Hierarchical Development of Photovoltaic (PV) Simulation for PV System with Commercial PV Modules

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Abstract. This paper originally proposes a hierarchical development of photovoltaic (PV) simulator for PV system design with different commercial PV modules by directly calling one of the built-in PV models that have well-verified accuracy and sufficient confidence. First, the modular models of some commercial PV modules are built as referenced models only using the available information in the manufacturers’ datasheets. These PV models are then verified to accurately simulate the electrical characteristics at the standard test condition (STC). Then PV system designers can simply call the referenced model of a commercial PV module to design and assess the output electricity of a PV array with sufficient degree of accuracy and confidence. This paper is aimed to develop the modular PV simulator with user-friendliness, verified accuracy, and reliable confidence for PV system engineers.

Introduction

Renewable energy is one of the most promising alternatives in face of the issues of environmental change and rising energy demand inducing convention fossil fuel depletion. The features of ubiquity, abundance, and sustainability of solar energy have made photovoltaic (PV) energy conversion being currently considered as the most alternative of choice for clean energy market penetration. With social awareness of PV power systems’ potential and value, the worldwide cumulative installed PV power capacity vitally grows with a nearly exponential increase during two decades the global PV market development has been promisingly progressing as much as 30% in more than twenty years and the cumulative installed capacity has reached up to 303 GW at the end of 2016 [1]. These results are chiefly attributed to the dramatic decline in prices of PV modules and systems, the awareness of environmental protection, and the continuous energy demand in the last years. The performance evaluation and quality assurance for PV system are of increasing importance to optimize the cost-effectiveness of PV power plants. In order to design and assess PV system for power applications, PV system designers can work by using some commercial PV simulators such as PV-SPS (PV Stand-alone Power Systems), PV*SOL, PVsyst, and PV-DesignPro [2]. Furthermore, the System Advisor Model (SAM) is a kind of open and free software developed by combining single-diode, 5-parameter model and maximum power point (MPP) model [3]. However, the accuracy of simulation results for different solar irradiance and cell operating temperatures is still being discussed. In fact, the model accuracy of a PV array simulator for commercial PV modules significantly depends on the model building and parameter configuration. A five-parameter model with one-diode equivalent circuit offers the high-confidence prediction for PV array with commercial PV modules using accurate parameter extraction [4,5]. These substantial advancements improve the prediction and assessment of output power for PV system design; yet assisting PV system engineers and designers remains a user-friendly gap due to interactive interface like commercial simulation software.

Modeling and simulation are a principle and indispensable process for PV system design. Simulink is a graphic user interface (GUI) platform that can rapidly and accurately build complex simulation models for linear or nonlinear systems. A modular PV simulator for different commercial modules with trustworthy precision can be used to arrange the series-parallel configuration for PV system
design. A reliable PV simulator can further be used to predict and diagnose the output characteristics of PV system for power applications. It is of great importance to accelerate the growth and success of PV technology and industry. Based on our previous study in PV modeling [6,7], this paper is aimed to develop a modular PV simulator to manifest one of the verified PV models of commercial modules using a top-down and button-up methodology in the MATLAB/ Simulink environment. This user-friendly GUI bridges both PV system engineer and theoretical simulation for PV performance and service prediction. Performance prediction through an accurate PV simulator would obtain credible prediction results and have the trustable warning ability for PV monitoring system. The main contribution of this paper is the hierarchical development of a modular PV simulator by calling one of the verified models of commercial PV modules. Both icon and dialog box are designed for end-users with user-friendliness like Simulink block libraries. The demonstration shows the simplicity, user-friendliness, and accuracy.

**Electrical Characteristics of PV Module and Array**

Solar cell is basically a p-n semiconductor that can directly convert solar energy into electricity through photovoltaic effect. In most commercially available PV modules, solar cells are arranged in series in order to have high output voltage. To size a PV array, the modules are assembled in a form of series-parallel configuration. These PV devices naturally exhibit nonlinear $I-V$ and $P-V$ characteristics that vary with radiant intensity and cell temperature. The practical PV model that describes the electrical output characteristics is derived as follows.

