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Explicit empirical model for general photovoltaic devices: Experimental validation at maximum power point

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Abstract

The validation of a new explicit empirical model for general photovoltaic devices, providing current and voltage at Maximum Power Point (MPP) and current–voltage/power–voltage characteristics under arbitrary conditions of temperature and irradiance, is presented. One of the main advantages of this model is the fact that the equivalent circuit parameters – such as series and shunt resistance, dark-saturation currents, etc. – are not needed, as the sole model input data are the device parameters commonly reported in the datasheets. Moreover, the model is explicit so that its application is very affordable from the computational standpoint. The model is applied to three different types of photovoltaic modules representing some of the most widely diffused technologies in the current market: multi-crystalline silicon, CdTe and CIGS. The calculated voltages, currents and powers at maximum power point are compared with the ones measured for three modules working at the photovoltaic test facility of the University of Trieste. A statistical analysis is presented in order to prove the effectiveness and reliability of the model at maximum power point. Finally, the results of the new explicit model are compared with those obtained by a polynomial regression, Artificial Neural Network (ANN), the well-known single-diode model and an additional, different explicit model. This work shows that the electric performance of a photovoltaic module can be predicted with a high degree of accuracy on the sole basis of parameters that are always found in the photovoltaic device's datasheet.

Keywords: Photovoltaic devices; Empirical; Explicit model; Current–power/voltage characteristic; Artificial neural network; Polynomial regression

1. Introduction

Models for photovoltaic devices (solar cells, photovoltaic modules, strings, fields, etc.) are being increasingly used by researchers, plant designers, Operation and Maintenance personnel (hereafter O&M personnel), electric grid operators, etc. As the market continues its impressive exponential growth shown in (IEA, 2012), models that are simple and easy to apply are needed. One important reason is that such rapid market expansions leads to a shortage of field professionals, which are oftentimes "borrowed" from other fields. The engineers involved in the design of photovoltaic plants have typically little experience with these installations, and moreover designers are often asked to deliver plans in a very short time. Simple and easy-to-apply models would enable direct application and use of the sole electrical data reported in the data-sheet on the photovoltaic modules – oftentimes the only document available to the designer.

Several models for determining the behavior of a solar cell – and consequently the one of the photovoltaic module, string and generator – have been presented in the literature.

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Nomenclature

Terminology

ANN	Artificial Neural Network
MPPT	Maximum Power Point Tracking
KS	Kolmogorov–Smirnov test
R^2	the coefficient of determination
RMSE	the root mean squared error
MPE	the mean percentage error
Dev	the deviation from the measured values

Symbols

G	irradiance (W/m^2)
I_{sc}	short circuit current (A)
$k_1,\ldots,k_6$	regression coefficients ()
T_c	cell temperature (K)
V_{oc}	open circuit voltage (V)
P_{STC}	produced power at STC (W)
b	bias

These models can be mainly classified into two categories – implicit and explicit models-:

– Implicit models are based on the physics of the solar cell and thus is obtained as a solution of the minority-carrier diffusion equation (Luque and Hegedus, 2006). These models may be applied for the determination of the current and power–voltage characteristics (hereafter c and P–V characteristics) at any condition of solar irradiance and solar cell temperature and thus allow a complete knowledge of the photovoltaic device (e.g. voltage and current at maximum power point, short circuit current and open circuit voltage). One of the disadvantages of this type of models is the introduction a series of parameters which are difficult or even impossible to obtain from solar cells manufacturers (i.e. R_S, R_{Sh}, I_{01}, etc.). In addition, these parameters are not constant and strongly depend on temperature and illumination conditions (Sites et al., 1990; Brus, 2012). A number of researchers have developed numeric techniques for the determination of these parameters, either from the module datasheet or from field measurements (De Soto et al., 2006; Bouzidi et al., 2007; Lo Brano et al., 2010; Sera et al., 2007; Chatterjee et al., 2011). All these techniques are effective, however the determination of the I–V and P–V characteristics is not immediate as there is the need of one additional step (i.e. the one for the determination of these parameters). In addition, these methods are sensitive to the initial values and often fail to converge even with good initial guess values (Lun et al., 2013).
– Explicit models are based on simple analytical equations that need less computational effort to be solved than implicit models. As an example of this type of models, the model presented in (Saloux et al., 2011) has been used to calculate the voltage, the current and the power at MPP as a function of the cell temperature and the solar irradiance. This type of models allows to obtain an explicit expression of important parameters of photovoltaic devices without the necessity of performing interactive numerical calculation. Even if the accuracy of this model is low – in (Saloux et al., 2011) the series and shunt resistance of the solar cells are neglected – its output is surely useful for sizing the electrical DC and AC circuits of a photovoltaic plant. In (Green, 1981; Araujo and Sanchez, 1982), the authors have focused on the derivation of approximate closed-form solutions for the maximum power point and the Fill Factor. An explicit power law model of a solar cell is proposed in Karmalkar and Haneefa (2011), which allows an easy closed-form estimation of the entire I–V curve, fill factor and peak power point of an illuminated solar cell from a few measurements as well as physical parameters. A simple explicit model for that is useful to determine the fill factor of a solar cell in a closed form equation is proposed in Das (2011). Additional effort has been done to find a simple explicit model based on implicit models(Das, 2012; Lun et al., 2013).

Both implicit and explicit models are characterized by their dependence on two classes of parameters, i.e. climatic conditions (e.g. the solar irradiance G or the solar irradiation $\hat{G}$, the air temperature T, etc.) and the system parameters (e.g. the module efficiency, open circuit voltage and short circuit current, etc.).

In addition to these two categories there are other approaches that can be used for estimating the behavior of photovoltaic modules, for example polynomial regression (Gianoli-Rossi and Krebs, 1988; Steele, 1991; Whitaker et al., 1997;Menicucci and Fernandez, 1998; Huld et al., 2011), and Artificial Neural Networks (ANN) (Mellit and Massi Pavan, 2010b; Almonacid et al., 2013; Mellit et al., 2013). Such approaches, which are based on power rating, have the great advantage that they can be used without knowing the system under study. Once the system has been characterized and the polynomial coefficients calculated, the power produced by the photovoltaic plant at different climatic conditions can easily be calculated as for example in (Huld et al., 2011). Polynomial regression models have also been used in order to calculate the soiling effect in (Massi Pavan et al., 2011, 2013) or the degradation rate of a module in (Adelstein and Sekulic, 2005). These techniques can also be useful for O&M personnel, for dispatching plans, fault