A Matlab/Simulink-Based Photovoltaic Array Model Employing SimPowerSystems Toolbox

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Abstract: The modeling of PV (photovoltaic) systems is very crucial for embedded power system applications and maximum power point tracking. This paper presents a PV array model using Matlab/Simulink with the assistance of SimPowerSystem toolbox. The PV cell is considered as the main building block for simulating and monitoring the PV array performance. The PV model has been developed and used as Simulink subsystems where the effect of solar insolation and PV array temperature on commercial PV modules have been studied throughout the simulated I-V and P-V output characteristics. The proposed model facilitates simulating the dynamic performance of PV-based power systems. The effect of different partial shading patterns of PV arrays under different configurations has been studied.

Key words: Modeling, PV, solar energy, Matlab, shading.

1. Introduction

Developing alternative energy resources with high efficiency and low emission has become of great importance with increasing concerns about fossil fuel deficit, high oil prices, global warming, and damage to environment and ecosystem. Abundance and sustainability of solar radiant energy are important factors that characterize the energy through the PV (photovoltaic) effect among the renewable energy resources. Regardless of the intermittency of sunlight, solar energy is widely available and completely free of cost [1-4]. Recently, PV array systems have been used in several electric power applications. Despite of the high initial cost and low efficiency, PV system has small operation and maintenance costs as it is a stationary source of energy fabricated from semiconductor material. Compared with the oil prices, the solar energy is a feasible energy supply with great long-term benefits. PV cell is considered the fundamental power conversion unit of a PV-based power system [1]. Solar insolation, temperature, and output voltage of PV are the essential factors that affect the output characteristics of a PV cell. Since the PV has a nonlinear current-voltage (I-V) characteristic, it is vital to model the PV unit for MPPT (maximum power point tracking) in PV-based power systems [1-5].

PV systems are considered an important type of distributed power generation systems. Also, it could be used as a standalone system. However, PV array operation in this type of power systems suffers from the effect of complete or partial shading, which is usually caused by clouds, trees, and near buildings. Under partially shaded conditions, the I-V characteristic of the PV array become complex with multiple peaks. These different peaks are generated due to the non-uniform insolation levels that are received on a partially-shaded PV array surface. The PV array efficiency is decreased due to these non-uniform characteristics. As a consequence, the conventional MPPT algorithm fails
to differentiate between local and global peaks [1-3]. Therefore, modeling of the PV has attracted the attention of the researchers to facilitate modeling the dynamic performance of the PV-based power systems. In Ref. [1], a generalized PV model has been developed with Matlab/Simulink and validated with a PV cell and a commercial module. This model has also been designed in the form of Simulink block libraries. However, the partial shading has not been considered. In Ref. [2], a Matlab-based modeling and simulation scheme suitable for studying the $I$-$V$ and $P$-$V$ characteristics of a PV array under a nonuniform insolation due to partial shading has been studied. In Ref. [3], a Matlab Simulink simulator for PV systems has been proposed where a two-diode model has been used to represent a PV cell. In Ref. [4], a simulation program of a single phase grid connected PV system using Matlab/Simulink and SimPowerSystem toolbox has been developed. In Ref. [6], PV systems have been modeled for maximum power tracking for the operation of grid connected photovoltaic power systems. In Ref. [7], analytical expressions are derived for the rapid extraction of solar cell single diode model parameters from experimental data. In Ref. [8], PV array has been modeled to investigate the maximum power tracking algorithms which were often used to compare the tracking efficiencies for the system operating under different controls. In Ref. [9], a $V^2$ based MPP (maximum power point) tracking scheme is developed using a SEPIC (single-ended primary inductance converter) topology. Mathematical models are formulated and a tracking algorithm then is developed with a combined photovoltaic-system simulation model using Simulink. In Ref. [10], the development of a general model which can be implemented on simulation platforms such as PSPICE (personal computer simulation program with integrated circuit emphasis) or SABER has been presented. In Ref. [11], a variable-structure observer for solar-array current estimation in a photovoltaic power generation system is presented. In Ref. [12], a method of modeling and simulation of photovoltaic arrays has been proposed where the main objective is to find the parameters of the nonlinear $I$-$V$ equation by adjusting the curve at three points: open circuit, maximum power, and short circuit. In Ref. [13], the operation and modeling of stand-alone power systems with PV power generators has been studied. In Ref. [14], a hybrid simulation model of PV cell/module and system using Matlab/Simulink and PSPICE has been presented. In Ref. [15], a technique to model PV characteristics under various environmental circumstances including non-shaded and partially shaded conditions has been proposed. The technique has been developed based on experimental study. It provides a versatile model using PSCAD (power system computer aided design) which can represent any form of PV array with any configuration of bypass diodes.