**Practical Model of Commercially Available PV Modules.** A one-diode five-parameter model can adequately describe the output $I-V$ characteristic of PV devices, which is composed of a photocurrent source, a diode in parallel with a shunt resistor, and a series resistor. A mathematical equivalent circuit model for a solar cell has been studied as shown in Fig. 1a. The mathematical description for characterizing $I-V$ output characteristics is given by

$$I = I_{\text{ph}} - I_S \left[ \exp \left( \frac{q}{kT_C} (V + IR_S) \right) - 1 \right] - \frac{V + IR_S}{R_{\text{sh}}}$$

(1)

where $I_{\text{ph}}$ is the light-generated current or photocurrent, $I_S$ is the cell saturation of dark current, $q$ is the charge of an electron, $k$ is the Boltzmann’s constant, $T_C$ is the working temperature of solar cell, $A$ is the ideal factor that depends on PV technology, $R_{\text{sh}}$ is the shunt resistance, and $R_S$ is the series resistance. Considering a commercial PV module that is arranged in $N_{\text{SM}}$ series configuration, the equivalent circuit of a single-diode practical model is then developed as shown in Fig. 1b. The $I-V$ characteristic equation can be described by

$$I = I_{\text{ph}} - I_S \left\{ \exp \left( \frac{q}{kT_C} \left( \frac{V}{N_{\text{SM}}} + IR_S \right) \right) - 1 \right\} - \frac{1}{R_{\text{sh}}} \left( \frac{V}{N_{\text{SM}}} + IR_S \right)$$

(2)

Based on some experimental data about electrical and thermal characteristics under the standard test condition (STC) with the irradiance of 1kW/m$^2$ and the reference cell temperature of 25 °C that are available from the PV manufacturer’s datasheets, the photocurrent that mainly depends on solar irradiance and cell’s temperature is given by

$$I_{\text{ph}} = [I_{\text{ph}}^{\text{SC}} + K_1 (T_C - T_{\text{C}}^{\text{SC}})] \frac{G}{G^{\text{SC}}}$$

(3)

where $I_{\text{ph}}^{\text{SC}}$, $K_1$, and $T_{\text{C}}^{\text{SC}}$ are the short circuit current, the temperature coefficient of the short circuit current, the reference cell temperature of a PV module at the STC, respectively. $G^{\text{SC}}$ is the standard test irradiance of 1kW/m$^2$ and $G$ is the solar irradiance in kW/m$^2$. In addition, the cell’s saturation current that varies with the cell temperature is given by
\[ I_s = I_{RS} \left( \frac{T_C}{T_{STC}} \right)^3 \exp \left[ qE_G \left( \frac{1}{T_{STC}} - \frac{1}{T_C} \right) / kA \right] \]  

(4)

where \( I_{RS} \) is the cell’s reverse saturation current at an operating temperature, \( E_G \) is the bang gap energy of the semiconductor used in the cell.

There are five independent parameters of the one-diode PV model for commercial PV modules unavailable in the PV manufacturers’ datasheets such as the band gap energy and the ideal factor of cell type, the diode’s reverse saturation current, and the resistance of the series and shunt resistors. Both band-gap and ideal factor are properly determined according to the cell type that both semiconductor material and PV technology can be found in PV datasheet. Further examining the manufacturer’s specifications of commercial PV products, the important parameters are the open-circuit voltage \( V_{OC}^{STC} \), the short-circuit current \( I_{SC}^{STC} \), the maximum power rating \( P_{max}^{STC} \), the rated voltage \( V_{MPP}^{STC} \) at the maximum power point (MPP), the rated current \( I_{MPP}^{STC} \) at the MPP, the temperature coefficients of short circuit current \( K_i \) and open circuit voltage \( K_V \). For easy description, Figure 2 portrays the \( I-V \) and \( P-V \) output curves for a practical model at the points of interest where four notable points \( (V_{OC}^{STC}, 0), \ (0, I_{SC}^{STC}), \ (V_{MPP}^{STC}, P_{max}^{STC}), \) and \( (V_{MPP}^{STC}, I_{MPP}^{STC}) \) are highlighted.

