Modelling and Simulation of Photovoltaic Solar Cell using Silvaco TCAD and Matlab Software

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***Abstract*—In this paper, a modelling approach for a photovoltaic solar cell has been proposed which begins with the development of a solar cell up to enabling the solar cell to be implemented at circuit level simulations. This modelling approach is useful in the photovoltaic field to have an initial or overall observation on the effects toward the photovoltaic system. The modelling approach begins with modelling a thin film $Cu(In,Ga)Se_2$ (CIGS) solar cell using Silvaco TCAD (Technology Computer-Aided Design) software with a predefined baseline parameters. The electrical parameters as well as the I-V curve of the TCAD model are obtained and the data is exported to be post-processed in Matlab software. Key parameters of the TCAD model are used to develop an equivalent electrical model. The Single-diode model topology is implemented for simplicity. In order to test the validity of the single-diode model, the I-V curve is compared to the I-V curve of the TCAD model. As an extension, the I-V curves are also presented across different temperatures in order to test the accuracy of the single-diode model**

Keywords—modelling, photovoltaic, solar cell, circuit level, TCAD, Matlab, I-V curve, single-diode

I. Introduction

Solar energy is a popular and emerging renewable energy source due to the theoretically infinite resource from the sun. Besides, there are no moving parts involved in the conversion of solar energy to electrical energy which makes it almost maintenance free. Solar energy is associated with the term photovoltaic (PV) which covers the conversion of solar energy into electrical energy using semiconductor materials known as the solar cell. Typically, an isolated, stand-alone, or off-grid PV system consists of three main components such as the solar module, the charge controller module, and the battery system. The solar module is a group of solar cells connected together to achieve a higher solar energy output. The charge controller module is where Maximum Power Point Tracking (MPPT) algorithm is implemented, and the battery system is to store the converted solar energy for later usage.

It can be observed that there are several areas available for research, such as the solar cell, the MPPT algorithm, and the power management of the battery system. The solar cell is the first component of the PV system where the sun's irradiance is taken as the input to be converted into electrical energy. The maximum output power is directly proportional to the efficiency of the solar cell. Thus, there are abundance of researches done to develop solar cells that are capable of converting solar energy to electrical energy at a higher efficiency. This includes developing solar cells from different kinds of materials and processes [1]. Besides the solar cell, there are also significant researches done on the MPPT algorithm to be implemented in the PV system. The objective is to ensure the PV system operates at the Maximum Power Point (MPP) of the solar cell by continuously tracking the MPP. There are continuous researches done to improve the conventional algorithm such as the Perturb and Observe (P&O) algorithm [1]. Besides, there are also new algorithms with higher complexity being introduced such as the fuzzy logic approach and the grey wolf algorithm [3], [4]. The battery system is another section in the PV system where till date, there are researches done to implement new or improve currently available power management systems [5], [6].

A modelling approach for PV solar cell which is a combination of Silvaco TCAD and Matlab software is proposed. The modelling approach begins with defining the baseline parameters of the solar cell. The resulting electrical characteristics and the non-linear I-V curve of the solar cell will be used to develop an equivalent electrical model of the solar cell. The validity of the model is tested at different temperatures such as 280K, 300K, and 320K.

The electrical model is used to provide an initial insight on the performance of the solar cell when implemented in a PV system. This includes the impact towards the PV system when changes are made to the baseline parameters of the solar cells. This is significant in the PV field as the performance of a solar cell can be observed as a single cell or as a whole PV system.

II. Description of the Modelling Approach

Solar cell device development and solar PV system are usually developed separately. During the solar cell device development, the baseline parameters of the solar cell are manipulated to improve the efficiency and electrical characteristics of the solar cell. For example, to improve the efficiency of a thin film CIGS solar cell, the thickness,

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doping concentration, electron affinity, and band gap energy are manipulated [7]. The results of the changes are discussed and concluded at the solar cell level.

For the latter, solar PV system includes development of the MPPT algorithms and the power management system. MPPT algorithms are usually developed and tested with a solar cell or solar module with commercially available data [2]. This is also similar on the development of PV power management systems where commercially available data of the solar cell or solar module are implemented [5].

In the proposed modeling approach, a new step is introduced to link between the solar cell device development and the solar PV system. It is the implementation of the solar cell as a part of a complete PV system. At this point, the solar cell can be implemented in the development of the MPPT algorithms as well as the power management system. With this approach, the flexibility of the PV simulation flow will improve in terms of the capability to manipulate the baseline parameters of the subjected solar cell.