The objective of this paper is to establish a PV model to be used as a subsystem block in power system simulation. In addition, the effects of different factors (insolation, temperature, rating, etc.) on the PV performance are encountered. Moreover, a 120 W polycrystalline PV panel output characteristics have been simulated and analyzed considering the effect of operating temperature and solar insolation on the maximum power point. In addition, a Simulink model has been developed to study the effect of partial shading patterns on the PV array with different series and parallel configurations.

1.1 PV Hierarchy

1.1.1 PV Cell

As shown in Fig. 1, PV cell is basically a semiconductor $p$-$n$ junction-based photodiode. This semiconductor photodiode generates electrical power when exposed to light [2-4]. PV cells can be made up of various semiconductor materials. But mono-crystalline silicon and poly-crystalline silicon are the most common types known commercially [2-4].

1.1.2 PV Module

The power produced by a single PV cell is not
enough for general use. Therefore, by connecting PV cells in series, higher voltage can be obtained and in parallel higher current can be obtained consequently higher power. Generally, a combined series and parallel connection of PV cells is known as a module. Mostly, commercial modules consist of 36 or 72 cells. The modules consist of transparent front side, encapsulated PV cells, and back side. The front side material is usually made up of low-iron and tempered glass. The efficiency of a PV module is less than a PV cell due to the fact that some solar irradiation is reflected by the glass cover and frame shadowing [2-4].

1.1.3 PV Array

As shown in Fig. 2, a PV array (system) is an interconnection of modules which in turn is made up of many PV cells connected in series and parallel. The power produced by a single module is seldom enough for commercial use, so modules are connected to form an array to supply the load. The connection of modules in an array is the same as that of cells in a module. Modules can also be connected in series to get an increased voltage or in parallel to get an increased current [2-4]. Connecting several modules in series gives a string where several strings in parallel is an array.

1.2 PV Cell Operation

As shown in Fig. 3, the principle of operation of a PV cell is based on the basic principle of photoelectric effect. Photoelectric effect can be defined as a phenomenon in which an electron gets ejected from the conduction band as a consequence of the absorption of sunlight of a certain wavelength by a material either metallic, non-metallic, solids, liquids or gases [3]. So, in a PV cell, when sunlight strikes its surface, some portion of the solar energy is absorbed in the semiconductor material. If the absorbed energy is greater than the band gap energy of the semiconductor, the electron from the valence band jumps to the conduction band. By this, pairs of hole-electron are created in the illuminated region of the semiconductor. The electrons thus created in the conduction band are now free to move. These free electrons are forced to move in a particular direction by the action of the electric field presented in the PV cells. These flowing electrons constitute current and can be drawn for external use by connecting a metal plate on top and bottom of PV cells. Current and voltage (created because of its built-in electric field) generate electric power [2-4]. The remainder of this paper is organized as follows: The PV models are addressed in Section 2; The Matlab/Simulink models and the $I-V$ and $P-V$ characteristics of commercial PV array are discussed considering the effect of shading in Section 3; Finally, brief conclusions are drawn in Section 4.
2. PV Models

2.1 PV Cell Model

2.1.1 General Model

A general mathematical description of the \(I-V\) output characteristic of a PV cell has been studied in Refs. [5-7]. This equivalent circuit-based model is mainly used for monitoring and assessing the PV performance and exploring different PV MPPT techniques. As shown in Fig. 4, the equivalent circuit of the general model is composed of photo current source, diode, parallel resistor expressing the leakage current, and series resistor describing the internal resistance to the current flow. The \(I-V\) characteristic equation of a PV cell is given as:

\[
I = I_{PH} - I_S \left( \exp \left[ \frac{q(V+I R_S)}{kTA} \right] - 1 \right) - \left( \frac{V+I R_S}{R_{SH}} \right)
\]  

where \(I_{PH}\) is a light-generated current or photocurrent, \(I_S\) is the cell saturation of dark current, \(q\) (\(= 1.6 \times 10^{-19}\) C) is the electron charge, \(k\) (\(= 1.38 \times 10^{-23}\) J/K) is Boltzmann constant, \(T\) is the cell working temperature, \(A\) is the ideal factor, \(R_{SH}\) is the shunt resistance, and \(R_S\) is the series resistance. The photocurrent mainly depends on the solar insolation and cell working temperature, which is given as:

\[
I_{PH} = A \left( I_{SC} + K_I (T - T_r) \right)
\]

where \(I_{SC}\) is the cell short-circuit current at a 25 °C and 1 kW/m², \(K_I\) is the cell short-circuit current temperature coefficient, \(T_r\) is the cell reference temperature, and \(\lambda\) is the solar insolation in kW/m². On the other hand, the cell saturation current varies with the cell temperature, which is described as:

\[
I_S = I_{RS} \left( \frac{T_r}{T} \right)^3 \exp \left[ q E_G \left( \frac{1}{kT_r} - \frac{1}{kT} \right) \right]
\]

where \(I_{RS}\) is the cell reverse saturation current at a reference temperature and a solar radiation, \(E_G\) is the band-gap energy of the semiconductor used in the cell. The ideal factor \(A\) is dependent on PV technology [8] and is listed in Table 1.

