A Simple Approach to Modeling and Simulation of Photovoltaic Modules

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***Abstract*—An accurate model is essential when designing photovoltaic (PV) systems. PV models rely on a set of transcendental nonlinear equations which add to the model complexity. This letter proposes a simple and easy-to-model approach for implementation in simulations of PV systems. It takes advantage of the simplicity of ideal models and enhances the accuracy by deriving a mathematical representation, capable of extracting accurate estimates of the model parameters, directly related to manufacturer datasheets. Experimental measurements proved the effectiveness of the proposed approach.**

***Index Terms*—Equivalent circuit, modeling, photovoltaic (PV).**

I. Introduction

PHOTOVOTAIC (PV) modules operate over a large range of atmospheric conditions, but manufacturing datasheets provide electrical parameters at only standard test condition (STC). PV studies rely on a PV simulation model to develop maximum power point (MPP) tracking algorithms and control strategies [1]. PV system designers need a reliable and easy-to-implement model to predict PV energy production under various conditions [1]. PV models can be classified into three main types (refer to Fig. 1). The simplest model is the ideal single-diode model (ISDM) [2]. Despite its simplicity, it does not guarantee an accurate I–V characteristic at the MPP [3]. The single-diode model (SDM) is most commonly used for conducting PV studies due to its accuracy. For such an approach, five parameters are essential to develop the PV simulation model. The parameters are determined by solving five nonlinear equations iteratively [4], or by tuning the value of some parameters such that the I–V characteristic coincides with the three operating points given by the datasheet [2]. Implementing a simulation model for such a method requires a numerical solver because $I = f(V, I)$ and $V = f(I, V)$ [2]. To reduce the complexity, some studies eliminate the shunt resistance ($R_{\rm sh}$), as shown in Fig. 1(c) [5]. Although the complexity is reduced, it exhibits deficiencies when subjected to temperature variations and still requires a numerical solver [6].

In this letter, a new approach for PV modeling is proposed that combines the advantages of previous models which include simplicity, ease of modeling, and accuracy. This approach relies on two newly developed mathematical equations, developed to estimate PV parameters, for the ISDM. The proposed approach is compared against previous methods using experimental measurements.

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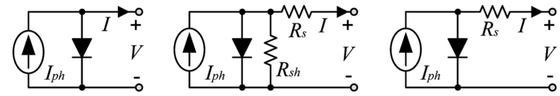

Fig. 1. Equivalent circuits for PV: (a) ISDM; (b) SDM; (c) simplified single-diode model (SSDM).

II. Proposed PV Modeling Approach

Generally, the I–V characteristic for a PV module composed of N_s series connected cells is expressed as follows:

$$I = I_{\rm ph} - I_s\left[e^{\left(\frac{q(V+IR_sN_s)}{N_sKTA}\right)} - 1\right] - (V + IR_sN_s)/(N_sR_{\rm sh}) \tag{1}$$

where q, K, and T are the electron charge, Boltzmann constant, and module temperature, respectively. The parameters $I_{\rm ph}$, I_s, A, and R_s are the photon current, saturation current, ideality factor, and the series resistance of the PV cell, respectively, which are commonly calculated through a set of nonlinear equations [4]. In [2], some parameters were assumed, thus reducing the number of unknowns. Unfortunately, this impacts the overall accuracy of the model. To avoid the complexity imposed by (1), the proposed approach will rely on the ISDM expressed in (2)

$$I = I_{\rm ph} - I_s\left[e^{\left(\frac{qV}{N_sKAT}\right)} - 1\right]. \tag{2}$$

This model has three unknown parameters ($I_{\rm ph}$, I_s, and A). $I_{\rm ph}$ is determined from manufacturer datasheets, as follows:

$$I_{\rm ph} = G(I_{\rm sc} + \alpha\Delta T) \tag{3}$$

where G is the irradiance (kW/m^2), $I_{\rm sc}$ is the short circuit current at STC, ΔT is the temperature difference between the module temperature and the STC temperature, and α is the current temperature coefficient given in the product datasheet. The expression for I_s is derived by first setting

$$V_{\rm oc}(G,T) - V_{\rm oc}(G,T_o) = -|\beta|\Delta T \tag{4}$$

where $V_{\rm oc}(G,T)$ and $V_{\rm oc}(G,T_o)$ are the open circuit voltages at a certain temperature (T) and the temperature at the STC (T_o), respectively, for a specific irradiance level. The parameter $|\beta|$ represents the absolute value of the voltage temperature coefficient given in datasheet. By substituting $\mathrm{I} = 0$ in (2), the open circuit voltage formula is determined as

$$V_{\rm oc} = \frac{N_sKTA}{q}\ln\left(\frac{I_{\rm ph}}{I_s} + 1\right). \tag{5}$$

Both $V_{\rm oc}(G,T)$ and $V_{\rm oc}(G,T_o)$ can be found using (5) and thus by substituting in (4)

$$\frac{N_sKA}{q}\left[T\ln\left(\frac{G(I_{\rm sc}+\alpha\Delta T)}{I_s} + 1\right) - T_o\ln\left(\frac{GI_{\rm sc}}{I_{rs}} + 1\right)\right] = -|\beta|\Delta T. \tag{6}$$

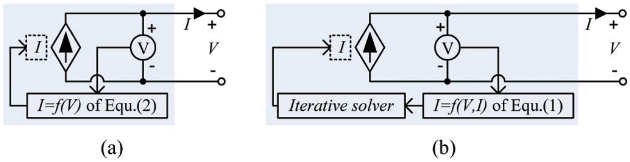

Fig. 2. Simulation model implementation: (a) proposed method where $I = f(V)$; (b) SDM with $R_{\rm sh}$ where $I = f(V, I)$.

