Solar Energy 155 (2017) 647–653

Contents lists available at ScienceDirect

Solar Energy

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

# Explicit empirical model for photovoltaic devices. Experimental validation

A. Massi Pavan [a,e,*], S. Vergura [b], A. Mellit [c,d], V. Lughi [a]

[a] Department of Engineering and Architecture, University of Trieste, Via A. Valerio, 6/A, 34127 Trieste, Italy
[b] Department of Electrical and Information Engineering, Politecnico di Bari, 70125 Bari, Italy
[c] Faculty of Sciences and Technologies, Renewable Energy Laboratory, Jijel University, Jijel 18000, Algeria
[d] Abdus Salam International Centre for Theoretical Physics, Strada Costiera, 11, 34151 Trieste, Italy
[e] Today with The School of Electrical and Electronic Engineering, The University of Manchester, Manchester, UK

ARTICLE INFO

*Article history:*
Received 16 December 2016
Received in revised form 22 May 2017
Accepted 3 July 2017

*Keywords:*
CdTe
CIGS
HIT
I-V and P-V characteristics

ABSTRACT

A comparison between the experimental current-voltage (I-V) and power-voltage (P-V) characteristics of PhotoVoltaic (PV) modules, and the prediction of an explicit empirical model has been carried out. The model consists of an explicit expression for the current as a function of the voltage; the only inputs are the parameters that are always directly available in the manufacturer's datasheet. The comparison was carried out on four representative PV technologies, based on polycrystalline Si, Heterojunction with Intrinsic Thin layer (HIT), Copper Indium Gallium Selenide (CIGS), and Cadmium Telluride (CdTe). The comparison reveals that the model replicates the experimental I-V and P-V curves to a very good degree of accuracy for the considered operating conditions and PV technologies. This validation sets a turning point in PV modelling, as it enables a reliable use of this accessible model.



## 1. Introduction

Nowadays, the main commercial Photovoltaic (PV) technology is based on crystalline silicon. These solar devices represent the first generation of photovoltaics and cover the 90% of the market. The remainder of the market is covered by thin film technologies mainly based on CdTe, CIGS, and amorphous silicon. These products, owning to the second generation of photovoltaics and characterized by a slightly lower efficiency than the devices from the first one, are today entering the market especially because of their lower manufacturing cost and continuous increase in performances (Lineykin et al., 2014). In the future, a third generation of photovoltaics should commercially guarantee higher efficiencies and lower costs. Dye Sensitized Solar Cells (DSSC), Organic PV (OPV), Intermediate electronic Band (IB) and Multiple Exciton Generation (MEG) are only some examples of third generation devices that today are either not commercially available or have a very small market (Choubey et al., 2012). The first and second generation technologies are based on different physical mechanisms, come from a wide range of fabrication techniques, and their electrical output in terms of current and power-voltage characteristics are slightly different.

Effective use of PV modules requires reliable modelling methods, aiming at predicting the behaviour of a PV system at conditions different from those characterized by the manufacturer's datasheet. Such methods are helpful for monitoring the performance (Vergura et al., 2009; Cristaldi et al., 2012, 2015; d'Alessandro et al., 2015) and the losses in solar systems (Massi Pavan et al., 2013; Moballegh and Jiang, 2014; Massi Pavan et al., 2015; Spertino et al., 2015), for forecasting the produced power (Bouzerdoum et al., 2013; Bizzarri et al., 2013; Dolara et al., 2015; Dellino et al., 2015; Chicco et al., 2016), and for development and testing of maximum power point tracking algorithms (Manganiello et al., 2014; Boztepe et al., 2014; Seyedmahmoudian et al., 2015). Reliable models are also needed for system fault diagnosis (Chine et al., 2014, 2016) and to study and evaluate the behaviour of defective PV cells. Description of known defects in PV cells is reported in Breitenstein et al. (2004, 2001), Acciani et al. (2010), while in-depth investigations of the thermal effects of defects are proposed in Vergura et al. (2012, 2009a,b) where a finite element approach to model some classes of defects commonly found in PV cells is presented.

