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Methods and techniques to determine the dynamic parameters of solar cells: Review

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ABSTRACT

The new types of solar cells, such as thin film, dye sensitized, organic and multi-junction are increasingly being used. The behavior of these solar cells in dynamic regime differs from the one of the mono-crystalline or polycrystalline solar cells. The review article critically outlines and discusses the main issues of the ten methods which have been presented in the research literature in previous years in order to analyze the dynamic behavior of solar cells. This paper presents the methods which allow the determination of either of all ac parameters of solar cells or only one of them. The methods analyzed allow measuring the dynamic impedances using the frequency and time domain techniques. It also discusses the methodologies to determine the dc parameters of solar cells from the variation of the capacitance applying reverse and forward bias. The different types of the solar cells ac equivalent circuits from a proper fitting are also discussed in this review. The paper presents pros and cons for each one of the ten methods allowing the determination of the ac parameters and some dc parameters of solar cells.

Contents

1. Introduction

The renewable energy is nowadays universally recognized as the main resource towards sustainability. The world is now more than ever energy conscious, due to the climatic changes. The need to live in an unpolluted world is a sine qua non and therefore extensive investments are made in renewable energy [1].

The determination of the electric parameters in any PV cell and module under any field conditions has been extensively studied especially under steady state conditions [2], but also transient conditions even at various solar radiation levels [3–10].

The dc parameters of any PV module attracted the interest as the PV panels produce dc current. However, the majority of the applications require current in ac form. The design of PV

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generators show diversified configurations. These include the power conditioning unit with charge controllers DC/AC inverters, switches, MPPT devices, battery storage systems in stand-alone PV systems, etc. For understanding the behavior of the photovoltaic cells and modules in various configurations it is useful to analyze and study their ac parameters.

Using proper mathematical models and the *I–V* characteristic, the important dc parameters of solar cells can be determined by more than 35 methods outlined in [2]. These parameters are: I_{ph} – the photogenerated current, I_{sc} – the short circuit current, V_{oc} – the open circuit voltage, n – the ideality factor of diode, R_s – the series resistance, R_{sh} – the shunt resistance, I_o – the reverse saturation current and P_m – the maximum power [2].

On the other hand, the dynamic regime of the solar cells was less studied until some years ago in comparison to the static regime [5]. Nowadays, due to the development of new types of photovoltaic cells and of a large number of photovoltaic power plants, the research reports published methods on studies of the ac behavior and the determination of the ac parameters of solar cells and modules [3–14].

The paper is structured as follows: in Section 2 the ac parameters of solar cells and the equivalent circuit in dynamic regime are outlined; Section 3 shortly presents the experimental methodologies along with the associated mathematical expressions which allow for the determination of the ac parameters of the solar cell. In Section 4 those methodologies are discussed. A comparison is given with arguments about the pros and cons for each method; the complex equivalent circuits for the determination of the ac parameters through fitting are presented, the application of suitable methodologies to new types of solar cells is argued, and the necessity to understand the dynamic behavior of the solar cells is explained. Finally, the Conclusions are presented in Section 5.

2. Electric equivalent circuits for the dynamic simulation of a PV cell

The solar cell electric equivalent circuit in dynamic regime is obtained from the dc one diode equivalent circuit by replacing the diode with the diffusion capacitance C_d, the transition capacitance C_t and the dynamic resistance of diode R_d, see Fig. 1a. The dynamic equivalent circuit can be simplified using the parallel resistance R_p which is the result of combining R_d with R_{sh} and the parallel capacitance C_p which is the result of combining C_d with C_t, see Fig. 1b. The simplified circuit is frequently used because of its small number of the fitting parameters [6,7].