By rearranging (6), I_s can be expressed as follows:

$$I_s = \frac{e^{\frac{|\beta|\Delta T q}{N_s K T A}} G[I_{\rm sc} + \alpha \Delta T]}{(G I_{\rm sc}/I_{rs} + 1)^{\frac{T_o}{T}} - e^{\frac{|\beta|\Delta T q}{N_s K T A}}} \tag{7}$$

where I_{rs} is the saturation current at STC and it can be calculated as follows [2]:

$$I_{rs} = I_{\rm sc} \Big/ \left[e^{\left(\frac{q V_{\rm oc}}{N_s K A T_o}\right)} - 1 \right]. \tag{8}$$

Under STC, (2) is expressed at MPP (V_m and I_m) as follows:

$$I_m = I_{\rm sc} - I_{rs} \left[e^{\left(\frac{q V_m}{N_s K A T_o}\right)} - 1 \right]. \tag{9}$$

The second unknown parameter "A" can be derived by substituting (8) into (9) and then solving the equation for the MPP (V_m and I_m). The derived formula (9) can be simplified as

$$\frac{I_m}{I_{\rm sc}} = e^{\frac{q V_m}{N_s K T_o A}} - \left(\frac{I_{\rm sc} - I_m}{I_{\rm sc}} \right) e^{\frac{q V_{oc}}{N_s K T_o A}}. \tag{10}$$

The PV datasheet parameters and the solution of (7) and (10) will be substituted in (2) to develop the PV simulation model.

III. Simulation and Validation

Fig. 2 presents the PV module circuit for the proposed approach and the method proposed in [2]. The proposed PV circuit model is implemented using a controlled current source and a simple computational block [refer to Fig. 2(a)]. The simulation circuit, shown in Fig. 2(b), requires a numerical solver. Therefore, constructing a simulation circuit using the proposed approach is simple and easy since $I = f(V)$. This approach avoids the use of a nonlinear solver and thus simple mathematical blocks are required. In addition, the accuracy of the proposed approach was evaluated experimentally and compared against previous approaches. Fig. 3 presents the I–V curves and absolute error for the three modeling approaches with respect to the experimental data for the MSX-83 mono-crystalline PV module [3]. Fig. 4 shows the I–V curves of the proposed model at various temperatures and irradiance. It can be seen that the simulation results of the proposed model coincides closely with the experimental measurements. Table I provides a definition for each modeling approach, the root mean square deviation, and simulation time. The results show that the proposed simple approach has comparable accuracy levels but less simulation time (33% reduction) due to the simplified simulation structure. The presented approach shows low root mean square deviation (RMSD) compared with previous proposed modeling approaches in [2] and [5].

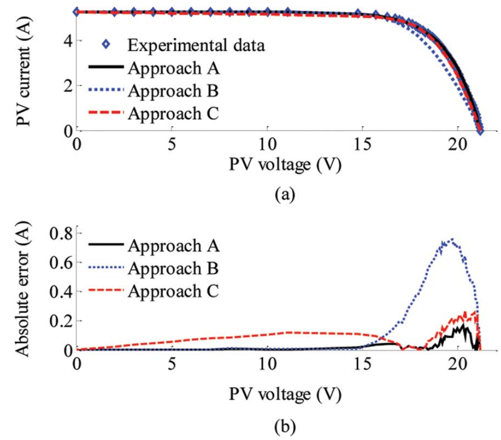

Fig. 3. (a) Comparison of I–V curves among the three modeling approaches; (b) comparison of absolute errors among the three modeling approaches.

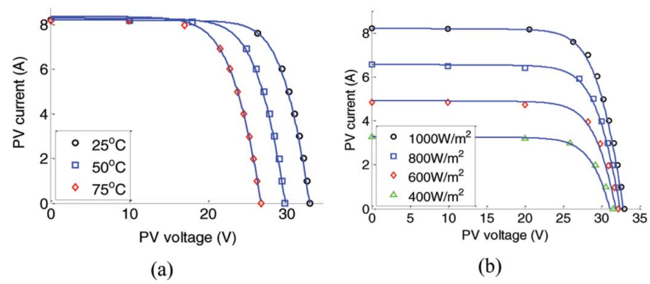

Fig. 4. Comparison between model output and measured data of KC200GT with (a) variation of temperature; (b) variation of irradiance.

TABLE I
Modeling Approach Definition and Performance

Approach	Equivalent circuit	Parameterization	RMSD	Simulation Time
A	ISDM	Proposed in this paper	0.40 (A)	4.04 s
B	SSDM	Proposed in [5]	3.12 (A)	6.02 s
C	SDM with R_{sh}	Proposed in [2]	0.95 (A)	6.70 s

IV. Conclusion

This letter proposes an effective approach to modeling of PV modules. The proposed modeling method avoids complexities involved in PV parameter identification while achieving comparable accuracy. The method is easy to implement in various simulation platforms for PV power systems studies. Experimental measurements validated and proved the effectiveness of the proposed modeling method.

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