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Statistical analysis and engineering fit models for two-diode model parameters of large area silicon solar cells

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ABSTRACT

In this paper, an attempt has been made to find the correlation between various parameters of the two-diode equivalent circuit model of silicon solar cells. The statistical analysis has been done to find the engineering fit models between these parameters. The solar cell parameter data of 82 solar cell samples has been estimated using the Particle Swarm Optimization method from the measured illuminated *I-V* characteristics of the cells. This data on estimated parameters has been used to find the Pearson's correlation coefficient between different parameters and the significant outcome of this work is that it revealed a high correlation between the first diode's reverse saturation current and its ideality factor and a medium correlation between the second diode's reverse saturation current and its ideality factor in the two-diode equivalent circuit model of a silicon solar cell. An engineering fit model has been suggested between the reverse saturation current and ideality factor of the first diode, based on the data of 82 large area (∼154.8 cm^2) silicon solar cells with AM1.5 conversion efficiency between 15% and 18.4%. The suggested engineering fit between the two would be a method to reduce the number of parameters needed for silicon solar cell modeling and to make it easier for predicting the module output.

1. Introduction

Due to growing problems of pollution and global warming from the use of fossil fuels, use of the solar energy has gained more attention in recent years. Photovoltaic (PV) conversion of solar energy into electricity is a pollution free and noise free source of energy for electricity generation and is being increasingly used due to the abundance of solar energy and decreasing cost of the generated PV electricity as a result of advancements in the semiconductor device technologies. Modeling of the solar/photovoltaic cells is required to analyze and predict the behavior of the PV system under various environment conditions. Many engineering equivalent circuit models of solar cells have been described in literature, but in practice two widely used PV cell models are the one-diode model and the two-diode model. These are non-linear lumped-parameter equivalent circuit models, where one-diode model is less accurate but is much simpler than its counterpart. Whatever model is used, the accurate extraction of the parameters of the model is needed to simulate the electrical behavior of the solar cells for design, performance evaluation and the control of the PV systems.

In literature, two types of approaches have been used for the parameter extraction of the solar cell models; analytical or traditional approaches and numerical or evolutionary approaches. Analytical approaches (Caracciolo et al., 2012; Haouari-Merbah et al., 2005; Hejri et al., 2014; Ortiz-Conde et al., 2006; Saleem and Karmalkar, 2009; Tivanov et al., 2005) require first derivative information and some key points from the *I-V* characteristics like short-circuit current, open-circuit voltage, maximum power point and the slope values at the axis intersections. These are simpler techniques but their accuracy depends on the measured key points, which at times may not be very accurate. To overcome these issues, the researchers have employed several evolutionary techniques, such as genetic algorithms (GA) (Jervase et al., 2001), pattern search (PS) (AlHajri et al., 2012; AlRashidi et al., 2011), simulated annealing (SA) (El-Naggar et al., 2012), artificial bee swarm optimization (ABSO) (Askarzadeh and Rezazadeh, 2013), particle swarm optimization (PSO) (Khanna et al., 2013b, 2015; Qin and Kimball, 2011; Sandrolini et al., 2010), chaos particle swarm optimization (CPSO) (Huang et al., 2011), and differential evolution (DE) (Ishaque and Salam, 2011; Ishaque et al., 2012; Jiang et al., 2013) for the accurate estimation of parameters of solar cell models. The evolutionary techniques are population-based optimization algorithms that perform well for almost all types of problems. Cotfas et al. (2013) have given a critical review of 34

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different methods to determine parameters of the various solar cell equivalent circuit models. Chin et al. (2015) have given a review of various analytical and soft computing approaches for parameter extraction of photovoltaic cells. The advantages and disadvantages of different PV cell models have also been discussed. Khanna et al. (2015) have suggested a three-diode equivalent circuit model of the large area solar cells and estimated their parameters using PSO.

In references Saleem and Karmalkar (2009), Tivanov et al. (2005), authors have only reported methods to estimate the parameters of one-diode equivalent circuit model of solar cells and other authors have reported methods (analytical or evolutionary) and incorporated those methods in the estimation of parameters of either solar cells or solar modules or both using one-diode, two-diode or three-diode equivalent circuit models. However, in the literature, there is no information available, if various parameters of the engineering one-diode, two-diode or three-diode models of a silicon solar cell determined using the above mentioned methods are independent variables or are dependent/correlated with each other. Such dependency or correlation between the parameters can be established using statistical analysis or engineering fit of the data on these parameters or through analytical methods. Such an analysis will reduce the number of independent parameters that would be required for modeling and simulation of the *I-V* characteristics of silicon solar cells and panels. In this paper, for the first time we have used statistical analysis and engineering fit of the data to establish correlations between some solar cell parameters of the two-diode equivalent circuit model and have shown how that can be used for modeling and simulation of silicon solar cells. This effort would facilitate arriving at engineering models for solar cell simulation.