The \( V_{OC}^{STC} \) parameter is obtained at \( V = V_{OC}^{STC} \) and \( I = 0 \). The reverse saturation current can be analytically found at open-circuit condition at STC and is given by

\[ I_{RS}^{STC} = I_{RS} \left( \frac{T_C}{T_{STC}} \right)^3 \exp \left[ qV_{OC}^{STC} / N_{SM}kAT_{STC} \right] \]  

(5)

The series resistance controls the slope of the \( I-V \) curve near \( (V_{OC}^{STC}, 0) \) and impacts the curve shape near the MPP. The derivative of maximum output power with respect to output voltage at the MPP is zero. The series resistance at the STC is directly calculated by

\[ R_s = \frac{N_{CS}R_s}{N_{CS}+N_{SH}} \]

Figure 1. Equivalent circuit models of practical PV devices: (a) solar cell; (b) \( N_{MS} \)-series PV module; (c) \( N_{MS} \)-series, \( N_{MP} \)-parallel PV array.
\[ R_{STC}^{SC} = \frac{V_{MPP}^{STC}}{N_{SM}^{MPP}} - kT_C^{STC} \frac{A}{q_{RS}^{STC}} \exp \left[ - \frac{q(V_{MPP}^{STC} + N_{SM}^{STC} I_{MPP}^{STC})}{N_{SM}^{STC} kT_C^{STC}} \right] \]  

(6)

There is only one pair resistance of series and shunt resistors meeting at the rated MPP point at STC. \( R_{RH}^{STC} \) is directly calculated by the following equation for a specific value of \( R_{STC}^{SC} \), obtained as

\[ R_{STC}^{SH} = \frac{V_{MPP}^{STC} + I_{MPP}^{STC} R_{STC}^{SC}}{I_{SC}^{STC} - I_{RS}^{STC}} \left\{ \exp \left[ - \frac{q(V_{MPP}^{STC} + N_{SM}^{MPP} I_{MPP}^{STC})}{N_{SM}^{STC} kT_C^{STC}} \right] - 1 \right\} - I_{MPP}^{STC} \]  

(7)

Figure 2. \( I - V \) and \( P - V \) output characteristics of a practical PV module and five notable points.

**Modeling of PV Array.** Basically, only commercially available PV modules with legal certification are considered to assemble PV arrays for the power applications. For a PV array with PV modules arranged in the form of \( N_{SA} \)-series and \( N_{PA} \)-parallel configuration as shown in Fig. 1c, the associated \( I-V \) characteristic equation for a PV system simulator is derived and expressed as

\[ I = N_{PA} I_{PH} - N_{PA} I_{S} \left\{ \exp \left[ - \frac{q(V_{MPP} + I R_{S} + V_{OC})}{N_{SA} N_{SM} + IR_{S}} \right] - 1 \right\} - \frac{1}{R_{SH}^{STC}} \left( \frac{N_{PA} V_{MPP}}{N_{SA} N_{SM} + IR_{S}} + IR_{S} \right) \]  

(8)

As a matter of course, the model accuracy of PV array explicitly depends on ones of PV modules. Having sufficient accuracy in mathematical model for commercial PV module, the introduction of \( N_{SA} \) and \( N_{SA} \) in PV array model cannot lead to any deviation of the confidence of the proposed PV simulator.
Model Building for PV Array

A hierarchical modeling technology is used to build PV array model using both top-down and bottom-up approaches. As mentioned, most of PV arrays are composed of commercially available PV modules. Following the top-down procedure, the model of PV array is decomposed to call one of built-in PV models for commercially available PV modules. On the basis of manufacturers’ datasheets at the present time, the PV model is built with sufficient accuracy and confidence. Having reliable PV models for commercial PV modules, the modular PV array model allows accurate prediction of PV system performance using bottom-up approach.

