МЕТРОЛОГІЯ, СТАНДАРТИЗАЦІЯ, СЕРТИФІКАЦІЯ ТА ВИМІРЮВАЛЬНА ТЕХНІКА В ТЕХНОЛОГІЧНИХ ПРОЦЕСАХ

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IMPROVED IMPEDANCE MATHEMATICAL MODEL OF A SOLAR CELL

The problem of finding alternative energy sources has become particularly important over the last few decades. The reasons for this are insufficient extraction of fossil fuels, primarily oil and gas, as well as environmental pollution caused by their use. On the other hand, solar energy is a free, almost everywhere available resource that allows generating environmentally friendly electricity without the least harm to the environment. In view of this, solar power is one of the most promising areas of rapidly developing alternative energy. Nowadays, semiconductor devices with p-n-junction, which are called solar cells or photocells, have become widely used in the field of solar power. In such devices, due to the internal photoelectric effect under the influence of solar radiation, there is a redistribution of charges that causes emergence of electromotive force, so that it becomes possible to directly convert solar energy into electric energy. The one-diode mathematical model of the solar cell is analyzed in the paper. The solar cell is characterized by impedance which depends of environmental conditions. The laboratory workbench is designed to measure the impedance of the solar cell. The improved impedance mathematical model of a solar cell is proposed. It consists of: the serial resistance, barrier capacitance, barrier resistance, diffusion resistance and fractional order diffusion capacitance. The experimental Nyquist plot was fitted by using of the improved expression for impedance of the solar cell.

Keywords: solar cell, one-diode mathematical model, impedance, Nyquist plot.

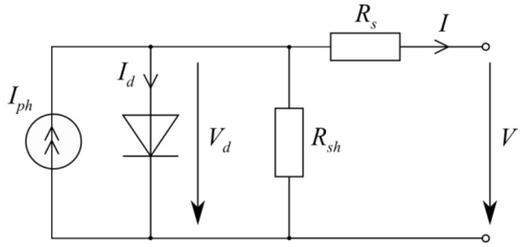
Introduction. The problem of finding alternative energy sources has become particularly important over the last few decades. The reasons for this are insufficient extraction of fossil fuels, primarily oil and gas, as well as environmental pollution caused by their use. On the other hand, solar energy is a free, almost everywhere available resource that allows generating environmentally friendly electricity without the least harm to the environment. In view of this, solar power is one of the most promising areas of rapidly developing alternative energy.

Nowadays, semiconductor devices with p-n-junction, which are called solar cells or photocells, have become widely used in the field of solar power. In such devices, due to the internal photoelectric effect under the influence of solar radiation, there is a redistribution of charges that causes emergence of electromotive force, so that it becomes possible to directly convert solar energy into electric energy.

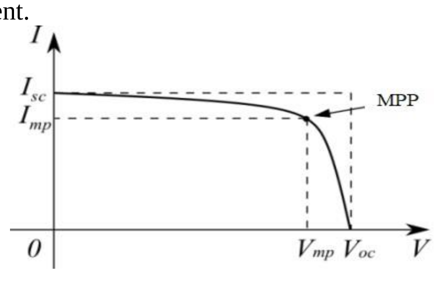
In mathematical modeling of solar power systems, a single-diode solar cell mathematical model gained widespread application [1, 2], which enables making calculations of the illuminated volt-ampere characteristics of a separate panel as well as an array (tape) of solar panels connected in series at different values of solar radiation intensity and temperature of the panel surface.

The equivalent circuit that corresponds to a single-diode solar cell mathematical model is shown in Figure 1, a. The circuit consists of a current source, a single diode and series and parallel resistances. Figure 1, b shows a graph of typical illuminated volt-ampere characteristics of a solar cell.