The reverse saturation current at reference temperature can be approximately obtained as:

\[
I_{RS} = \frac{I_{SC}}{\exp \left[ \frac{qV_{OC}}{kT_r} \right] - 1}
\]

where \(V_{OC}\) is the PV open-circuit voltage at the reference temperature.

2.1.2 Double Exponential Model

The double exponential model is another more accurate model that describes the PV cell [9]. It is derived from the physical behavior of PV cell constructed from polycrystalline silicon [9]. This model consists of a light-generated current source, two diodes, a series resistance and a parallel resistance. However, because implicit and nonlinear nature of the model is difficult to develop expressions for the \(I-V\) curve parameters, therefore, this model is not widely used in literature and is not taken into consideration for the generalized PV model.

2.1.3 Approximate Model

The approximate model of a PV cell with suitable complexity [8] can be derived from Eq. (1) via neglecting the effect of the shunt resistance and be rewritten as:

\[
I = I_{PH} - I_S \left( \exp \left[ \frac{q(V+I R_S)}{kTA} \right] - 1 \right)
\]

2.1.4 Simplified Model

For an ideal PV cell (no series loss and no leakage to ground, i.e., \(R_S = 0\) and \(R_{SH} = \infty\), respectively). The equivalent circuit of PV cell can be further simplified [5, 6, 10, 16], where Eq. (1) can be rewritten as:

\[
I = I_{PH} - I_S \left( \exp \left( \frac{qV}{kTA} \right) - 1 \right)
\]
2.2 PV Module and Array Model

Since a PV cell produces very low power, the cells should be arranged in series-parallel configuration on a module to produce enough power. As mentioned earlier, PV array is a group of PV modules which are connected in series and parallel circuit configurations to generate the required current and voltage. The equivalent circuit for a PV module arranged in \( N_P \) parallel and \( N_S \) series cells is shown in Fig. 5a. The terminal equation for the current and voltage of the array becomes as follows [11, 12, 17]:

\[
I = N_P I_{PH} - N_P I_S \left( \exp \left( \frac{q(V + I_{SH} R_S)}{N_S k T A} \right) - 1 \right) - \frac{(N_P V + N_S R_S + I_{SH})}{N_S R_S + N_P R_S} (7)
\]

An approximate equivalent circuit for PV cell, module, and array can be generalized and expressed in Fig. 5b. Therefore, the current can be expressed as:

\[
I = N_P I_{PH} - N_P I_S \left( \exp \left( \frac{q(V + I_{SH} R_S)}{N_S k T A} \right) - 1 \right) (8)
\]

where \( N_S = N_P = 1 \) for a PV cell, \( N_S \) and \( N_P \) are the series-parallel number for a PV array. The simplified model [6, 10] of a generalized PV array is illustrated in Fig. 5c. The equivalent circuit is described as:

\[
I = N_P I_{PH} - N_P I_S \left( \exp \left( \frac{qV}{N_S k T A} \right) - 1 \right) (9)
\]

3. Simulation and Results

In this paper, the simplified PV module and array models have been used for the PV modeling using Matlab/Simulink. The main reason for choosing this model is that the other two models experience algebraic loop problem in Matlab/Simulink simulation, as the output current is required to be an input to the equations of output current in these models. Iterations may be needed for solving this problem which in many cases end up with simulation break.

3.1 Simulation Using Matlab/Simulink

The simplified PV module model has been simulated using two methods, the mathematical modeling and the physical modeling. These models are used for monitoring and assessing the nonlinear \( I-V \) and \( P-V \) output characteristics of the PV module/array.
3.1.2 Mathematical Modeling

As shown in Fig. 9, using Simulink math operations toolbox and SimPowerSystems toolbox, the simplified model of the PV cell has been simulated using math function block for the equations of the PV simplified model. The inputs and the parameters are the same as in the physical model with additional parameters such as, the quality factor, semi-conductor band-gap energy, and number of cells in parallel.

