Solar Energy 153 (2017) 360–365

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

An empirical approach towards photovoltaic parameter extraction and optimization

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ARTICLE INFO

Article history:
Received 21 October 2016
Received in revised form 9 May 2017
Accepted 26 May 2017

Keywords:
Solar cell modeling
Differential Evolution Algorithm
Levenberg-Marquardt analysis
Gauss-Newton analysis

ABSTRACT

Solar cell modeling is deemed to be an important research area as it certifies the quality of the solar cell in terms of efficiency, peak power point, fill factor, open circuit voltage and short circuit current. The parameters usually used in current-voltage (I-V) model correlate the output current and voltage in terms of the physical parameters. In this manuscript, a mathematical model with only two parameters is developed through empirical analysis to describe the characteristics of the solar cell and hence simplify the performance analysis. The parameter extraction method follows the optimization techniques such as Levenberg-Marquardt (LM) optimization, Gauss-Newton (GN) method and Differential Evolution Algorithm (DEA) and avoids the cumbersome process like analytical analysis through bias points, peak power calculation or differential approach. When the derived results are observed on the basis of error comparison and analysis through percentage deviation, DEA is proved to be more efficient by resulting the best optimization with minimal error.

1. Introduction

With rising eminent energy crisis across the globe, achieving high efficiency solar cells have been a key challenge for photovoltaic researchers. The way of approaching towards the conversion of solar energy to electrical energy and its measurements are required to understand the detail behavioral impact in the presence of abundant source of solar radiation (Pallares et al., 2006; Fjeldly et al., 1991). Solar cells are used for various terrestrial and space applications such as electric power supply units for electronics instruments, power satellites and other communication equipment. Solar cell modeling is deemed necessary for the quality control, performance evaluation of solar panel (Bag et al., 2014; Doumane et al., 2015).

In a solar panel, the Photo Voltaic (PV) array is designed using several PV modules which consist of PV cells in integrated form. Polynomial equations are widely used to represent the practical I-V characteristics over equivalent circuit representation that involves iterative calculation in parameter extraction (Jiang et al., 2013). However, the derivation of analytical expressions for current and voltage with an acceptable degree of accuracy is of great interest (Araujo and Sanchez, 1982). Several models already exist for predicting maximum power and current-voltage (I-V) relationships, but improvements may be possible by utilizing additional data recently provided by manufacturers (Boyd et al., 2011; Green, 1981).

The Single Exponential Model (SEM) Kammer and Ludington, 1977 describes, the J-V equation by

$$J = J_{ph} - J_0\left[\exp\left(\frac{V+JR_S}{\eta V_t}\right) - 1\right] - \frac{V+JR_S}{R_{Sh}} \quad (1)$$

where J_0 is the dark current density, V_t is the thermal voltage at temperature T, R_s is the unit area parasitic series resistance and R_{sh} is the unit area parasitic shunt resistance, J_{ph} is the photo generated current density, η is the ideality factor. The equivalent circuit of the single diode model for a solar cell is shown in Fig. 1. For the extraction of parameters, fill factor (FF) and maximum power point (J_p, V_p), lots of iterative calculation is required and it is a cumbersome process. Akbaba and Aiattawi (1995) proposed a model in the form of the following equation

$$J = (V_{oc} - V)/[(V_{oc}/J_{sc}) - CV + BV^2] \quad (2)$$

where V_{oc} is open circuit voltage and J_{sc} is the short circuit current.

It is very difficult to represent the constants B and C in terms of physical parameters. In other articles, mathematical formulation like Lambert W–functions (Jain and Kapoor, 2004) and Green's function (Cavassilas et al., 2014) are used to develop the model, which seems a complex approach. The parameter extraction using the

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http://dx.doi.org/10.1016/j.solener.2017.05.076
0038-092X/© 2017 Published by Elsevier Ltd.

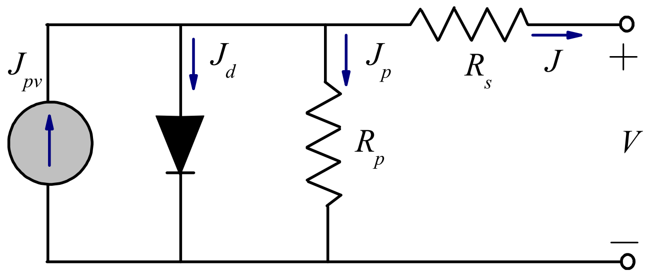

Fig. 1. Equivalent circuit for the single exponential model.

analytical method needs a thorough calculation and deducing the actual values of dI/dV|V = V_{oc} and dI/dV|I = I_{sc} and peak power point is also challenging. Measuring the parameters directly is also difficult however it is easier than the process based on the assumption that the only parameter extracted is not affected by the change in other parameters. The model (Dash et al., 2015) developed by our group before, used two biasing points for parameter extraction. These parameters are more important in device modeling and characterization.

