Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays

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***Abstract*—This paper proposes a method of modeling and simulation of photovoltaic arrays. The main objective is to find the parameters of the nonlinear *I–V* equation by adjusting the curve at three points: open circuit, maximum power, and short circuit. Given these three points, which are provided by all commercial array datasheets, the method finds the best *I–V* equation for the single-diode photovoltaic (PV) model including the effect of the series and parallel resistances, and warranties that the maximum power of the model matches with the maximum power of the real array. With the parameters of the adjusted *I–V* equation, one can build a PV circuit model with any circuit simulator by using basic math blocks. The modeling method and the proposed circuit model are useful for power electronics designers who need a simple, fast, accurate, and easy-to-use modeling method for using in simulations of PV systems. In the first pages, the reader will find a tutorial on PV devices and will understand the parameters that compose the single-diode PV model. The modeling method is then introduced and presented in details. The model is validated with experimental data of commercial PV arrays.**

***Index Terms*—Array, circuit, equivalent, model, modeling, photovoltaic (PV), simulation.**

I. Introduction

A PHOTOVOLTAIC (PV) system directly converts sunlight into electricity. The basic device of a PV system is the PV cell. Cells may be grouped to form panels or arrays. The voltage and current available at the terminals of a PV device may directly feed small loads such as lighting systems and DC motors. More sophisticated applications require electronic converters to process the electricity from the PV device. These converters may be used to regulate the voltage and current at the load, to control the power flow in grid-connected systems, and mainly to track the maximum power point (MPP) of the device.

In order to study electronic converters for PV systems, one first needs to know how to model the PV device that is attached to the converter. PV devices present a nonlinear I–V characteristic with several parameters that need to be adjusted from experimental data of practical devices. The mathematical model of the PV device may be useful in the study of the dynamic analysis of converters, in the study of MPP tracking (MPPT) algorithms, and mainly to simulate the PV system and its components using circuit simulators.

The first purpose of this paper is to present a brief introduction to the behavior and functioning of a PV device and write its basic equations, without the intention of providing an indepth analysis of the PV phenomenon and the semiconductor physics. The introduction on PV devices is followed by the modeling and simulation of PV arrays, which is the main subject of this paper.

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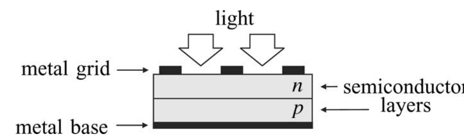

Fig. 1. Physical structure of a PV cell.

Some terms used in this paper require an explanation. A PV *device* may be any element that converts sunlight into electricity. The elementary PV device is the PV *cell*. A set of connected cells form a *panel*. Panels are generally composed of series cells in order to obtain large output voltages. Panels with large output currents are achieved by increasing the surface area of the cells or by connecting cells in parallel. A PV *array* may be either a panel or a set of panels connected in series or parallel to form large PV systems.

Electronic converter designers are usually interested in modeling PV panels (called arrays henceforth in this paper), which are the general purpose off-the-shelf PV devices available in the market. This paper focuses on PV arrays and shows how to obtain the parameters of the I–V equation from practical data obtained in datasheets. The modeling of elementary PV cells or arrays composed of multiple panels may be done with the same procedure.

II. How a PV Cell Works

A photovoltaic cell is basically a semiconductor diode whose p–n junction is exposed to light [1], [2]. Photovoltaic cells are made of several types of semiconductors using different manufacturing processes. The monocrystalline and polycrystalline silicon cells are the only found at commercial scale at the present time. Silicon PV cells are composed of a thin layer of bulk Si or a thin Si film connected to electric terminals. One of the sides of the Si layer is doped to form the p–n junction. A thin metallic grid is placed on the Sun-facing surface of the semiconductor. Fig. 1 roughly illustrates the physical structure of a PV cell.

The incidence of light on the cell generates charge carriers that originate an electric current if the cell is short-circuited [2]. Charges are generated when the energy of the incident photon is sufficient to detach the covalent electrons of the semiconductor—this phenomenon depends on the semiconductor material and on the wavelength of the incident light. Basically, the PV phenomenon may be described as the absorption of solar radiation, the generation and transport of free carriers at the p–n junction, and the collection of these electric charges at the terminals of the PV device [3], [4].

The rate of generation of electric carriers depends on the flux of incident light and the capacity of absorption of the semiconductor. The capacity of absorption depends mainly on the semiconductor bandgap, on the reflectance of the cell surface (that depends on the shape and treatment of the surface), on the intrinsic concentration of carriers of the semiconductor, on the electronic mobility, on the recombination rate, on the temperature, and on several other factors.