The mathematical PV cell model that is illustrated in Fig. 9 has been used as a sub-system to be integrated into other system simulation and provide an easy way to input the parameters of the PV module. The $I-V$ and $P-V$ output characteristics are shown in Figs. 10 and 11. The mathematical model has more advantages than the physical model, because additional parameters as quality factor and semi-conductor band gap energy can be varied/controlled. Moreover, parallel and series PV cells combinations can be formed without the need for repeating the block diagrams. On the other hand and in order to make a parallel combination in the physical model, the block of the PV cell has to be duplicated, which add more complexity to the model.

3.1.3 Interfacing Mathematical Model with Power System Toolbox

Since Simulink has a powerful toolbox for modeling the power systems and power electronics components, it is important to illustrate how to interface the mathematical PV model with the power system toolbox.

As shown in Figs. 12 and 13, the PV model output current has been fed to a DC controlled current source and the output voltage has been measured then fed back into the voltage input of the PV panel. This circuit has been transformed into a subsystem that is masked with a PV array icon so it can be easily implemented with any power system toolbox simulation. As observed in Fig. 13, it has been connected to a variable voltage source to observe the $I-V$ and $P-V$ output characteristics of the modeled PV module.

3.1.4 PV Array Model under the Effect of Shading

In order to study the effect of shading on the PV array, it is important to know the shading pattern along with the PV arrays series and parallel configurations.
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Fig. 10  Simulink model of a mathematically-modeled PV module.

Fig. 11  PV module masked mathematical model block parameters.

Fig. 12  Interfacing the mathematical PV module model to physical ports.

Fig. 13  Simulink simulation to illustrate the P-V and I-V PV module output characteristics.

To study the effect of shading, a group of PV modules are modeled using a subsystem that includes the effect of by pass diode as shown in Fig. 14. This group of PV module has specific series and parallel configuration which could be specified in the group parameter input dialog as shown in Fig. 15. A set of PV module groups are connected together in order to simulate the effect of shading on a PV array. Each module group can have different insolation level and temperature. Also the effect of by-pass diodes can be toggled for each group separately. For example, assume different insolation levels (partial shading) 1 kW/m² and 0.1 kW/m² at the same temperature (25 °C) for a set of PV array module groups as shown in Table 2 and Fig. 16. As shown in Fig. 16, the un-shaded modules are colored in orange and shaded modules are colored in blue. Also it is observed form Table 2 and Fig. 16 that some groups are supplements to each other. For example, G1-A and G1-B are on the same series PV module lines, thus they have the same number of parallel modules in the same group. As shown in Fig. 17, Simulink model has been developed to simulate this shaded PV array. PV module group subsystem blocks have been used to simulate the different groups of PV modules with different insolation levels. These groups are connected...
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![Simulink model of PV module group (assembly) with by-pass diode.](image)

**Table 2** PV array shading pattern example at 25 °C.

<table>
<thead>
<tr>
<th>Group</th>
<th>Number of series modules in each group (S)</th>
<th>Number of parallel modules in each group (P)</th>
<th>Insolation level in kW/m² (λ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G1-A</td>
<td>4</td>
<td>40</td>
<td>1 (un-shaded)</td>
</tr>
<tr>
<td>G1-B</td>
<td>6</td>
<td>40</td>
<td>0.1 (shaded)</td>
</tr>
<tr>
<td>G2-A</td>
<td>7</td>
<td>38</td>
<td>1 (un-shaded)</td>
</tr>
<tr>
<td>G2-B</td>
<td>3</td>
<td>38</td>
<td>0.1 (shaded)</td>
</tr>
<tr>
<td>G3</td>
<td>10</td>
<td>22</td>
<td>1 (un-shaded)</td>
</tr>
</tbody>
</table>

![Simulink model of PV array with different shading patterns.](image)

**Table 3** Solarex MSX 60 PV module specifications at 1 kw/m², 25 °C.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical peak power (Pₚ)</td>
<td>60 W</td>
</tr>
<tr>
<td>Voltage at peak power (Vₚₚ)</td>
<td>17.1 V</td>
</tr>
<tr>
<td>Current at peak power (Iₚₚ)</td>
<td>3.5 A</td>
</tr>
<tr>
<td>Short-circuit current (Iₚₛ)</td>
<td>3.8 A</td>
</tr>
<tr>
<td>Open-circuit voltage (Vₒₚ)</td>
<td>21.1 V</td>
</tr>
<tr>
<td>Temperature coefficient of open-circuit voltage</td>
<td>-73 mV/°C</td>
</tr>
<tr>
<td>Temperature coefficient of short-circuit current (kₖ)</td>
<td>3 mA/°C</td>
</tr>
<tr>
<td>Approximate effect of temperature on power</td>
<td>-0.38 W/°C</td>
</tr>
<tr>
<td>Number of series cells in the array</td>
<td>36</td>
</tr>
</tbody>
</table>

together in order to simulate a PV array. This in turn can be used as a subsystem in order to be connected/interfaced with other SimPowerSystems Simulink toolbox components.