Equivalent circuits, including a photocurrent source, one or more resistors, and one or more nonlinear elements typically represented by semiconductor diodes, are the most common topology

* Corresponding author at: Department of Engineering and Architecture, University of Trieste, Via A. Valerio, 6/A, 34127 Trieste, Italy.
*E-mail address:* apavan@units.it (A. Massi Pavan).

http://dx.doi.org/10.1016/j.solener.2017.07.002
0038-092X/

for modelling crystalline Si PV devices (Duffie and Beckman, 1991). A widely used equivalent circuit is the "single-diode" model – often referred to as the "five-parameter" model (Fig. 1), as it may be completely characterized by five parameters: shunt and series resistances, diode ideality factor, photocurrent, and diode reverse saturation current. The single diode model ensures high accuracy through three characteristic points in the PV datasheet (open-circuit voltage, short-circuit current, and maximum power point), it guarantees that the maximum point generated by the mathematical model coincides with the datasheet, and provides an excellent fit between to the experimental current-voltage (I-V) curve (Mahmoud et al., 2013).

The five-parameters model is accurate enough for modelling and simulation of crystalline Si PV modules, but the applicability to other PV technologies (especially owning to the second generation of photovoltaics) is found to be limited since the single-diode equivalent circuit fails to describe the significantly different physical processes of converting radiant energy into electrical energy (Lineykin et al., 2014). For this reason, today many researchers are focusing in the development of new models capable of describing the behaviour of different technologies, such as for example thin-films (Miceli et al., 2015).

The explicit empirical model for general PV devices - that was introduced in order to enable modelling based only on the parameters that are always listed in the datasheet of solar devices - overcomes these drawbacks. It was initially introduced in Pavan et al. (2007) and then applied in Massi Pavan et al. (2014a), Barbini et al. (2014) in a revised form for assessing the mismatch effect due to the use of different classes of PV modules in large-scale solar parks. A revised form of the model was validated experimentally for operation at Maximum Power Point (MPP) (Massi Pavan et al., 2014b), showing a very good prediction performance, better than the ones obtained with the golden standard in PV modelling, i.e. the five-parameters model. The explicit empirical model has been lately improved, introducing a correction factor that leads to a good match with the experimental electrical characteristics also for operating points other than the MPP (Vergura and Massi Pavan, 2015).

As mentioned, the model is based exclusively on the parameters commonly found in the datasheets provided by the manufacturers, and is explicit – and therefore quite easy to implement in computer-aided calculations. Explicit models are today increasingly being studied (Batzelis et al., 2014) due to these characteristics, and they represent a useful tool not only for scientists, but also in all practical cases for PV plant designers, Operation and Maintenance (O&M) personnel, and in general for PV professionals. In particular, the model has a distinct advantage in terms of computational complexity and time, both because its explicit form, and because the input parameters are readily available and do not need to be computed in advance (see for example Sandrolini et al., 2010; Chatterjee et al., 2011; Lo Brano et al., 2010; Saleem and Karmalkar, 2009; Bouzidi et al., 2007; Ortiz-Conde et al., 2003; Amit and Kapoor, 2004; Ishaque et al., 2011; Vergura, 2016).

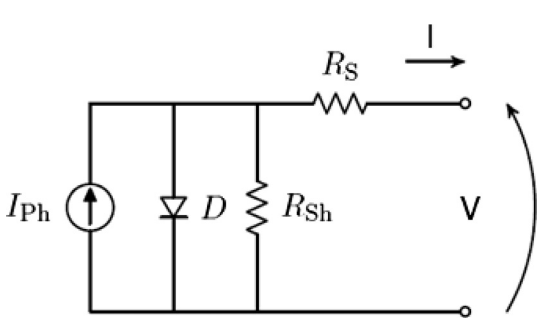


**Fig. 1.** Solar cell equivalent circuit – five-parameters model.

Validation of this model along the entire I-V and P-V characteristics is therefore of paramount importance for ensuring that this very accessible tool does have the necessary accuracy and reliability for professional and scientific purposes. In this work, we focus on the validation of the model for the entire current-voltage (I-V) and power-voltage (P-V) characteristics of four representative commercial PV modules based on polycrystalline silicon, HIT technology, CIGS, and CdTe. With reference to the solar irradiance, the validation was carried out in the range [900–1000 W/m$^2$].