Model Building for PV Modules. The model for a commercially available PV module with practical considerations is built in a graphic user interface (GUI) environment of Simulink to simulate and analyze both nonlinear $I-V$ and $P-V$ output characteristics. The PV model is further refined by the arrangement of reference temperature and reverse saturation current in the Initialization commands of Mask Editor. There are seven kinds of commercial PV modules in the Energy Research and Development Center (ERDC), Da-Yeh University in Taiwan. The specifications of the five modules are listed in Tables I. Having built one model for one commercial PV module using the one-diode five-parameter PV model, the accuracy of the electricity model is validated using PV manufacture datasheets one by one. Taking an AP200 PV module (A+, Taiwan) as an example, PV manufactures generally only provide experimental data with reference to STC and the nominal conditions. In order to validate the $I-V$ and $P-V$ output characteristics of PV electricity model for a commercial AP200 module at the so-called STC, the cell temperature is fixed at 25 °C, the solar irradiance is given by 1 kW/m², and the operating voltage increases from 0 to 50 V at 0.1 V steps. The built PV block is masked with a user-friendly icon as shown in Fig. 3(a) and contains the block diagram of the subsystem that is connected to build the final model as shown in Fig. 3(b). In the subsystem, the $I-V$ characteristic equation, photovoltaic current and output current are implemented using built-in Fcn blocks in Simulink. Each Fcn block contains a single field with a MATLAB expression that is used to implement an equation in the C language syntax. In order to make the proposed block library easy to use and understand, an image file of custom PV icon is adopted as a masking one. The image file PV_Moduel.jpg is first saved in the MATLAB current path and is then called in an Icon page in the built-in Mask Editor of Simulink. Manufactures typical provide the experimental data for PV modules, such as the rated voltage ($V_{mwp}$) and current ($I_{mpw}$) at the maximum power rating, the short circuit current ($I_{sc}$), the open circuit voltage ($V_{oc}$), and the temperature coefficient of short circuit current ($K_{i}$) that can be easily configured through the designed dialog box as shown Fig. 3(c). The Cell-Type variable is further used to determine the associated ideal factor $A$ and band gap $E_{G}$. In the built-in Initialization commands field, the values of both electron charge and Boltzmann’s constant are assigned, and the command statements of bisection algorithm to calculate the variables of the series and shunt resistance are programmed. On the other hand, both series resistance and shunt resistance are obtained using the bisection algorithm to match the experimental $I_{mpw}$. The results are, respectively, $R_{S} = 2.15 \times 10^{-3} \Omega$ and $R_{SH} = 9.58 \Omega$ as listed in Table III. The simulation results of the other commercial PV modules are also listed in Table 2. Figure 4 shows the nonlinear $I-V$ and $P-V$ output characteristics of the five commercial PV model. It is obvious that the built models for the five commercial PV modules have a good degree of accuracy compared with the experimental data of PV manufacture datasheets in the standard test conditions. In general, PV manufactures provide some experimental data about electrical and thermal characteristics at the STC in the datasheets. Examining the manufacturer’s specifications of commercial PV products, only some experimental data under the STC are listed including the open-circuit voltage $V_{oc}^{STC}$, the short-circuit current $I_{sc}^{STC}$, the maximum power rating $P_{max}^{STC}$, the rated voltage $V_{mpw}^{STC}$ and the rated current $I_{mpw}^{STC}$ at the MPP, the temperature coefficient of short circuit current $K_{i}$, and the temperature coefficient of open circuit voltage $K_{V}$.
Figure 3. PV model for A+ AP200 PV module: (a) PV model; (b) subsystem implementation; (c) dialog box; (d)-V characteristics.

Table 1. Specifications of five commercial PV modules (1kW/m², 25°C).

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Siemens SM46</th>
<th>Siemens SM55</th>
<th>Lucky Power Tech. LPS-196-3S</th>
<th>Motech America LLC GEPVp-205-M</th>
<th>Siemens SM46</th>
<th>Siemens SM55</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{max} (W)</td>
<td>200</td>
<td>195</td>
<td>205</td>
<td>46</td>
<td>55</td>
<td>55</td>
</tr>
<tr>
<td>V_{mpp} (V)</td>
<td>26.3</td>
<td>25.95</td>
<td>27.6</td>
<td>14.6</td>
<td>17.4</td>
<td>17.4</td>
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<tr>
<td>I_{mpp} (A)</td>
<td>7.61</td>
<td>7.52</td>
<td>7.6</td>
<td>3.15</td>
<td>3.15</td>
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<tr>
<td>V_{oc} (V)</td>
<td>32.8</td>
<td>32.70</td>
<td>33</td>
<td>18</td>
<td>21.7</td>
<td>21.7</td>
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<tr>
<td>I_{sc} (A)</td>
<td>8.21</td>
<td>8.06</td>
<td>8.2</td>
<td>3.35</td>
<td>3.45</td>
<td>3.45</td>
</tr>
<tr>
<td>K_{i} (mA/K)</td>
<td>3.2</td>
<td>3.2</td>
<td>5.6</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
</tr>
<tr>
<td>K_{v} (V/K)</td>
<td>−0.123</td>
<td>−0.1112</td>
<td>−0.12</td>
<td>−0.077</td>
<td>−0.077</td>
<td>−0.077</td>
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</table>
As mentioned, most of PV array are been built on the roof of the Energy Research and Development Center (ERDC) building in Da-Yeh university. The PV modules was arranged in a configuration of 18-series and 10-parallel to form a PV array. The PV module was mounted in an open rack and placed in a south-facing position with an

