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A novel and accurate photovoltaic simulator based on seven-parameter model

M. Sheraz Khalid, M.A. Abido *

Department of Electrical Engineering, King Fahd University of Petroleum & Minerals, Dhahran, Saudi Arabia

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ABSTRACT

The output characteristics of a photovoltaic (PV) array are highly non-linear. Therefore, an accurate and efficient PV model is required to study and analyze the operation of PV system in the changing environmental conditions. This paper proposes a precise PV simulator based on the seven-parameter electric circuit model. The proposed simulator can generate the output characteristics of a PV system precisely at different operating conditions. It has also enough flexibility to simulate different configurations of PV panels with series/parallel connections. The robustness of the proposed simulator is demonstrated under the partial shaded conditions. Additionally, the performance of the developed simulator is verified by interfacing it with the actual power electronic converter and maximum power point tracking (MPPT) controller. The proposed PV simulator will facilitate the design aspects of PV systems and help in behavior assessment of newly developed controllers prior to practical implementation.

1. Introduction

The demand of electrical energy is increasing day by day and the world is more concern about the high oil prices, fossil fuel deficit, global warming and environmental damages. The participation of renewable and green energy sources in the generation of electrical energy is indispensable now-a-days. Among the renewable energy sources, solar energy is the most promising and photovoltaic (PV) system provides the most direct method to convert solar energy into electrical energy. Despite of the intermittency of sunlight, many PV system have been developed in different countries of the world because of its long term benefits, benevolent fed in tariff initiatives and other schemes offered by governments to encourage the use of renewable energy sources (RES). The world's cumulative installed capacity of PV was 23GW in year 2009 [1]. In 2011, more than 69GW of PV power is installed worldwide that can generate 85 TWh of electricity per year [1]. Among all RES the growth rate of PV power is incomparable and reached almost 70% in year 2011 [1]. The large penetration of PV power into the electricity grid would have adverse effects on electrical power system. To study these effects and to design power electronic converters and MPPT controllers, an efficient and accurate model of PV is required.

The output of PV is extremely non-linear and it is not suitable to represent it with a constant or controlled voltage/current source. Several PV electrical models have been proposed and developed in literature [2–7]. Some of these models are described vaguely and some of them are much complex for the simple power system studies. The simplest model is temperature and radiation scaling of maximum power point which requires the temperature and irradiation coefficients of MPP and predicts the performance of PV only at one point [2]. In [3,4] a method of translation of *I*–*V* curve from one environmental condition to another was presented. Bilinear interpolation method is presented that requires four practically determined *I*–*V* curves, two at different insolations and two at different temperatures [4]. These models are quite complex and require a large amount of data that is not usually provided by the manufacturers. The most efficient and practical model for PV is developed in Sandia Lab [5]. This model takes three inputs that are temperature, irradiation and wind speed and computes the voltage and current of PV at five main points on the *I*–*V* curve. This model also requires thirty practically determined coefficients to simulate the behavior of any PV panel [5]. Values of these coefficients are available for a large number of commercial PV panels [6]. Due to the complexity of these models power system studies such as load flow, maximum power point tracking, and load frequency matching become difficult and require large computational time. Electrical characteristics of PV can be modeled by representing it with equivalent electrical circuit [7]. This model has advantage over the other models due to its electrical circuit nature and behavior of PV can

* Corresponding author. Tel.: +966 13 860 4379.
E-mail addresses: isheraz@kfupm.edu.sa (M. Sheraz Khalid), mabido@kfupm.edu.sa (M.A. Abido).

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be easily understood and investigated. It is very suitable for the dynamic and transient study of the power electronic converters.

The electric circuit based model of PV is further classified as an ideal diode model, four-parameter model, five-parameter model and two-diode model. These models are different from each other in accuracy and implementation. The simplest among these models is the ideal diode model which consists of a single diode and irradiation dependent current source [8,9]. Performance of this ideal model is enhanced by means of series resistance and it is generally known as four-parameter model [10,11]. This model is easy to implement and provides acceptable results. However, its performance deteriorates at high temperatures and low irradiation [12] and also for thin film technology based PV panels [13]. To overcome these shortcomings, an improved circuit based model is developed by adding shunt resistance and it is widely known as five-parameter model [13–15]. Comparison of four and five-parameter model is done in [16] for mono-crystalline PV panel and showed that the five-parameter model is more efficient in estimating the operating current and power at different atmospheric conditions. To further improve the efficiency of the circuit based model some authors used the two-diode model [12,17]. The model non-linearity and the number of parameters to be computed during simulation are increased by inclusion of an extra diode that will make the model computationally inefficient. The competency of the two-diode model over four- and five-parameter models is shown in [12]. To make the model computationally efficient, values of some parameters are assumed constant which deteriorate its performance under the partial shading condition. Five-parameter model is a good compromise between accuracy and simplicity as given in [18].