The single-diode solar cell mathematical model shown in Figure 1 is characterized by small deviations of the theoretically calculated characteristics from the real solar cell characteristics, one of the reasons being the difficulty in precise measurement of solar cell series resistance [1]. The problem of precise measurement of solar cell series resistance can be solved by measuring its impedance at alternating current.



a)



b)

a) a solar cell equivalent circuit; b) typical solar cell illuminated volt-ampere characteristics
Figure 1. A single-diode solar cell mathematical model

Despite the fact that a solar cell is a DC device, it is characterized by its impedance, which depends on the surrounding conditions. Knowledge of the solar cell parameters on alternating current, as well as their variations at

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different levels of illumination and offset voltages, is important because these parameters change during the day and depend on the temperature. Thus, we can conclude that development of the solar cell data acquisition system is an important task.

2. Laboratory unit for measuring complex resistance of solar cells

The basis of the work of a laboratory unit for measuring the complex resistance of solar cells on AC is a direct method of measuring the complex resistance. A block diagram explaining the direct method of measuring complex resistance is shown in Figure 2.

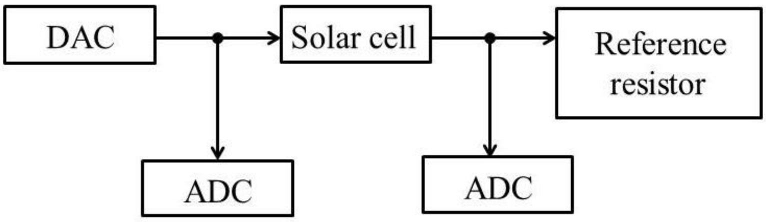


Figure 2. Block diagram of a laboratory unit for measuring the complex resistance of solar cells

The digital-to-analog converter (DAC) generates a measuring sine wave. This signal arrives at the element under study. Analog-to-digital converters (ADCs) are connected at its input and output to measure the signal at the input and output of the element under study. Structurally, the laboratory unit for measuring the complex resistance of solar cells consists of an Analog Discovery 2 device from the American company Digilent and an adapter assembled on the motherboard (Figure 3).

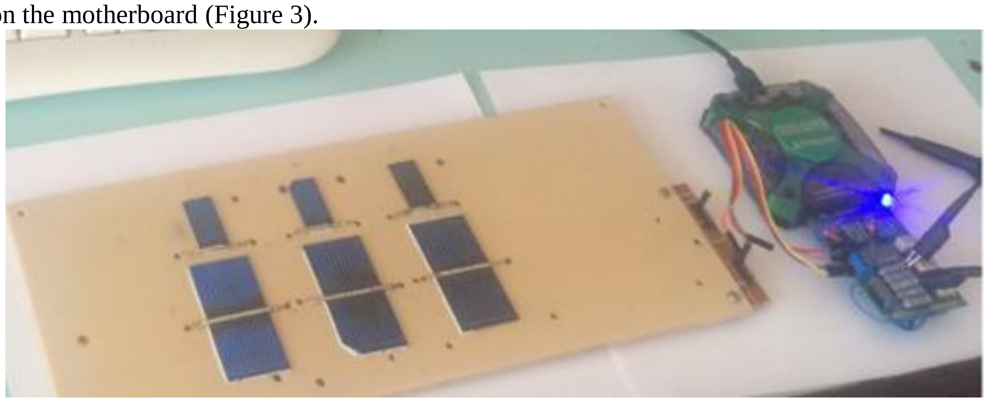


Figure 3. Picture of a laboratory installation for measuring the complex resistance of solar cells

The analog outputs of the Analog Discovery 2 are used to connect one of the sample resistors that is required to measure current through a solar cell. To measure the complex resistance of the solar cells, the specialized Wave Forms software of the American company Digilent was used (Figure 5).

3. Improved impedance mathematical model of solar panel

In terms of electrical engineering, a solar panel is an active bi-polarity with frequency dispersion of its electrical parameters. According to the theory of mathematical modeling, any mathematical model can be represented graphically and analytically.

Proceeding from this, under the impedance mathematical model of the solar panel in graphical form, we mean its equivalent circuit on alternating current. In analytical form, the impedance mathematical model of the solar panel is the analytical expression of its impedance, which combines the parameters of the equivalent circuit elements with the electrical parameters of the solar panel.

