Available online at www.sciencedirect.com

ScienceDirect

Solar Energy 100 (2014) 31–41

SOLAR ENERGY

www.elsevier.com/locate/solener

Development of a model to simulate the performance characteristics of crystalline silicon photovoltaic modules/strings/arrays

Tao Ma *, Hongxing Yang, Lin Lu

Renewable Energy Research Group (RERG), Department of Building Services Engineering, The Hong Kong Polytechnic University, Hong Kong

Received 28 June 2013; received in revised form 6 September 2013; accepted 1 December 2013
Available online 20 December 2013

Communicated by: Associate Editor Elias K. Stefanakos

Abstract

In this study, a novel theoretical model, offering a good compromise between accuracy and simplicity, was developed in Matlab for determining solar photovoltaic (PV) module parameters and then fitting the model to experimental *I–V* characteristic curves of a PV module/string/array. A few inputs are only needed for the model, which can be obtained from the manufacturer datasheet. With this newly developed model, the performance of a PV module/string/array at any solar irradiance and module cell temperature can be easily simulated. To validate the simulation model, the parameters from the simulation and *I–V* characteristic curves were compared with those from the DeSoto model and other simulation software (INSEL and PVsyst) at different temperature and irradiation. The comparison results present a high degree of agreement. Moreover, a series of field measurements were carried out from an existing 22 kWp grid-connected PV system located in The Hong Kong Polytechnic University to further validate the simulation results at a wide range of real operating conditions. To have more realistic results, the model was then slightly modified by including the effect of soiling, aging and other derating factors. Field test results demonstrate that the modified simulation model can accurately predict the *I–V* curve characteristics of PV modules/strings/arrays demonstrating the feasibility and reliability of the developed simulation model.

Keywords: Mathematic model; PV module/string/array; Experimental verification; Field measurement

1. Introduction

Energy is an essential component for all social activities, required for production of all goods and provision of all services (Muneer et al., 2003). At present our world is mainly powered by fossil fuels. With the wide concerns in recent years on global warming and harmful environmental effects from carbon fuels, a global movement to utilizing renewable energy, such as solar photovoltaic (PV), is therefore under way to help meet increased energy needs and carbon reduction target. As for China, the national energy administration announced that the cumulative installed solar PV capacity would increase from 3.3 GW in 2011 to 20 GW in 2015 from its 12th Five-Year Plan (Jäger-Waldau, 2012).

With the robust growth of solar PV applications, accurate prediction of the characteristic parameters of solar PV models/strings/arrays becomes an essential topic of research since it is very important to actually know the system's performance in the planning and design stages of PV systems. The designers require a reliable tool to predict PV module energy production under real conditions to make a sound decision on selection of different PV modules (Carrero et al., 2007; De Soto et al., 2006; Dongue et al., 2012). Besides, engineers also need an accurate tool to simulate the power output from a PV plant under real operating conditions for evaluating the system's energy performance. However, the specifications of a PV module from its manufacturer cannot help us to determine its

* Corresponding author. Tel.: +852 27664836; fax: +852 27657198.
E-mail address: Tao.Ma@connect.polyu.hk (T. Ma).

0038-092X/$ - see front matter
http://dx.doi.org/10.1016/j.solener.2013.12.003

power production in real conditions, since the specifications are obtained at standard test condition (STC): incident sunlight of 1000 W/m^2, a cell temperature of 25 °C and an air mass of 1.5. To make them effective at other general conditions, an accurate and reliable solar PV power prediction model, therefore, is urgently needed (Lo Brano et al., 2010, 2012).

The electrical behavior of a crystalline silicon photovoltaic device is characterized by its current–voltage (I–V) curve. Substantial research on I–V curve predictions can be founded in literatures. The overview of various methods commonly used can be seen from the literatures (Ishaque and Salam, 2011; Ishaque et al., 2011a,b; Saloux et al., 2011). Among them, the most accurate model, denoted as two-diode model (Gow and Manning, 1999), uses an equivalent circuit with double diodes, while it is quite complex and computational time is long since it is a nonlinear and implicit equation with two exponential terms and up to seven unknown parameters (Ishaque et al., 2011a,b).