In the present work, PSO algorithm has been implemented for the extraction of parameters of two-diode model of 82 numbers of large area (~154.8 cm^2 area) single crystalline silicon solar cells. Due to simplicity and faster convergence of PSO algorithm (Khanna et al., 2013b, 2015; Qin and Kimball, 2011; Sandrolini et al., 2010), it has emerged as a promising algorithm and is being used in various optimization problems in engineering and science. In literature, the purpose of various authors has been to suggest reliable methods for estimation of solar cell parameters and hence work has been done only on a few cells or modules. In this work, the parameters of 82 cells were estimated for the purpose of arriving at the statistical correlation between different parameters of the two-diode model of solar cells. From the statistical analysis of the estimated parameters, some useful information could be extracted in terms of engineering fit between a few parameters.

The remainder of the paper is organized as follows. Section 2 briefly discusses about the theory of the one-diode, two-diode and three-diode models, the type of solar cells used in this study and the measurement of the *I-V* characteristics of these cells. Implementation and results of the PSO algorithm in the form of extracted parameters of the cells are discussed in Section 3. Three-diode model and its comparison with two-diode model is also discussed in detail in Section 3. Section 4 describes about the statistical analysis of the extracted parameters of 82 cells, followed by testing and simulation of a single solar cell based on the statistical analysis results, in Section 5. Finally the paper is concluded in Section 6.

2. Theory and experimental methods

2.1. One-diode and two-diode models

Several equivalent circuit models for the solar cells have been suggested in literature, but most commonly used models are the one-diode model and the two-diode model. In the equivalent circuit model, the photon generated current through a solar cell is represented by the photon current, I_{ph}, which is proportional to the solar radiation falling on it. Many of the work reported in literature on solar cell modeling has been done on the simplified one-diode model; where one diode is connected in parallel to the current source, with a series resistance and a shunt resistance to take care of resistive losses in the solar cell. The load current (I) as a function of the load voltage (V) then is given as:

$$I = I_{ph} - I_0\left[\exp\left(\frac{V_d}{nV_t}\right) - 1\right] - \frac{V_d}{R_{sh}} \tag{1}$$

where V_d = voltage across the diode = $V + IR_s$, $V_t = k_BT/q$, I_0 is the reverse saturation current of the diode, I_{ph} is the photon generated current, R_s is the series resistance that represents the total resistance in the path of the current due to the resistance in the bulk regions, emitter resistance and the contact resistances, whereas R_{sh} is the shunt resistance that represents the loss in current due to resistive leakage current across the p-n junction of the solar cell, n is the ideality factor, k_B is the Boltzmann Constant, T is the temperature of the solar cell expressed in K and q is the electron charge. For an ideal diode considering only diffusion and recombination in quasi-neutral regions (QNRs) of the diode, $n = 1$. But experimental results show that n can vary between 1 and 2 (Green, 1982a; Ma et al., 2014; Solanki, 2012).

In two-diode model, two diodes are connected in parallel to the current source, with two resistors R_s, the series resistance, and R_{sh}, the shunt resistance. The current through the first and second diodes represent the losses in the current due to the diffusion and recombination of carriers in the QNRs in the bulk and emitter regions and mid-band Shockley-Read-Hall (SRH) recombination in the space charge regions (SCR) near the p-n junction of the solar cell respectively and these currents flow in the opposite direction to the photon generated current. Eq. (1) gives the load current (I) for the theoretical/ideal two-diode model (Green, 1982a; Solanki, 2012)

$$I = I_{ph} - I_{01}\left[\exp\left(\frac{V_d}{V_t}\right) - 1\right] - I_{02}\left[\exp\left(\frac{V_d}{2V_t}\right) - 1\right] - \frac{V_d}{R_{sh}} \tag{2}$$

where I_{01} and I_{02} are the reverse saturation currents of the two diodes The total number of parameters for modeling the ideal two-diode model (Eq. (2)) is five which are as follows:

$$\text{Parameters(ideal two-diode model)} = \{I_{ph}, I_{01}, I_{02}, R_s \text{ and } R_{sh}\} \tag{3}$$

This theoretical/ideal model although theoretically correct, cannot explain the experimental $I - V_d$ data for silicon solar cells (Ma et al., 2014). Most of the authors who have reported extraction of parameters for two-diode model of solar cell using evolutionary algorithms, such as genetic algorithms (GA) (Jervase et al., 2001), pattern search (PS) (AlHajri et al., 2012; AlRashidi et al., 2011), simulated annealing (SA) (El-Naggar et al., 2012), artificial bee swarm optimization (ABSO) (Askarzadeh and Rezazadeh, 2013), particle swarm optimization (PSO) (Khanna et al., 2013b, 2015; Sandrolini et al., 2010), and differential evolution (DE) (Ishaque et al., 2012) have used the engineering two-diode model as in Fig. 1(a). The load current (I) at a load voltage (V) can be represented by Eq. (4).

$$\begin{aligned} I &= I_{ph} - I_{d1E} - I_{d2E} - I_{sh} \\ &= I_{ph} - I_{01E}\left[\exp\left(\frac{V_d}{n_{1E}V_t}\right) - 1\right] - I_{02E}\left[\exp\left(\frac{V_d}{n_{2E}V_t}\right) - 1\right] - \frac{V_d}{R_{sh}} \end{aligned} \tag{4}$$

where I_{01E}, I_{02E} are the reverse saturation currents and n_{1E}, n_{2E} are the ideality factors of the two diodes respectively. The difference between this engineering two-diode model (Eq. (4)) and ideal two-diode model (Eq. (2)) lies in the ideality factors n_{1E} and n_{2E},