Hierarchical Model for PV Array. A hierarchical modeling technology is used to build PV models using both top-down and bottom-up approaches. As mentioned, most of PV array are composed of commercial PV modules. First, the model for a PV module with practical complexity is built in a GUI environment of Simulink to simulate and analyze both nonlinear $I$-$V$ and $P$-$V$ output characteristics. As shown in Fig.5, a 10 kWp PV array with Siemens SM55 PV modules was been built on the roof of the Energy Research and Development Center (ERDC) building in Da-Yeh university. The PV modules was arranged in a configuration of 18-series and 10-parallel to form a PV array. The PV module was mounted in an open rack and placed in a south-facing position with an

<table>
<thead>
<tr>
<th></th>
<th>Kyocera Corporation KC200GT</th>
<th>Lucky Power Tech. LPS-196-3S</th>
<th>Motech America LLC GEPVp-205-M</th>
<th>Siemens SM46</th>
<th>Siemens SM55</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{	ext{oc}}$ (V)</td>
<td>26.3</td>
<td>25.95</td>
<td>27.6</td>
<td>14.6</td>
<td>17.4</td>
</tr>
<tr>
<td>$I_{	ext{sc}}$ (A)</td>
<td>7.6100</td>
<td>7.5200</td>
<td>7.600</td>
<td>3.1500</td>
<td>3.1500</td>
</tr>
<tr>
<td>$P_{	ext{max}}$ (W)</td>
<td>200.1431</td>
<td>195.1444</td>
<td>209.7596</td>
<td>45.9901</td>
<td>54.8103</td>
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<tr>
<td>$R_s$ (Ω)</td>
<td>$4.17 \times 10^{-3}$</td>
<td>$5.35 \times 10^{-3}$</td>
<td>$0.72 \times 10^{-3}$</td>
<td>$11.5 \times 10^{-3}$</td>
<td>$11.198 \times 10^{-3}$</td>
</tr>
<tr>
<td>$R_{sh}$ (Ω)</td>
<td>9.198</td>
<td>20.08</td>
<td>4.9477</td>
<td>24.8140</td>
<td>6.4373</td>
</tr>
</tbody>
</table>

Table 2. Simulation results of five commercial PV modules (1kW/m², 25°C).

Figure 4. $I$-$V$ characteristics of PV modules: (a) Lucky Power Tech. LPS-196-3S; (b) Motech GEPVp-205-M; (c) Siemens SM46; (d) Siemens SM55.
inclination angle of 23.5°. The PV array was connected an inverter (Fronius IG Plus 120 Inverter with an built-in MPPT controller and fed to. A meteorological station composed of a Second Class pyranometer (LP PYRA 03 AC), an anemometer (JWSD-821 A-Type wind speed transmitter), and a temperature sensor (PT-100) was installed near the PV system to provide the data of solar irradiation, wind speed and ambient temperature. A temperature sensor (PT-100) was fixed to the rear surface of PV module to further estimate the cell temperature that is equal to the addition of the back-surface temperature and a temperature difference 2.5λ [19].

Using the proposed PV array model, both $I-V$ and $P-V$ output characteristics of the 10 kWp PV array under the STC are depicted in Fig. 6. It is observed that all of the short-circuit current, open circuit voltage, both rated current and maximum power rating under the operating voltage at the MPP for the proposed model has a good degree of precision compared to the calculated ones.
Conclusions
The proposed modeling for a PV array is programmed with credible precision by calling the verified PV model for commercially available PV modules. Both designed mask icon and dialog of the model demonstrate the easy-to-use, configurable, and user-friendly advantages like the Simulink block libraries. The proposed model takes sunlight irradiance and cell temperature as input parameters and outputs the I-V and P-V characteristics under various conditions. This makes the output characteristics of proposed model have a sufficient agree with these of commercial PV modules.

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References