III. Simulation of Solar Cell Using Silvaco TCAD Software

For the modelling approach, a CIGS solar cell is designed using Silvaco TCAD based on a predefined baseline parameters. These parameters such as shown in Table 1 are chosen to model an optimal thin-film CIGS solar cell based on results of prior researchers [8], [9], and [10].

TABLE 1. PREDEFINED BASELINE PARAMETERS FOR CIGS SOLAR CELL

Parameters	Layers		
	ZnO	*CdS*	*CIGS*
Thickness (nm)	150	50	3000
Band gap, E_g (eV)	3.3	2.4	1.27
Donor concentration, N_D (cm^{-3})	$1x10^{18}$	$1x10^{17}$	0
Acceptor concentration, N_A (cm^{-3})	0	0	$2x10^{16}$
Conduction band effective density of states, N_C (cm^{-3})	$2.2x10^{18}$	$2.2x10^{18}$	$2.2x10^{18}$
Valence band effective density of states, N_V (cm^{-3})	$1.8x10^{19}$	$1.8x10^{19}$	$1.8x10^{19}$

Fig. 1 shows the designed TCAD solar cell model with the baseline parameters described in Table 1. The structure of the TCAD model is composed of Molybdenum (Mo) back contact, a p-type wide-band gap absorber layer (CIGS), followed by n-type buffer layer made of cadmium sulphide (CdS) and a window layer made of doped zinc oxide (ZnO).

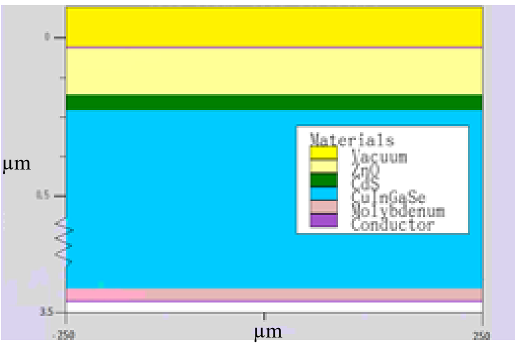

Fig. 1. TCAD model structure designed with Silvaco TCAD

The I-V curve of the designed solar cell at standard test condition (STC) usually at 300 K and 1000 W/m^2 and air mass 1.5 (AM 1.5) is depicted in Fig. 2. From the I-V curve, short-circuit current (I_{sc}), open-circuit voltage (V_{oc}), current at MPP (I_{mp}), and voltage at MPP (V_{mp}) is 40.3 mA, 0.752 V, 36.3 mA, and 0.649 V respectively.

These parameters will be used to develop an equivalent electrical model of the TCAD model in the next step of this modelling approach using Matlab software. Besides the I-V curve, a logfile of the TCAD model is available as the output of Silvaco TCAD. The logfile containing electrical parameters of the TCAD model can be exported into comma separated values (csv) file by utilizing TonyPlot (Silvaco's interactive visualization tool) for post-processing with other software, which is described in the next section of this paper.

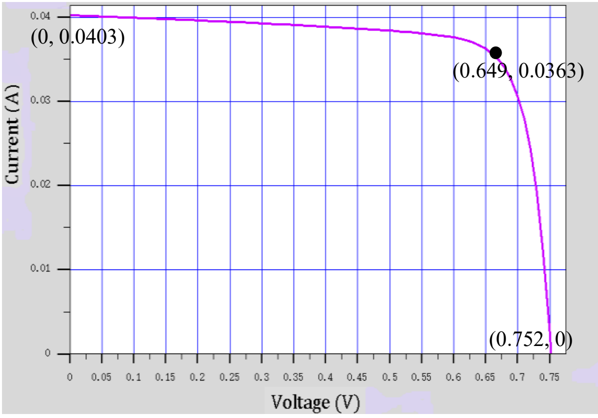

Fig. 2. I-V curve of the TCAD model designed with Silvaco TCAD

IV. Modelling of the Solar Cell Using Matlab Software

The main purpose of using Matlab software is to construct an equivalent electrical model of the TCAD model, which is to reproduce the non-linear I-V curve. In a standard non-linear I-V curve, three marked points are highlighted such as the short-circuit (0, I_{sc}), MPP (V_{mp}, I_{mp}), and open-circuit (V_{oc}, 0) as shown in Fig. 3.