### 3.2 Results and Discussion

Using the Simulink models of PV array mentioned in the previous section, the Solarex MSK 60 PV module (parameters are listed in Table 3) output I-V and P-V characteristics are simulated using Simulink. In this section, the I-V and P-V characteristics are studied first with varying the operating temperature at constant isolation level then varying the solar insolation level at constant temperature level. The effect of shading, array configuration, varying insolation levels, and different shading patterns on the characteristics of the PV array are studied and analyzed.

#### 3.2.1 I-V and P-V Characteristics with Varying Operating Temperature

As shown in Fig. 18, it is observed that with the increase of the operating temperature, the short-circuit current of the PV module increases. However, the maximum power output decreases.
3.2.2 $I$-$V$ and $P$-$V$ Characteristics with Varying Solar Insolation Level

As shown in Fig. 19, it is observed that with the increase of the solar insolation, the short-circuit current of the PV module increases and the maximum power output increase.

3.2.3 $I$-$V$ and $P$-$V$ Characteristics Including the Shading Effect

In this part, Solerx MSK 60 PV module is used to study the effect of partial and complete shading on PV array (interconnected several PV modules) $P$-$V$ and $I$-$V$ characteristics. Also, the effects of different shading patterns and configurations on the PV array characteristics are investigated. This section will be divided into two case studies.

Case study 1: Effect of partial shading on PV array

In order to simulate the effect of partial shading on a PV array, Simulink model of partially shaded PV array that is developed in Section 3.1 is used to simulate a partially shaded PV array (composed of Solex MSK 60 PV modules) with by pass diode at a constant temperature. The shading pattern configuration of the simulated PV array is shown in Table 2 and Fig. 16.

Each module of this simulated PV array has a by-pass diode that passes the current across the shaded modules (shaded modules limit the flow of current across them). The $I$-$V$ and $P$-$V$ characteristics of the simulated PV array are shown in Figs. 20 and 21, it is observed that the $I$-$V$ characteristics of the PV array have multiple steps with non-uniform $I$-$V$ characteristic. Also, the $P$-$V$ characteristic has multiple peaks (global maximum and local maxima points) due to the effect of...
partial shading of the PV array. This happens as the current is the same across the series PV modules (string) in the PV array having different insolation (some are shaded and others are not), but the voltage across them is different.

Case study 2: Comparison between unshaded and shaded PV array characteristics

The presence of by-pass diodes in a PV array will greatly affect the characteristics of a shaded PV array. In order to compare PV array characteristics under unshaded and shaded conditions, the same Simulink model and PV array discussed in simulation 1 are used. The I-V and P-V characteristics of the PV array will be studied under two situations: (1) under uniform insolation (all modules receive the same insolation level of 1 kW/m²); (2) under partially shaded condition (same conditions used in simulation 1 which are insolation levels of 1 kW/m² and 0.1 kW/m²).

I-V and P-V characteristics of the two cases are shown in Figs. 22 and 23. It is observed that under uniform insolation (1 kW/m²) of the PV modules with by-pass diode conducted the highest PV output power, while in the case of partially shaded PV array with by-pass diodes it resulted in several peaks of the PV array output power. The presence of multiple peaks in PV array characteristics under shaded conditions decreases the efficiency of conventional MPPT since it fails to differentiate between global and local peaks of PV array output power.

In this simulation, the effect of different PV module configurations of a partially shaded PV array is explored. Simulated module configurations are shown in Table 4, where G1-A, G2-A and G3 are shaded groups of PV modules (insolation level of 1 kW/m²), G1-B, G2-B are shaded groups of modules (insolation level of 0.5 kW/m²). The P-V characteristics of different array configurations of Table 4 are shown in Fig. 23.

4. Conclusions

A Matlab/Simulink-based photovoltaic array model employing SimPowerSystems toolbox for cells, modules, and arrays has been developed and verified with a commercial PV array. The developed model inputs are solar insolation and PV array operating temperature, and the outputs are the I-V and P-V characteristics at different values of operating temperature or solar.
insolation. Both models have been built as a sub-system with masked icon and parameters input fields that facilitate the customizing of the PV array model. Also it can be used with SimPowerSystems toolbox to model PV power system. Finally, $P-V$ and $I-V$ characteristics have been studied at different operating temperatures and solar insolation levels.

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