It is known that any solar cell is based on the p-n-junction, and its impedance mathematical model in graphical form is represented by the equivalent circuit, which is shown in Figure 4.

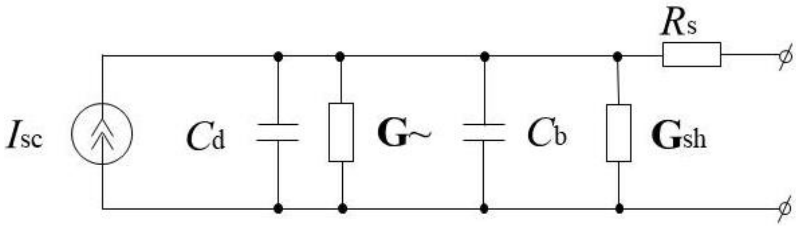


Figure 4. The solar cell equivalent circuit

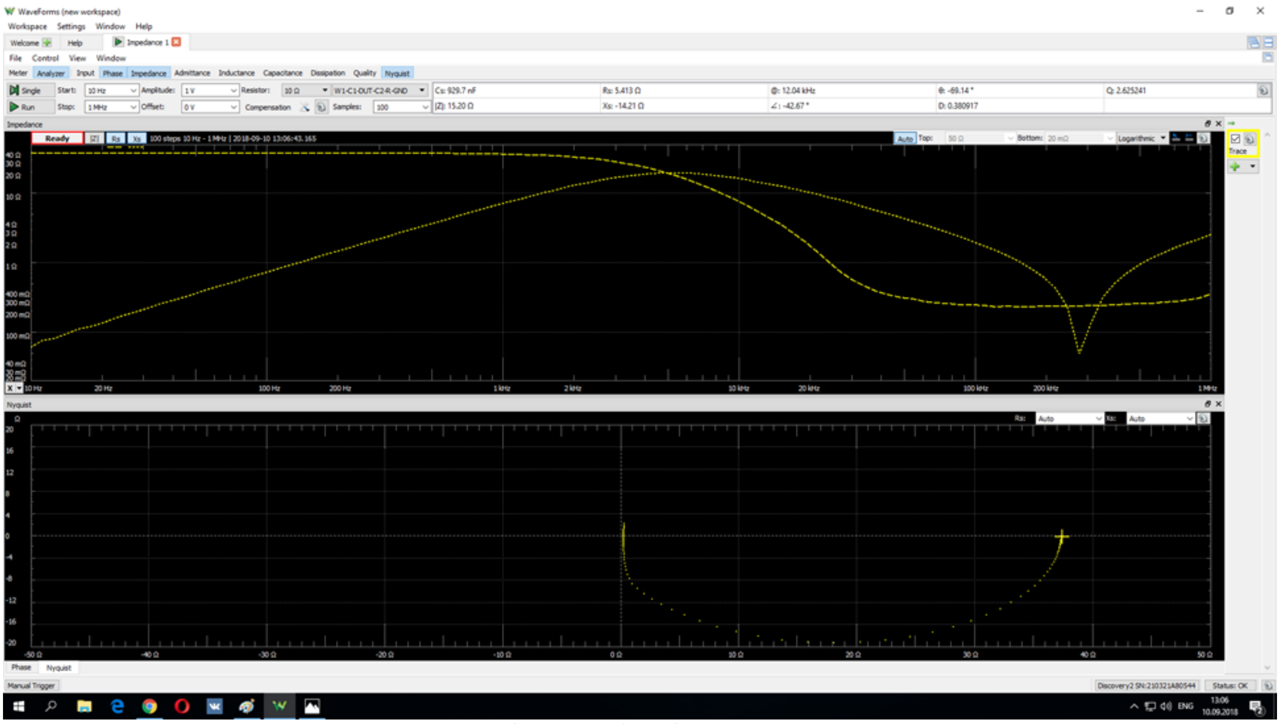


Figure 5. Wave Forms software interface of the American company Digilent

The solar cell equivalent circuit (Figure 8) consists of the following components: short circuit current source Isc, diffusion capacitance C_d, frequency-dependent conductivity G~, barrier capacitance C_b, shunt resistance R_{sh} and series resistance R_s.

