation and has a high precision. Regrettably, $r$ is a change variable and is closely related to the terminal current and terminal voltage. Therefore, LBER still has an implicit characteristic. As compared to the alternative models, these new explicit solutions of DDM retain the concept and values of conventional double-diode parameters. However, the new parameter is either difficult to solve or has implicit features.

In light of the preceding discussions, this paper proposes an improved explicit double-diode model based on the Lambert W function (EDDM-LW) of solar cells. In contrast to existing works, the new parameters for the coefficients of the Lambert W function can readily be computed by the electrical characteristics of the standard test condition (STC), which leads to the fact that EDDM-LW contains only seven parameters identical to those included in DDM and does not exhibit an implicit characteristic. Moreover, it is derived from the general model DDM and should therefore suitable for various solar cells. To verify the accuracy of EDDM-LW, the proposed model is first investigated on the fitness difference among EDDM-LW, DDM and LBER under the same parameter values of the solar cells. It is implemented on the reported parameter values and experimental *I-V* data of a solar cell and three types of solar modules: commercial RTC France silicon solar cell [32], mono-crystalline (SM55) module [33], multi-crystalline (S75) module [34], and thin-film (ST40) module [35]. This paper then investigates the parameters exaction performance of EDDM-LW. An improved teaching-learning-based optimization (ITLBO) algorithm is employed for parameter extraction of EDDM-LW with the aim of validating the higher accuracy of the optimal parameter values extracted from EDDM-LW as compared those extracted from DDM.

The remainder of this paper is structured as follows. Section 2 describes the derivation of the EDDM-LW in detail. Section 3 investigates the fitness difference of the EDDM-LW with DDM and LBER. Section 4 presents an ITLBO algorithm base on the hybrid strategy. This is followed by the parameter extraction results, simulated curves and discussions in Section 5. Finally, Section 6 presents the conclusions.

## 2. Explicit double-diode model based on the Lambert W function (EDDM-LW)

### 2.1. Double-diode model

DDM [36] is one of the most popular models because of its accurate representation of solar cell characteristics, especially at low illumination levels. It is widely used for first- and second-generation PVs [37]. The equivalent circuit of DDM represented in Fig. 1(a). The two diodes reflect the physical phenomena of the P-N junction. One indicates the diffusion process whereas the other shows the composite effect of the space charge regions. Series resistance represents initial losses and shunt resistance represents the modeling of the reverse saturation current [30].

According to Kirchhoff's current law, the *I-V* relationship can be represented by the following DDM Eq. (1).

$$I = I_L - I_{D1} - I_{D2} - \frac{V + IR_s}{R_p} \tag{1}$$

where $I$ is the terminal current; $V$ is the terminal voltage; $I_L$ is the photogenerated current; $I_{D1}$ and $I_{D2}$ define the diffusion and recombination currents, respectively; $R_s$ is the series resistance; and $R_p$ is the shunt resistance. In addition, according to the Shockley equation, $I_{D1}$ and $I_{D2}$ can be expressed as follows:

$$I_{D1} = I_{o1}\left[\exp\left(\frac{V + IR_s}{n_1 V_{th}}\right) - 1\right] \tag{2}$$

$$I_{D2} = I_{o2}\left[\exp\left(\frac{V + IR_s}{n_2 V_{th}}\right) - 1\right] \tag{3}$$

where $n_1$ and $n_2$ are the diode ideality factors; $I_{o1}$ and $I_{o2}$ are the