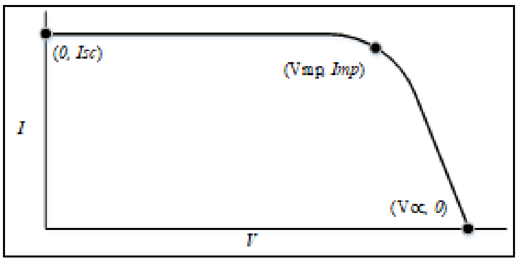

Fig. 3. Standard non-linear I-V curve with the three marked points

Previous PV system studies have utilized different circuit topologies to represent solar cells such as the single-diode model, two-diode model, and three-diode model [11]-[13]. In this work, the single-diode model circuit topology is chosen because the model offers good compromise between simplicity and accuracy [11]. Fig. 4 shows the electrical circuit of a practical single-diode solar cell with the equivalent series and parallel resistance.

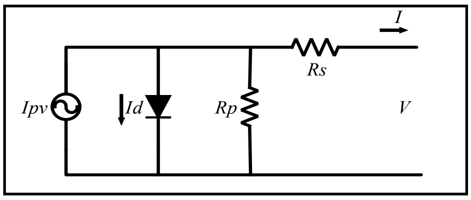

Fig. 4. Electrical circuit representation of a practical single-diode solar cell

The I-V characteristics of a practical single-diode solar cell is mathematically described as below [14].

$$I = I_{pv} - I_o\left[e^{\left(\frac{V+R_sI}{V_t\alpha}\right)} - 1\right] - \frac{V+R_sI}{R_p} \quad (1)$$

where:
- I_{pv} = PV current
- I_o = Diode reverse saturation current
- V_t = Thermal voltage
- α = Diode ideality constant
- R_s = Equivalent series resistance
- R_p = Equivalent parallel resistance

From equation (1), the thermal voltage, $V_t = kT/q$ where k is the Boltzmann constant (1.3806503×10^{-23} J/K), T is the temperature in Kelvin, and q is the electron charge (1.60217646×10^{-19} C). The PV current, I_{pv} depends on the solar irradiation and the temperature of the solar cell where it is described as shown below [15].

$$I_{pv} = \left(I_{pv,n} + K_I\Delta_T\right)\frac{G}{G_n} \quad (2)$$

where:
- $I_{pv,n}$ = PV current at STC
- K_I = Short-circuit current temperature coefficient
- Δ_T = Difference between actual and nominal temperature
- G = Irradiation
- G_n = Irradiation at STC

I_o on the other hand, is further elaborated as in equation (3) [15].

$$I_o = \frac{I_{sc,n} + K_I\Delta_T}{e^{([V_{oc,n}+K_V\Delta_T]/\alpha V_t)} - 1} \quad (3)$$

where:
- $I_{sc,n}$ = Short-circuit current at STC
- $V_{oc,n}$ = Open-circuit voltage at STC
- K_V = Open-circuit voltage temperature coefficient

Equations (1) – (3) are used to develop the single-diode model. The key parameters of the TCAD model are implemented such as $I_{sc,n}$, $V_{oc,n}$, I_{mp}, and V_{mp}. The temperature coefficients, K_I and K_V are taken from the average of commercially available CIGS solar cells datasheet [16]-[20]. The values of the equivalent resistances R_s and R_p are obtained through Newton-Raphson iteration method [11]. Fig. 5 shows the reconstructed I-V curve of the single-diode model based on the I-V curve of the TCAD model at STC.

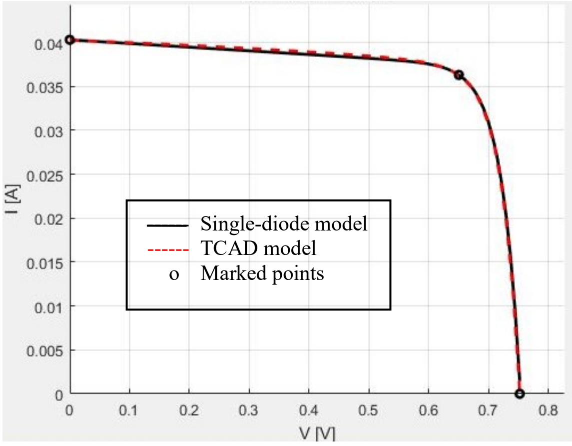

Fig. 5. I-V curve of single-diode model and I-V curve of TCAD model

From Fig. 5, it can be observed that the single-diode model can reconstruct the I-V curve of the TCAD model with great accuracy. This observation validates the I-V curve of the single-diode model to that of the TCAD model. The curves are exactly matched at the three marked points denoted by the dots since these points are used as the basis in developing the single-diode model. Slight error gaps are observed at other points of the I-V curve. This is the limitation of the single-diode model, although the error gaps can be reduced by increasing the number of iterations in finding the values of R_s and R_p.