By analysing Figure 5, we can conclude that diffusion capacitance C_d and barrier capacitance C_b are connected in parallel, so they can be represented by one equivalent capacitance C_e. Similarly, frequency-dependent conductivity G~ and shunt resistance R_{sh} are also connected in parallel, so they can be represented by one equivalent frequency-dependent conductivity G_e~. Then, the solar cell equivalent circuit (Figure 8) can be represented as shown in Figure 9.

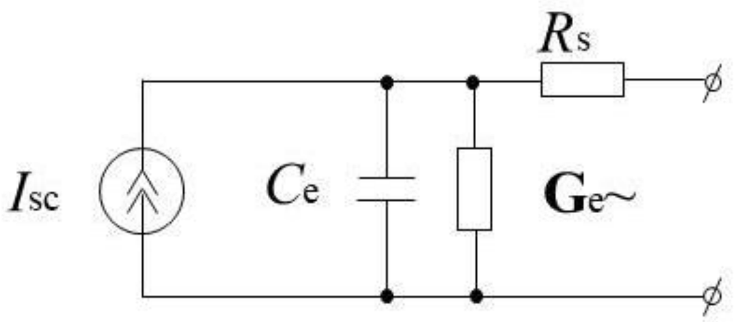


Figure 6. The modified solar cell equivalent circuit

Impedance of the modified solar cell equivalent circuit (Figure 9) can be expressed as the sum of the series resistance R_s with equivalent capacitance C_e and equivalent frequency-dependent conductivity G_e~ connected in parallel (4).

$$Z(j\omega) = R_s + \frac{1}{j\omega C_e + \mathbf{G}_e \sim} \tag{1}$$

By analysing expression (1) of the impedance and the solar cell equivalent circuit (Figure 6) we can conclude that the drawback of such an impedance mathematical model of the solar cell is an unknown expression of the equivalent frequency-dependent conductivity G_e~.

The experimental measurements of impedance in the experimental solar cells performed by the authors show that its experimental Nyquist plot (Figure 7) has the form of two semicircles. The large semicircle corresponds to the barrier capacitance C_b of the solar cell, the effect of which is observed at high frequencies (from 100 Hz to 1 MHz).

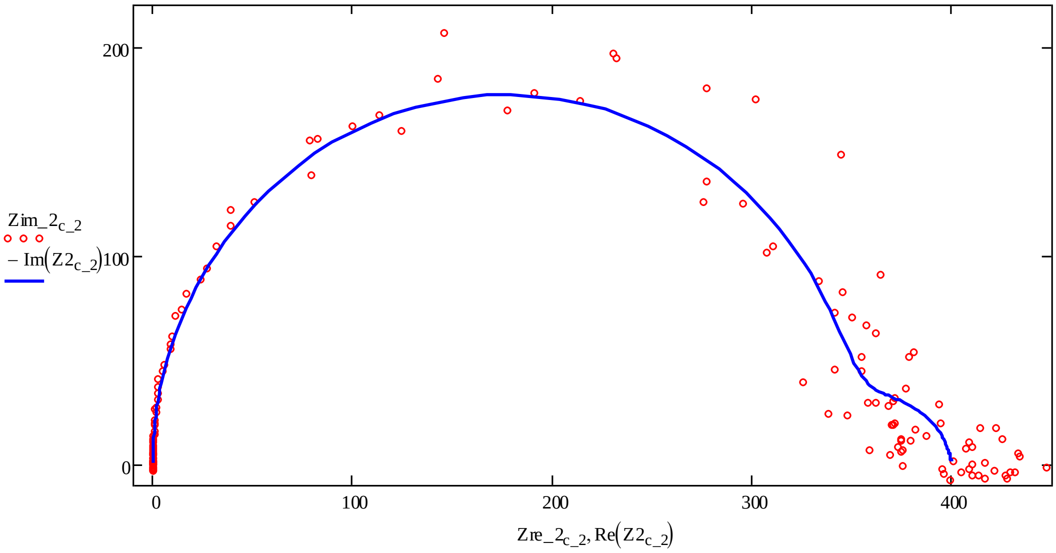
The small semicircle corresponds to diffusion capacitance C_d and frequency-dependent conductivity G~ the influence of which is observed at low frequencies (from 1 Hz to 100 Hz). By analysing the experimental Nyquist plot (Figure 7), we can conclude that the small semicircle is substantially deformed by the loss of electric energy and is under the influence of noise obstruction. Such a character of the Nyquist plot (Figure 7) corresponds to the fractional capacitor with significant losses of electric energy. Thus, the authors suggest an improved impedance mathematical model of the solar cell, related to the improved expression of impedance (2).

