Renewable and Sustainable Energy Reviews 60 (2016) 75–83

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser

An overview of solar photovoltaic panel modeling based on analytical and experimental viewpoint

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ARTICLE INFO

Article history:
Received 10 November 2014
Received in revised form
18 August 2015
Accepted 14 January 2016
Available online 2 February 2016

Keywords:
PV panel
Analytical
Experimental
Mathematical modeling
Shading effect

ABSTRACT

This paper provides a comprehensive review of available models of photovoltaic panel. Modeling and simulation of photovoltaic panel (PV) in virtual environment helps in designing and performance analysis of solar based power system. This paper analyses the currently available models from two different aspects. First aspect is based on electrical characteristics of PV panel using electrical equivalent circuit or through set of mathematical equations. The other aspect is based on the characteristics of PV panel under different environmental conditions. Environmental conditions include varying temperature and non-uniform solar irradiance due to partial shading. Varying environmental conditions causes continuous change in PV panel operating point corresponding to Maximum Power Point (MPP). Therefore an accurate PV panel model built with robust control that includes these environmental conditions will certainly improve the overall performance of the solar power plant. This paper can help researchers in selecting a specific objective based PV panel model out of several models available in literature.

Contents

1. Introduction

With worldwide emphasis on use of non-conventional energy sources, solar photovoltaic power generation is gaining momentum. Power generating device that is used in photovoltaic solar system is PV panel. A PV panel is a series and parallel combination of solar cells which helps in enhancing current and voltage level.

Modeling is the first step in analyzing behavior and characteristics of PV panel in virtual environment. For perfect analysis of its performance, an accurate model of PV system is important considering its low power density and poor efficiency. Also, a reliable and accurate model of PV panel will help in predicting energy production from power plant under varying environmental conditions.

With introduction of MPPT and power electronic converters, solar PV (SPV) system is becoming more and more complex. Therefore, it is very important to analyze the dynamic characteristics of SPV system before and after its integration to the grid. So, the model of PV panel with all complexities should be useful for dynamic studies as well. Also the model should be simple and presenting the nonlinear PV characteristics without going much into the semiconductor physics. Accuracy of the model is decided by the proximity of model performance to that of the experimental characteristics of the system.

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http://dx.doi.org/10.1016/j.rser.2016.01.087
1364-0321/

Several models have been proposed in the literature to present the electrical characteristics of PV panel. All these proposed models are governed by either of the two aspects as follows. First aspect does the analytical study of PV panel by modeling it through electrical equivalent circuit or through mathematical equations. This study viewpoint obtains standard *I–V* and *P–V* characteristics of PV panel either through equivalent circuit or through a set of mathematical equations. Another study viewpoint covers the modeling of PV panel based on its characteristics under different environmental conditions. These conditions include the variation of solar irradiance, temperature and shading effect. An experimental verification is required to establish the accuracy of such models.

In [1–3], the PV panel model based on electrical equivalent circuit aspect is presented. One diode model is thoroughly analyzed and its practical verification is presented in [1] and [3]. In [2], the two diode model and associated mathematical formulation is described. From the literature, it can be concluded that the two diode model is more accurate and presents a model whose *I–V* characteristics is closer to the practical behavior of PV cell. But the two diode model involves complex and more computational effort as compared to the one diode model. Due to this reason one diode model based analysis is abundant in the literature. In [1,4], the study of solar cell is extended to include the effect of solar cell junction capacitance.

Mathematical representation of solar cell is based on Shockley diode equation [5,6]. This model represents the non-linear characteristics of PV cell with parameters such as shunt and series resistance, reverse saturation current and diode ideality factor. Shockley diode equation is an exponential expression. An alternative mathematical representation incorporates sine and cosine function based model [7].

Above explained models often require material specific standard data which are generally not provided by manufacturer datasheets. Attempts have been made to obtain a generalized model of PV cell that utilizes only the data provided in the manufacturing datasheet. In [8–10], the parameters of non-linear *I–V* equation are obtained by adjusting the curve at three known points viz. open circuit, maximum power and short circuit. A measurement based parameter estimation technique is discussed in [11,12]. Genetic algorithm, particle swarm optimization and differential evolution based parameter to determine the unknown parameters estimation methods are found to be more accurate [13–15]. In [16–18], the authors have obtained the unknown parameters by using the data available at standard test condition.