For simplification, the one-diode model of crystalline silicon modules is usually employed in literatures, based on the assumption that the recombination loss in the depletion region is absent (Ishaque et al., 2011a). The single diode models can be further divided in to two categories. If the shunt resistance is considered as infinite, it is the so-called four-parameter model (Mellit et al., 2007). However, Dongue et al. (2012) reported that the four-parameter model that neglects the effects of the shunt resistance was inadequate to fit experimental I–V and P–V data in current-source operation.

To have a more accurate result but not to complicate the calculation, the five-parameter model based on the one-diode equation is put forward. The complete five-parameter model (Karatepe et al., 2006; Lo Brano et al., 2010, 2012; Sera et al., 2007; Tian et al., 2012) consists of photo-generated current, diode reverse saturation-current, series resistance, shunt resistance and diode ideality factor of PV modules. The five-parameter developed by De Soto et al. (2006) can accurately simulate the I–V characteristics, while the ideality factor calculated from this model is usually less than one, not within the reasonable range.

Apart from the diode based model, the model developed by Sandia National Laboratory (King et al., 2004) can accurately predict the power production of crystalline silicon PV modules, but it requires some inputs that are not normally available from manufacturers. Some other models that describe the behavior of a photovoltaic module or the energy produced from it, based on empirical approaches, are studied elsewhere (Durisch et al., 2000; Meyer and van Dyk, 2000). In addition, some commercial software, such as TRNSYS, PVsyst, Simulink and INSEL, also has the PV performance simulation function for users to easily understand PV module operating performance. Unfortunately, these models are too general and the results are not so accurate, so that they are not suitable for particular PV modules.

In this study, a novel theoretical model was developed in the Matlab environment to determine PV module's parameters and then fit the model to experimental I–V characteristic curves obtained from real PV systems, especially at the vicinities of characteristic points: the short circuit (0, I_{sc}), maximum power point (MPP) (V_{mp}, I_{mp}), and open circuit (V_{oc}, 0) of a PV module. Only a few inputs are needed for this model and all of them can be directly obtained from the manufacturer datasheet. This model offers a good compromise between simplicity and accuracy. With this newly developed model, the electrical parameters of a PV module or PV array can be easily obtained and the performance of a PV module or PV array under any weather conditions can be simulated. If a model is able to accurately represent the entire I–V characteristics, it will be suitable for any general purpose.

2. Simulation model

A solar cell is traditionally represented by an equivalent circuit composed of a current source, a diode (D), a shunt/parallel resistance (R_p) and a series resistance (R_s). As shown in Fig. 1, available electrical power from the solar cell is modeled with this well-known equivalent circuit.

The photovoltaic generator is neither a constant voltage source nor a current source. It is modeled and described by the relationship between current and voltage. Based on Shockley diode equation, the mathematical model (I–V characteristic) for an individual PV cell is as follows (Benlarbi et al., 2004; Gow and Manning, 1999; Hadj Arab et al., 2004; Sera et al., 2007):

$$I = I_{ph} - I_D - I_p = I_{ph} - I_0\left(e^{\frac{V+IR_s}{V_t}} - 1\right) - \frac{V+IR_s}{R_p} \qquad (1)$$

where I_{ph} is the photo current (A); I_0 is the diode saturation current (A); R_s is the series resistance (Ω); R_p is the shunt/parallel resistance (Ω); $V_t = \frac{nKT}{q}$ is the diode thermal voltage; n is the diode ideality factor; q is the charge of the electron (1.602E−19 Coulomb); K is the Bolzmann's constant (1.381E−23 J/K) and T is the temperature of solar cell (K). Eq. (1) presents that a solar cell is a nonlinear power source. Determination of an analytical solution of the implicit equation is a difficult and challenging work. Therefore, its numerical solution is employed in the present study.

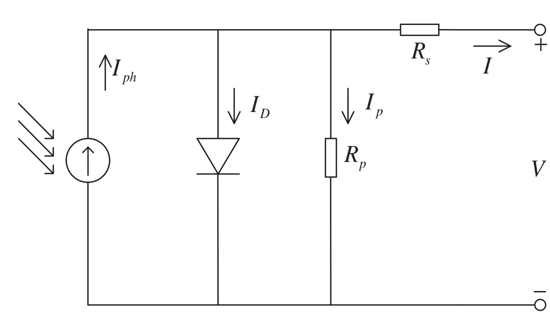

Fig. 1. Equivalent circuit for a solar cell.