The paper is organized as follows: the next Section is on the description of the model under validation. Section 3 presents the test facility. Section 4 deals with results and discussion. Section 5 presents the conclusions.

## 2. The explicit empirical model

The behaviour of a solar cell is commonly modelled with the well-known five-parameter equivalent model represented in Fig. 1.

The solar cells is modelled by an ideal current source in parallel with a diode. The circuit is described by the following equation:

$$I = I_{Ph} - I_o \times \left[e^{(V+IR_s)/nV_t} - 1\right] - \frac{V + IR_s}{R_{sh}} \tag{1}$$

where $I_{Ph}$ (A) is the light generated current (i.e. the short circuit current neglecting the parasitic resistances), $I_o$ (A) is the dark saturation current due to recombination, n is the ideality factor, $V_t$ (V) is the thermal voltage, $R_s$ (Ω) is a series resistance, and $R_{sh}$ (Ω) is a shunt resistance. The light generated current is directly proportional to the solar irradiance (Townsend et al., 1989):

$$I_{Ph} = \frac{G}{1000} \times \left[I_{Lref} + \alpha \cdot (T_c - 25)\right] \tag{2}$$

where G (W/m$^2$) is the solar irradiance, 1000 W/m$^2$ is the solar irradiance at Standard Test Conditions (STC), $I_{Lref}$ (A) is the short circuit current at STC, α (A/°C) is the current-temperature coefficient at STC, $T_c$ (°C) is the cell temperature and 25 °C is the STC cell temperature.

Combining Eqs. (1) and (2), we can write:

$$I = \frac{G}{1000} \times \left[I_{Lref} + \alpha \cdot (T_c - 25)\right] - I_o \times \left[e^{(V+IR_s)/nV_t} - 1\right] - \frac{V + IR_s}{R_{sh}} \tag{3}$$

The dark saturation current $I_o$ is a function of the cell temperature and can be written as (Kichou et al., 2016):

$$I_o = I_{oref} \cdot e^{\left(\frac{E_{go}}{V_{to}} - \frac{E_g}{V_t}\right)} \cdot \left(\frac{T_c}{25}\right)^3 \tag{4}$$

where $I_{oref}$ (A) and $V_{to}$ (V) are the saturation current and the thermal voltage at STC, respectively, $E_g$ (V) is the energy bandgap, while $E_{go}$ (V) is the energy bandgap at T = 0 K. Combining Eqs. (3) and (4), we can write:

$$I = \frac{G}{1000} \times \left[I_{Lref} + \alpha \cdot (T_c - 25)\right] + I_{oref} \cdot e^{\left(\frac{E_{go}}{V_{to}} - \frac{E_g}{V_t}\right)} \cdot \left(\frac{T_c}{25}\right)^3 - I_{oref} \cdot \left(\frac{T_c}{25}\right)^3 \cdot e^{\left(\frac{E_{go}}{V_{to}} - \frac{E_g}{V_t} + \frac{(V+IR_s)}{n \cdot V_t}\right)} - \frac{V + IR_s}{R_{sh}} \tag{5}$$

The series resistance $R_s$ is also a function of the operating conditions being (Markvart and Castaner, 2006):

$$R_s = \frac{V_{OC}}{I_{SC}} \times r_s \tag{6}$$

where $V_{oc}$ (V) and $I_{sc}$ (A) are the open circuit voltage and the short circuit current at arbitrary conditions of solar irradiance and cell