The solar radiation is composed of photons of different energies. Photons with energies lower than the bandgap of the PV cell are useless and generate no voltage or electric current. Photons with energy superior to the bandgap generate electricity, but only the energy corresponding to the bandgap is used—the remainder of energy is dissipated as heat in the body of the PV cell. Semiconductors with lower bandgaps may take advantage or a larger radiation spectrum, but the generated voltages are lower [5]. Si is not the only, and probably not the best, semiconductor material for PV cells, but it is the only one whose fabrication process is economically feasible in large scale. Other materials can achieve better conversion efficiency, but at higher and commercially unfeasible costs.

The study of the physics of PV cells is considerably complicated and is out of the scope of this paper. For the purpose of studying electronic converters for PV systems, it is sufficient to know the electric characteristics of the PV device (cell, panel, and array). The manufacturers of PV devices always provide a set of empirical data that may be used to obtain the mathematical equation of the device *I–V* curve. Some manufacturers also provide *I–V* curves obtained experimentally for different operating conditions. The mathematical model may be adjusted and validated with these experimental curves.

III. Solar Radiation

The efficiency of a PV device depends on the spectral distribution of the solar radiation. The Sun is a light source whose radiation spectrum may be compared to the spectrum of a black body near 6000 K. A black body absorbs and emits electromagnetic radiation in all wavelengths. The theoretical distribution of wavelengths of the black body radiation is mathematically described by Planck's law, which establishes the relations and interdependencies of the wavelength (or frequency), the temperature and the spectral distribution of the black body [5]–[7]. Fig. 2 shows the spectral distribution of the black body radiation compared with the extraterrestrial and terrestrial solar radiations [2].

The study of the effect of the solar radiation on PV devices is difficult because the spectrum of the sunlight on the Earth's surface is influenced by factors such as the variation of the temperature on the solar disc and the influence of the atmosphere [8]. In the extraterrestrial space, at the average distance between the Sun and the Earth, the irradiated solar energy is about 1.353 kW/m^2. On the Earth's surface, the irradiation is approximately 1 kW/m^2 (this is a reference value only, as the net irradiation on Earth's surface depends on many factors).

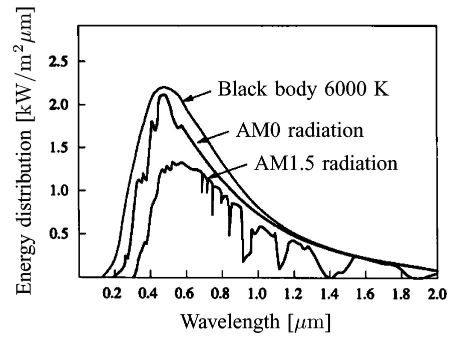

Fig. 2. Spectral distribution of the black body radiation and the Sun radiation in the extraterrestrial space (AM0) and on Earth's surface (AM1.5). *Source:Möller* [2].

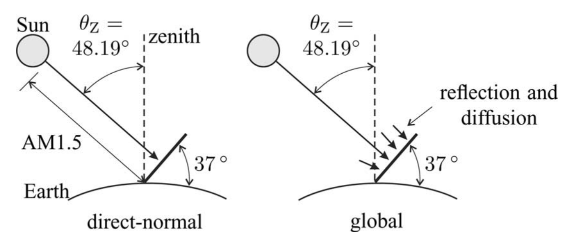

Fig. 3. Illustration of the AM1.5 path and the direct-normal and global incident radiations on a Sun-facing surface at 37° tilt.

PV devices are generally evaluated with reference to a standard spectral distribution. The American Society for Testing and Materials (ASTM) defines two standard terrestrial spectral distributions [9], [10]: the direct-normal and global AM1.5. The direct-normal standard corresponds to the incident radiation that perpendicularly reaches a Sun-facing surface directly from the Sun. The global or total standard corresponds to the spectrum of the direct and diffuse radiations. Diffuse radiation is the radiation influenced by the atmospheric steam and the reflection on Earth's surface. The AM1.5 standards are defined for a PV device whose surface is tilted at 37° and faces the Sun rays.

The AM initials stand for *air mass*, which means the mass of air between a surface and the Sun that affects the spectral distribution and intensity of sunlight [11]. The AMx number indicates the length of the path of the solar radiation through the atmosphere. With longer paths more light deviation and absorption occur. These phenomena change the spectral distribution of the light received by the PV device. The length of the path of the sun rays (given in number of atmospheres) is indicated by the x coefficient of AMx defined as

$$x = \frac{1}{\cos \theta_{\mathrm{z}}} \tag{1}$$

where θ_z is the angle of the Sun with reference to the zenith, as shown in Fig. 3. A bigger x corresponds to a longer path and a greater air mass between the Sun and the surface of the terrestrial PV device. The standard AM1.5 distributions correspond to the spectrum of the solar radiation with a solar angle $\theta_{\mathrm{z}} = 48.19°$. Fig. 3 illustrates the definitions of the AM1.5 path and the direct-normal and global radiations.