Recently, seven-parameter model has been proposed in [19] in which efficiency of five-parameter is further improved by adding two additional parameters and without compromising its computational efficiency. Authors have modified the translational equations by adding two exponential constants and showed that the model accuracy has been enhanced and given it the name of seven-parameter model.

There is a need of an accurate and generalized PV simulator that can generate output characteristics of a PV panel or a large PV array precisely at different operating conditions, including the non-uniform irradiation condition. It should be able to work in conjunction with power electronic converters and MPPT controllers for their design and control. Several PV simulators have been presented in the literature based on different PV models discussed above [15,20–24]. Most of these are developed in MATLAB script file and implemented in Simulink using S-function block and some of them can simulate only a single PV panel. Furthermore, very few of them have shown their working under partial shaded condition [23,24].

In this paper, a generalized PV simulator is proposed and developed using the very accurate seven-parameter PV model. To the best of authors' knowledge, such simulator is proposed for the first time. It is employed using only the blocks of the Simulink and have resemblance with the actual PV electric circuit model, which will facilitate the design engineers and researchers in understanding the overall PV power system. Similar to Simulink blocks, the proposed simulator is implemented as a masked block and prompts the user to enter attributes of the PV array under consideration. The effectiveness of the proposed simulator is investigated under different operating conditions including the harsh partial shaded condition. The robustness of the proposed simulator is analyzed in conjunction with the DC–DC converter and MPPT controller. It is envisaged that the developed simulator can be very helpful for the PV design engineers in the simulation study before any experimental verification. Additionally, detailed electrical modeling of PV panel and PV array is also discussed.

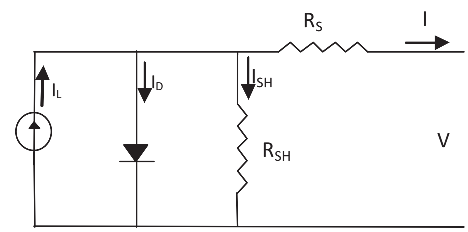

Fig. 1. PV electric circuit model.

The rest of this paper is described as follows. In Section 2, electrical modeling of a PV is discussed that includes a comprehensive PV panel and PV array modeling. MATLAB/Simulink implementation of this model is presented in Section 3. It is followed by results and discussion in Section 4 and conclusion is made in Section 5.

2. PV modeling

Commercially available PV is in the form of PV panels. Maximum output power of a single PV panel is in the range of tens of Watts to some hundreds of Watts that would be acceptable for the small-scale applications. For large-scale applications, however, series and parallel combinations of these panels are needed to enhance the PV output power. Connecting PV panels in series increases the current capability of PV source and parallel connection increases the voltage rating of PV source. This series/parallel combination of PV panels is commonly known as PV array. Considering the importance of PV panel as a basic unit of PV array, model of the PV panel is developed which is then modified to stand for a complete PV array.

2.1. PV panel modeling

The seven-parameter electric circuit model of PV is shown in Fig. 1. It consists of light depended current source, a p–n junction diode and two resistances one in series and another in shunt. Seven parameters are defined as:

I_L	Light generated current
I_0	Diode saturation current
R_S	Series resistance
R_{SH}	Shunt resistances
"a"	Diode modified ideality factor
"m"	Exponential constant for I_L
"n"	Exponential constant for "a"

where "m" and "n" are the two additional parameters and are exponential constants for "I_L" and "a", respectively and proposed in Ref. [19].

Using simple Kirchhoff's current law following relationship can be found:

$$I = I_L - I_D - I_{SH} \tag{1}$$

Here I_D and I_{SH} depicts the diode current and shunt branch current, respectively and given by;

$$I_D = I_0 \left\{ \exp\left[\frac{(V + IR_S)}{a}\right] - 1 \right\} \tag{2}$$

$$I_{SH} = \frac{V + IR_S}{R_{SH}} \tag{3}$$

Putting these expressions of I_D and I_{SH} into Eq. (1) gives the complete I–V characteristics of a PV panel;

$$I = I_L - I_0 \left\{ \exp\left[\frac{(V + IR_S)}{a}\right] - 1 \right\} - \frac{V + IR_S}{R_{SH}} \tag{4}$$