V. Validating the Single-Diode Model at Different Temperatures

To further validate the I-V curve of the single-diode model, a set of I-V curves of the single-diode model and TCAD model are plotted at different temperatures. This is to ensure the single-diode model is able to accurately represent the TCAD model for further usage in the PV system. Fig. 6 shows the I-V curves of the single-diode model and the I-V curves of the TCAD model at three different temperatures such as 280K, 300K, and 320K.

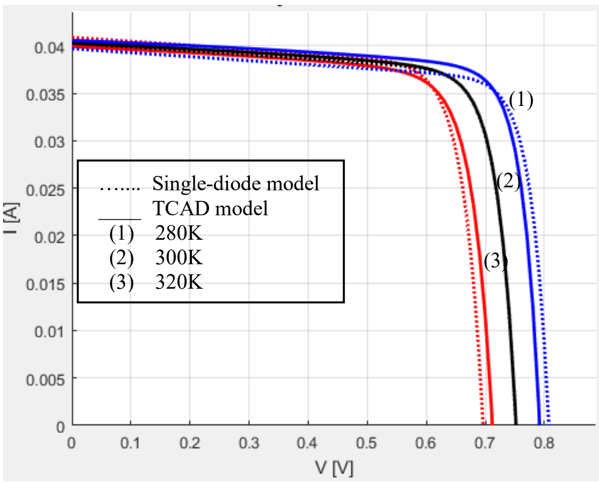

Fig. 6. I-V curves of the single-diode model and TCAD model at different temperatures

As shown in Fig. 6, the I-V curves of the single-diode model and TCAD model are denoted by the dotted line and solid line respectively. The different temperatures are denoted by the colors and numbers where blue (1) is for

280K, black (2) is for 300K, and red (3) is for 320K. The absolute error between the I-V curves are as described in Table 2.

TABLE 2. ABSOLUTE ERROR BETWEEN SINGLE-DIODE MODEL AND TCAD MODEL AT DIFFERENT TEMPERATURES

Temperature	280K		320K	
	V_{oc}	I_{sc}	V_{oc}	I_{sc}
Single-Diode Model (a)	0.807V	38 mA	0.696 V	41 mA
TCAD Model (b)	0.790V	41 mA	0.710 V	40 mA
Absolute Error gap (|[a-b]/b × 100|)	2.15%	7.32%	1.97 %	2.50 %

The I-V curves are almost accurate at temperature 300K. However, when the temperature is increased or decreased to 320K and 280K respectively, the absolute error between the I-V curves increases. From Table 2, it can be observed that the single-diode model is able to maintain at most an absolute error of 7.32% which is at 280K. This result indicates that the single-diode model is sufficiently accurate to the TCAD model at temperature ranging from 280K to 320K. This is significant in implying the validity of the single-diode model to replace the TCAD model for circuit level simulations.

VI. CONCLUSION & DISCUSSION

In this paper, a modelling approach has been proposed to be implemented in PV systems. The approach is an extension of the conventional modelling approach for solar cells by introducing another step which enables circuit implementation of the solar cell. This is significant in the PV field since the approach is able to provide initial or overall insight on how the baseline parameters of a solar cell affects the performance of the PV system.

The modelling approach is a combination of Silvaco TCAD and Matlab software where Silvaco TCAD is used to develop a TCAD model of a thin-film CIGS solar cell from a predefined baseline parameters and Matlab software is used to post-process the output file. Matlab software is also used to develop an equivalent single-diode model to represent the TCAD model. The I-V curve of the single-diode model is validated against the I-V curve of the TCAD model at three different temperatures such as 280K, 300K, and 320K. At most, the absolute error between the curves is at 7.32%.

This modelling approach is not only limited to model and simulate thin-film solar cells. As long as there are information on the electrical characteristics and the I-V curve of a solar cell, this modelling approach can be utilized to develop an equivalent electrical model for circuit level simulations.

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