Available online at www.sciencedirect.com
SCIENCE DIRECT®
Energy Conversion and Management 47 (2006) 2424–2430
ENERGY CONVERSION & MANAGEMENT
www.elsevier.com/locate/enconman

Modelling power output in photovoltaic modules for outdoor operating conditions

J.I. Rosell, M. Ibáñez *

Department Medi Ambient, Universitat de LIeida, Av. Rovira Roure 191, E25198 LIeida, Spain

Received 25 May 2005; accepted 15 November 2005
Available online 27 December 2005

Abstract

A methodology to estimate PV electrical production from outdoor testing data is presented. It is based on the adjustment of a well known *I–V* model curve slightly modified and a new maximum power output expression. The method is developed to provide PV module performance parameters for all operating conditions encountered by typical photovoltaic systems. The method, theoretically based, is reasonably simple, yet accurately predicts operating conditions performance. The main advantage of the methodology developed is that it allows photovoltaic users to control the PV modules production based on measurements that can be performed far away from specialized photovoltaic reference laboratories even when standard testing conditions can not be achieved.

Keywords: Photovoltaic; *I–V* curve; Maximum power; Modelling

1. Introduction

Though photovoltaic modules are a very reliable source of electrical energy, field results indicate that the modules can fail or degrade in a number of ways when operating outdoors for extended periods. Little attention has been paid to the estimation of output power in these non-optimum conditions. The objective of this work is to present a semi-empirical model, accurate, reliable and easy to apply, for predicting the energy production of photovoltaic modules at outdoor operating conditions using field measured data.

Outdoor measurement procedures and photovoltaic performance models have evolved over many years in laboratories all over the world, and considerable effort has been spent by agencies such as ASTM, IEEE and IEC toward standardizing test methods, giving some models that predict energy production for outdoor conditions. Most of these models are based on the characterization of outdoor *I–V* curves. Some authors (King et al. [1]) calculated the current at five strategically located points throughout the current–voltage (*I–V*) curve. Although the results of the errors obtained by them are considered to be small, its disadvantage consists in the large amount of input data it requires. Luft et al. [2], in work done for TRW Inc., proposed an equation to

* Corresponding author. Tel.: +34 973 702538; fax: +34 973 702613.
E-mail address: m.ibanez@macs.udl.es (M. Ibáñez).

0196-8904/$ - see front matter
doi:10.1016/j.enconman.2005.11.004

predict the current produced. This equation is designed to calculate the entire I–V curve, in contrast to King's model that focuses only on five points. Different modifications of this five parameter model have been developed by Hadj Arab et al. [3] and De Soto [4]. Moreover, little attention has been dedicated to maximum power output estimation.

Standard simulations of photovoltaic systems use a basic and wide spread method to evaluate the maximum power output in operating conditions [5]:

$$P_{\mathrm{mp}} = \frac{G}{G_{\mathrm{ref}}} P_{\mathrm{mp,ref}}[1 + \gamma(T - T_{\mathrm{ref}})] \tag{1}$$

where G is the incident irradiance, P is the power output, T is the temperature, subscript 'mp' refers to maximum power, subscript 'ref' refers to standard testing conditions ($G_{\mathrm{ref}} = 1000\ \mathrm{W\,m^{-2}}$, $T_{\mathrm{ref}} = 25\ ^{\circ}\mathrm{C}$) and γ is the maximum power correction factor for temperature.

From field experience, the authors found that this classical expression does not work properly when some conditions are observed. The need to propose a better approach that could improve the results has encouraged the present study. The main objectives of the methodology developed here are: (1) it has to be applied using input data from outdoor operating conditions as no standard testing condition will be available, (2) complete measured I–V curves would not be needed, (3) it has to be an accurate approach for simulating or testing even degraded modules and (4) the model can not be specific for each PV technology.

2. The output power model

The methodology proposed here assumes that the I–V curve under illumination is well described by the superposition of a dark I–V current and a voltage independent of the photogenerated current. The equivalent circuit widely used for analysis of solar cells consists of a lumped series resistance and a diode represented in Fig. 1. The model depicted in Fig. 1 considers the series R_{s} and shunt R_{sh} resistances together with the photon generated current I_{ph}. The resistances R_{s} and R_{sh} can be considered to be parasitic circuit elements, introduced by the behavior of real solar cells with their technical limitations.

Because PV cells are not identical, it can be a complex task to relate the I–V curve of a cell with the whole module. Hereafter, it is assumed that the mean cell intensity is obtained from the module intensity divided by the number of cells in parallel, and the mean cell voltage is determined from the voltage module divided by the number of cells in series. Therefore, the current I of the mean solar cell in the light may be written using the classical single diode model of a photovoltaic cell

$$I = I_{\mathrm{ph}} - I_0\left[\exp\left\{\frac{(V + R_{\mathrm{s}}I)}{nV_{\mathrm{T}}}\right\} - 1\right] - \frac{V + R_{\mathrm{s}}I}{R_{\mathrm{sh}}} \tag{2}$$

where I_0 is the reverse saturation diode current corresponding to the diffusion and recombination of electrons and holes in the p and n sides; n is the ideality factor >1; V is the mean cell voltage and V_{T} is the thermodynamic voltage, $V_{\mathrm{T}} = kT/\mathrm{e}$. Eq. (2) defines the five parameter model: I_{ph}, I_0, n, R_{s} and R_{sh}.

The proposed approach applies Eq. (2) while introducing the irradiance and temperature dependence of some elements: I_{ph}, I_0 and nV_{T}. The variation of series resistance R_{s} versus temperature could be explained by variation of the resistivities of the different layers. It is the sum of the grid, contact, sheet, base and back

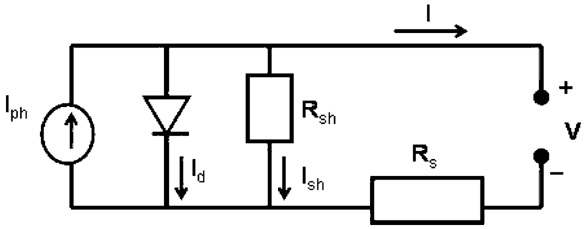

Fig. 1. Equivalent circuit for photovoltaic solar cells and modules.