The transition capacitance of the photovoltaic cell, which is voltage dependent, can be calculated using the following equation for an abrupt junction [5,8]:

$$C_t = \frac{b}{\sqrt{V_j - V_a}} = A\sqrt{\frac{eN\varepsilon_o\varepsilon_r}{2(V_j - V_a)}}, \quad N = \frac{N_D N_A}{N_D + N_A} \tag{1}$$

where b is a constant which depends on the photovoltaic cell, V_j is the junction voltage V_a is the applied voltage, A represents the area

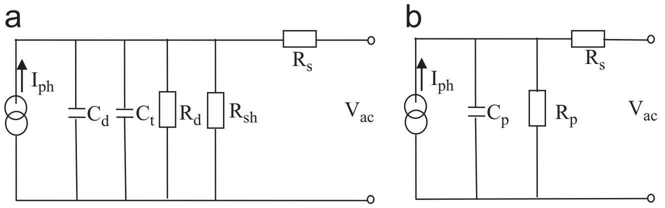

Fig. 1. The ac equivalent circuit and the simplified ac equivalent circuit for a solar cell.

of the solar cell, e is the elementary charge, ε_o is the permittivity of free space, ε_r represents the relative permittivity of the solar cell material, N_D and N_A are the doping concentration in cm^{-3} in the n and p region, respectively.

The diffusion capacitance of the photovoltaic cell, which is frequency and voltage dependent [8], can be determined by the following equation:

$$C_d = \frac{\tau e}{2kT} I_o \exp\left(\frac{eV_a}{nkT}\right), \quad w\tau < < 1 \tag{2}$$

where τ represents the minority carrier lifetime, k denotes the Boltzmann constant, T represents the photovoltaic cell temperature, n is the ideality factor of the PV cell diode and w represents the angular frequency.

For the calculation of the dynamic resistance of the photovoltaic cell, which is voltage dependent, the following expression can be used [5]:

$$R_d = \frac{kTn}{eI} \tag{3}$$

The dynamic impedance of the photovoltaic cells or panels in dark conditions under the bias voltage and the signal frequency ω can be calculated using the following equation [4,9]:

$$\begin{aligned} Z(V,\omega) = R(V,\omega) + jX(V,\omega) = R_s + \left\{ \frac{[R_{sh} + R_d(V)]R_{sh}R_d(V)}{\omega^2 R_{sh}^2 R_d^2(V)[C_d(V,\omega) + C_t(V)]^2 + [R_{sh} + R_d(V)]^2} \right\} \\ - j\left\{ \frac{\omega R_{sh}^2 R_d^2(V)[C_d(V,\omega) + C_t(V)]}{\omega^2 R_{sh}^2 R_d^2(V)[C_d(V,\omega) + C_t(V)]^2 + [R_{sh} + R_d(V)]^2} \right\} \end{aligned} \tag{4}$$

Eq. (4) can be rewritten, in case of the simplified ac equivalent circuit, using the formula for parallel connection of resistors and the capacitors [9]:

$$Z(V,\omega) = \left[R_s + \frac{R_p}{(\omega R_p C_p)^2 + 1}\right] - j\left[\frac{\omega R_p{}^2 C_p}{(\omega R_p C_p)^2 + 1}\right] \tag{5}$$

3. Methods used to determine the PV cell ac parameters

Several methods for the determination of the ac parameters of the PV cells have been proposed and studied. Most of them apply the technique of the impedance spectroscopy [6]. The impedance spectroscopy is a powerful technique developed by researchers in the electrochemistry domain [10].

3.1. Methods to determine all ac parameters of solar cells

Method 1 – In this method the impedance spectroscopy with the frequency domain technique is used. The ac signal which is superposed on the dc bias is a pure sinusoidal signal. Its amplitude must be smaller than the thermal voltage, (nkT/e), with a varying frequency. The value of the thermal voltage at the 25 °C is approximately equal to 25.7 mV. The dynamic impedance is measured at different values of the bias voltage, in general from 0 V to the open circuit voltage of the solar cell for forward voltage; the frequency can vary from 1 Hz to 1 MHz. The measurements can be made in dark conditions as well as under different levels of illumination. The results are plotted in a complex impedance plane-impedance loci, Nyquist diagram [11,12], see Fig. 2. The semicircular shape of the plot certifies an ac equivalent circuit with capacitance in parallel to a resistance.

This method, by directly analyzing the plot, allows the determination of the series and the parallel resistance of the photovoltaic cells or panels. For the analysis, the applied bias voltage might be applied in reverse or forward mode.