$$Z(j\omega) = R_s + \frac{R_b}{1 + j\omega C_b R_b} + \frac{R_d}{1 + (j\omega)^{\alpha} C_d R_d} \qquad (2)$$

The adequacy of the suggested improved impedance mathematical model of the solar cell is confirmed by the convergence of the experimental and theoretical Nyquist plots, which are shown in Figure 7.

By analysing the improved expression (8) of impedance the authors propose an improved solar cell equivalent circuit (Figure 8), consisting of series resistance R_s, barrier capacitance C_b, barrier resistance R_b, diffusion resistance R_d and diffusion capacitance C_d of the fractional order [3-5].

As a result of the approximation of the experimental Nyquist plot (Figure 7) the following values of the parameters of the improved solar cell equivalent circuit have been obtained (Figure 8)): R_s=0,1 Ω, C_b=200 nF, R_b=350 Ω,



C_d=100 μF, R_d=50 Ω, α=0,9.

Figure 7. Experimental and theoretical Nyquist plots of the solar cell

$$Z(j\omega) = R_s + \frac{R_b}{1 + j\omega C_b R_b} + \frac{R_d}{1 + (j\omega)^{\alpha} C_d R_d}. \qquad (3)$$

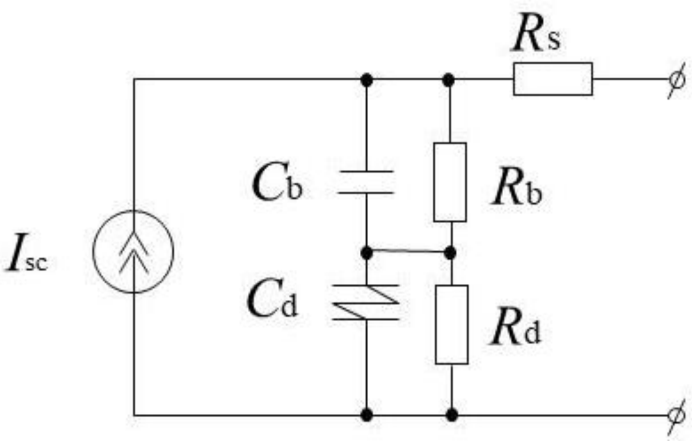


Figure 8. The improved solar cell equivalent circuit

Conclusions. 1. The single-diode mathematical model of the solar cell has been analyzed and it has been established that the solar cell is characterized by the impedance, which depends on the surrounding conditions. Knowledge of the parameters of the solar cell on the alternating current, as well as their variations at different levels of illumination and offset voltages, is important because these parameters change during the day and depend on the temperature [6–10].

2. A laboratory set for measuring impedance of solar cells, consisting of an Analog Discovery 2 device produced by the US Digilent and an adapter assembled on a model board, has been developed.

3. The improved impedance mathematical model of the solar cell consisting of series resistance R_s, barrier capacitance C_b, barrier resistance R_b, diffusion resistance R_d, and diffusion capacitance C_d of the fractional order has been suggested.

4. As a result of the approximation of the experimental Nyquist plot the following values of the parameters of the improved solar cell equivalent circuit have been obtained for the experimental solar cell: R_s=0,1 Ω, C_b=200 nF, R_b=350 Ω, C_d=100 μF, R_d=50 Ω, α=0,9.

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