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A three diode model for industrial solar cells and estimation of solar cell parameters using PSO algorithm

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ABSTRACT

A new lumped-parameter equivalent circuit model using three-diodes is presented in this work for large area (~154.8 cm^2) industrial silicon solar cells. The estimation of values of ideality factors n_1 (>1) and n_2 (>2) using a Particle Swarm Optimization (PSO) algorithm for the two-diode model of the industrial samples has been found not to be in conformity with the theoretical values ($n_1 = 1$ and $n_2 = 2$ in the literature). The two diodes of the two-diode model are not able to define the different current components of the solar cells clearly. A model with three-diodes has been proposed to better explain the experimental data. In the proposed model, we considered the series resistance, R_s, of the solar cell to vary with the current flowing through the solar cell device. All the parameters of the proposed model have been estimated using a PSO algorithm and they were compared with the parameters of the two-diode model. The new model has been found to be a better model to define clearly the different current components of the large size industrial silicon solar cells.

1. Introduction

Modeling of a solar cell is required to predict the behaviour of a real solar cell under various environmental conditions and thereafter to generate its current–voltage (I–V) and power-voltage (P–V) characteristic curves. The common approach is to utilize the electrical equivalent circuit, which is primarily based on a light generated current source connected in parallel to a p–n junction diode. Many models have been proposed for the simulation of a single solar cell or for a complete photovoltaic (PV) system at various solar intensities and temperature conditions [1–5]. Different models have also been used to study the shading effect on PV systems [6–8]. Two most commonly used equivalent circuit models of the solar cell in the literature are one-diode and two-diode models [1–8].

1.1. One-diode and two-diode models

An ideal solar cell is represented by a light generated current source, I_{ph}, where I_{ph} is proportional to the solar radiation falling on it. Practical light generated current behaviour deviates from the ideal behaviour due to optical and electrical losses inside the solar cell. In the one-diode model, one diode is connected in parallel to a light generated current source as shown in Fig. 1(a). Diode current, I_d, represents the current due to diffusion and recombination in the Quasi Neutral Regions (QNRs) of the emitter and bulk regions of the P–N junction. The series resistance, R_s, represents the resistance in the path of the current, due to contact resistances and resistance in the emitter and bulk regions. Shunt resistance, R_{sh}, represents the current leakage across the P–N junction of the solar cell and so it is connected in parallel to the diode in the equivalent circuit model. On the other hand, the two-diode model shown in Fig. 1(b) considers two-diodes connected in parallel to the current source. The current through the first diode, I_{d1}, is the current component, which is the same as I_d in the one-diode model. The current due to recombination in the Space Charge Regions (SCRs) is also considered in the two-diode model and is represented by the diode current, I_{d2} through a second diode. Series resistance, R_s, and shunt resistance, R_{sh}, are the same resistance components as defined for the one-diode model.

The load current (I) and the load voltage (V) are related through Eqs. (1a) and (2a) for the one-diode and the two-diode models respectively.

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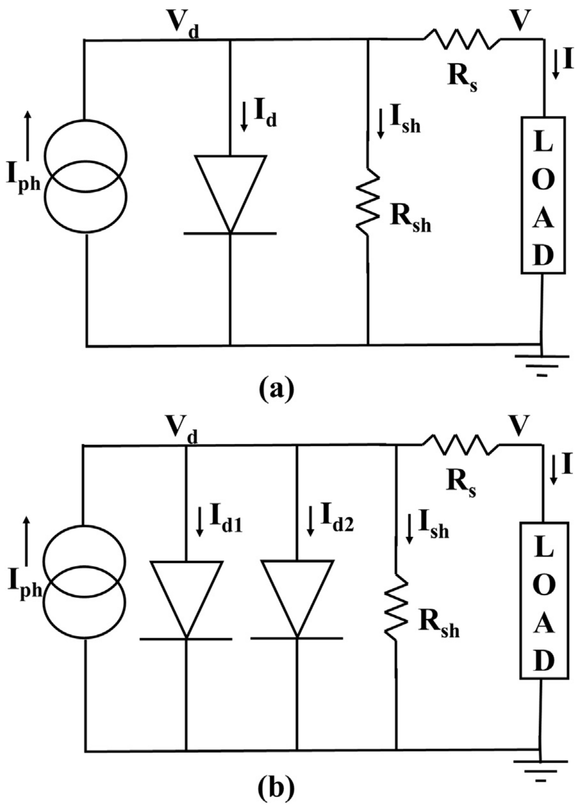

Fig. 1. (a) One-diode model of a solar cell (b) Two-diode model of a solar cell.