Based on the second approach, effect of environmental conditions like variation of solar irradiance, temperature and shading effect have also been investigated. In the literature, effect of variation of solar irradiance and temperature has been analysed with the help of model based on Shockley diode equation [19–21]. Study of shading effect is rather a complex task as it involves multiple power peaks in *P–V* characteristics of PV cell. In [22–24], the study of effect of bypass diode configuration on PV cell is presented. Bypass diodes are provided with PV panel to avoid hot spot formation due to partial shading or non-uniform irradiance. Presence of bypass diode causes multiple peaks in PV panel characteristics. Modeling of partial shading effect is done by considering the configuration of solar panel [25,26]. The number of modules in series and parallel, and their respective received irradiance is considered while modeling shading effect. Representation of shading effect can also be done through mathematical model using numerical techniques like Newton–Raphson algorithm, analytical approximation and interpolation methods. Voltages of series connected modules are added while currents are added for parallel connected modules. Addition of voltage and current require numerical technique due to non-linear characteristics of individual solar module. Lambert W function represents a set of exponential equations with inverse function. This tool is also utilized to represent the shading effect on PV panel [27,28]. Modules in a PV panel can be configured in series–parallel, bridge-linked or total-cross-tied. A study compares the shading effect for different module configuration [29,30]. Different testing platforms have been used to model the shading effect. S-function builder based model presents the PV panel as constant current source. Shading effect is analyzed using pre-digested function [31].

In recent years, solar PV power generation has immensely increased and efforts have been made to explore the behavior of PV systems under different working conditions. This paper presents an overview of existing models of PV systems available in the literature, which considers various aspects. This work aims at providing a strong foundation for those who aspire to model the complete solar PV system.

Similar kind of study has been reported in the literature, although the depth and coverage of different kind of models is much higher in this article. Ref. [32] compares three different models that are based on mathematical tools. In all three models, *I–V* and *P–V* characteristics was obtained with the help of predictive techniques. All three methods can be categorized under analytical study viewpoint. It does not discuss any experimental model. In [33], different existing performance and reliability evaluation models are discussed. Classification of these models is based on different photovoltaic technologies. All models that have been discussed in this paper are material specific and cannot be generalized for all kind of PV panels. In [34], a comparison of eight models is given. All these models are based on temperature estimation of PV panel under operating conditions. Since *I–V* and *P–V* characteristics of PV panel varies with panel temperature, so these models are very useful and can be put under experimental viewpoint. However this study has included only those models which discuss only temperature as a parameter and has left solar irradiance. In [35], a very useful compilation of five heuristic models is done. All the models use solar irradiance and temperature as input parameter and obtain maximum power point. This study is very useful from controlling aspect as maximum power point is obtained in all these models. However, it does not discuss mathematical formulation for all these models. Ref. [36] presents a comparative study between various models that use datasheet for PV panel characterization. All these models discuss uniform irradiance condition only. Ref. [5] presents a compilation of analytical models that include both single and double diode electrical circuit based models. Effect of various parameters like series and shunt resistances on behavior of PV panel have been included. Ref. [37] presents a compilation of one diode models that are based on experimental viewpoint. A detailed mathematical analysis for all the models has been presented. This study includes the uniform irradiance condition only and the partial shading condition is overlooked.

Organization of this paper as follows. In this paper, Section 2 gives a brief introduction of equivalent circuit based PV panel modeling. Section 3 discusses various existing mathematical models. Models discussing the effect of environmental conditions on PV system behavior are discussed in Section 4. Finally, conclusion summarizes various models and their respective applications in designing the solar energy based power system.

2. Equivalent circuit based modeling

Fig. 1(a) shows the one diode model of solar cell in which the amount of electrical energy produced by PV cell is represented by a current I_{ph}, which is proportional to the solar irradiation. Internal resistance is represented by series resistance while a shunt