The physical parameters are extracted for a single diode solar-cell (Ghani et al., 2014) by using the Lambert W-function. Here multi-dimensional variant of the Newton-Raphson method is applied to solve the system of non-linear equations. The effect of temperature and irradiance on the I-V characteristics (Rusirawan and Farkas, 2014) is analyzed by studying the single-diode model's internal parameters. Search and optimization technique like Simulated Annealing is used (Asif and Li, 2008) for the determination of equivalent circuit parameters.

The objective of this work is to overcome all the aforesaid difficulties by proposing a simple and more accurate compact model that facilitates easy extraction of the parameters and helps in analyzing the PV cells. Some standard techniques like LM method, GN method and DEA are used in our proposed model for parameters optimization. These are the iterative methods used for reducing errors between measured data points and experimental data points in order to optimize the parameter values. Global search technique like DEA is being programmed in MATLAB environment for non-linear optimization of model leads to a local minima solution. These parameterized values help in process optimization and cell array simulation when solar cells are fabricated. The rest of the paper is organized as follows. The proposed model is discussed in Section 1. Section 2 highlights the optimization techniques like LM, GN and DEA those are used to extract the model parameters. The result analysis is done on average error and average percentage deviation in Section 3 followed by conclusion in Section 4.

2. Experimental

The photovoltaic device is fabricated on n-type Si(100) substrates (ρ ~ 5 Ω-cm), cleaned using Piranha solution followed by dipping in 1% hydrofluoric (HF) acid for 1 min to remove the surface native oxide layer. After cleaning, the Si substrate is immediately loaded into the magnetron sputtering (Hind High Vacc Sputter coater) chamber. The chamber is then evacuated to a base pressure of 1×10^{-6} millibars. A layer of 40 nm thick Al-containing amorphous $FeSi_2$ (iron disilicide) is deposited by co-sputtering of $FeSi_2$ and pure Al targets in Ar ambient. A thin Al interlayer of thicknesses 10 nm were sputter deposited from pure Al target prior to deposition of amorphous-$FeSi_2$(Al) layer. The sample is then subjected to RTA in N_2 at 650 °C for 2 min (ULVAC-RIKO, MILA-5000). Hetero-junction solar cell is fabricated by sputter deposition of ITO (120 nm thick) on p-β-$FeSi_2$(Al) as top electrode and by evaporating Al layer at the back-side of n-Si substrate. Current density-voltage (J-V)

Table 1
Detail of solar cells considered for parameter extraction and their fill factors.

Different cells	Gauss Newton					Levenberg Marquardt					Differential Evolution Algorithm			
	A	B	R-Square	Average error (mA/cm^2)	Average % deviation	A	B	R-square	Average error (mA/cm^2)	Average % deviation	A	B	Average error (mA/cm^2)	Average % deviation
GaInP-GaAs-GaInNAs Akbaba and Aiattawi, 1995	7.89	2.2×10^{-14}	0.99	0.76	18.26	9.35	7.6×10^{-17}	0.99	0.24	6.94	10.75	1.7×10^{-32}	0.02	3.40
GaInP-GaAs-GaInNAs-Ge (Akbaba and Aiattawi, 1995)	6.70	2.9×10^{-14}	0.99	0.47	6.77	5.67	3.1×10^{-12}	0.99	0.02	1.26	6.10	4.0×10^{-13}	−0.02	−0.07
InGaAsP-GaAs Jain and Kapoor, 2004	13.71	2.5×10^{-21}	0.99	0.02	1.16	10.33	1.2×10^{-16}	0.99	0.03	5.07	16.39	2.1×10^{-37}	−0.02	−1.12
InGaAsP-InGaAs (Cavassilas et al., 2014)	24.62	2.3×10^{-14}	0.99	0.14	4.70	35.10	7.7×10^{-24}	0.99	−0.01	−0.04	35.15	3.8×10^{-33}	1.18	13.80
InGaP-GaAs Dash et al., 2015	11.56	1.8×10^{-16}	0.98	0.07	1.78	11.36	1.0×10^{-18}	0.99	0.18	3.05	15.00	1.0×10^{-34}	−0.02	−0.50
p-β-$FeSi_2$(Al)/n-Si	5.249	1	0.98	1.88×10^{-1}	4.96	5.375	1	0.98	1.47×10^{-1}	4.65	5.394	0.99	1.42×10^{-1}	4.61