$$I = I_{ph} - I_0\left\{exp\left[\frac{q(V+IR_S)}{nkT}\right] - 1\right\} - \frac{V+IR_S}{R_{sh}} = I(V, I, parameters1) \tag{1a}$$

$$where\ parameters1 = \left\{I_{ph},\ I_0,\ n,\ R_S,\ R_{sh}\right\} \tag{1b}$$

$$I = I_{ph} - I_{01}\left\{exp\left[\frac{q(V+IR_S)}{n_1kT}\right] - 1\right\} - I_{02}\left\{exp\left[\frac{q(V+IR_S)}{n_2kT}\right] - 1\right\} - \frac{V+IR_S}{R_{sh}} = I(V, I, parameters2) \tag{2a}$$

$$where\ parameters2 = \left\{I_{ph},\ I_{01}, n_1, I_{02}, n_2,\ R_S, R_{sh}\right\} \tag{2b}$$

For one-diode model, the value of ideality factor, n, is between 1 and 2. For two-diode model, two ideality factors, n_1 and n_2 should be 1 and 2 respectively.

The number of parameters as given in Eq. (1b) for modeling in case of the one-diode model is five. These parameters are light generated current, I_{ph}, diode parameters: reverse saturation current, I_0, and ideality factor, n, series resistance, R_s, and shunt resistance, R_{sh}. In the two-diode model, the number of parameters becomes seven as given in Eq. (2b). The parameters are the reverse saturation currents I_{01} and I_{02} and ideality factors n_1 and n_2 for the two diodes, along with other parameters - I_{ph}, R_s and R_{sh}. Estimation of all parameters of a solar cell model is required for modeling the performance of any photovoltaic system. Many analytical and numerical methods [9–14] have been suggested in the literature to estimate some or all parameters of the one-diode model or the two-diode model from measured I–V characteristics. Heuristic methods such as genetic algorithms, pattern search algorithm, differential evolution and particle swarm optimization have been suggested by others [15–26] for the same purpose. Heuristic methods have shown better precision and computational efficiency for estimation of solar cell parameters as compared to analytical and numerical methods. Recently, a swarm intelligence based method called Particle Swarm Optimization (PSO) has been successfully applied to various fields of power system. Phuangpornpitak et al. [19] have presented a survey on the application of PSO in solving optimization problems in electric power systems. Kongnam and Nuchprayoon [20] have applied PSO to a wind energy control problem. PSO algorithm has been used to solve for optimum rotor speed under fixed-speed operation and optimum tip-speed ratio under variable-speed operation. Qin and Kimball [21] presented an approach to extract parameters of a PV cell using PSO. PSO was applied only on single diode model and some parameters were predicted beforehand. Only n, R_s and R_{sh} were estimated using PSO. Sandrolini et al. [22] used a PSO algorithm for the extraction of the double-diode model parameters of photovoltaic (PV) modules. Authors used PSO algorithm to fit the calculated current–voltage characteristic of a PV module to the experimental one.

In this paper, a new lumped-parameter equivalent circuit model using three diodes, has been proposed for large area crystalline silicon solar cells. In addition, in the proposed model, the parameter, R_s has been considered to vary linearly with the load current through the device and thus the variation of R_s with the load current has been studied on the same large area solar cell samples in this work. The aim of this work is to suggest a better model for the bigger size industrial solar cells and to estimate the parameters of the model by fitting the calculated I–V curves to the measured I–V curves, through an iterative process using the PSO algorithm.

This paper is organized as follows. Section 2 discusses the theory of the proposed model followed by an overview of the PSO algorithm. Section 3 describes the experimental methods used for the fabrication of the solar cell samples and measurement of the current–voltage characteristics. The procedure used for parameter extraction is discussed in Section 4. Results are discussed in Section 5. The comparison of two models, existing and new, is highlighted in Section 6 and finally the paper is concluded in Section 7.

2. Theory

2.1. Proposed model: three-diode model with variable R_s

For the two-diode model, the ideal values of n_1 and n_2 would be 1 and 2 respectively; but for industrial samples of size as big as about 154.8 cm^2 and efficiency about 16%, n_1 was estimated between 1 and 1.5 and n_2 was estimated between 2 and 5. These values indicated that the two diodes were not sufficient to represent the different current components of the experimental solar cells clearly.

In this work, a three-diode model has been proposed, as illustrated in Fig. 2. In the model, the first diode would contribute the diode current (I_{d1}) due to diffusion and recombination in the quasi neutral regions (QNRs) of the emitter and bulk regions with $n_1 = 1$, and the second diode would contribute the diode current (I_{d2}) due to recombination in the space charge region (SCR) with $n_2 = 2$. The purpose of adding a third diode in parallel to the two diodes is to consider contribution of the diode current component (I_{d3}), due to recombination in the defect regions, grain sites, etc. The ideality factor, n_3, of the third diode is to be estimated along with other parameters of the model and is predicted to be varying between 2 and 5 depending on the local factors as mentioned in Ref. [27].