



# Single-pulse method for measuring the current-voltage characteristics of solar panels

**K.M. Bozhko, N.M. Zashchepkina, M.O. Markin, O.M. Markina \***

Department of Scientific, Analytical and Ecological Instruments and Systems,  
National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute»,  
Peremohy ave., 37, Kyiv, 03056, Ukraine

\* Corresponding e-mail address: o.n.markina@gmail.com

## ABSTRACT

**Purpose:** The purpose of the paper is to substantiate the new method of measuring the voltage-current characteristics of solar batteries based on the use of a digital oscilloscope and a special linear sweep device.

**Design/methodology/approach:** To solve this problem, a test bench was developed on the basis of a solar radiation simulator.

**Findings:** Practically it is proved that within the duration of a single pulse of 40  $\mu$ s, it is possible to measure the voltage-current characteristics of an SB with a short-circuit current of up to 5.8 A.

**Research limitations/implications:** The method is relevant for all types of solar batteries, but the measurements were carried out on serial samples of mono and polycrystalline silicon with a nominal output power of 30 to 140 W and a voltage of 12 V.

**Practical implications:** The method can find its practical application in the development of an intelligent solar module. The technology of the intelligent module is based on the periodic removal of information on the operational parameters of the solar battery based on the measured voltage-current characteristic.

**Originality/value:** Experimental confirmation of the effectiveness of the single-pulse measurement method of the voltage-current characteristic of a solar battery based on a linear current sweep.

**Keywords:** Solar battery, Voltage-current characteristic

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## METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

## 1. Introduction

Current-voltage characteristic (I-V Characteristic) is the main source of information about the parameters of solar batteries (SB). Distinguish between light and dark I-V Characteristic. On the basis of light I-V Characteristic, the following parameters of SB are determined: open circuit voltage, short-circuit current, maximum power, voltage and current at maximum power, form factor (Fill Factor – FF) shunt resistance, series resistance, efficiency [1].

The improvement of methods and the development on their basis of means with improved characteristics for measuring voltage-current characteristics solve important scientific and production problems. In particular, their use will allow implementing the technology of an intelligent solar module, when each solar battery has autonomous software and hardware for continuous monitoring of its operating parameters and characteristics. This will increase the efficiency of the solar energy system as a whole, since it will ensure optimal coordination of each module with the load.

For scientific and technological laboratories, instruments and methods have been developed for measuring the voltage-current characteristics of solar elements (SE) and SB [2], which are generally intended for operating in stationary conditions in the presence of powerful solar radiation simulators. At the same time, portable testers [3] are used for measurements under natural light from the Sun, which can be used to periodically monitor the SB under operating conditions.

The above-mentioned devices operate based on methods of pulsed or linear sweep voltage, which is fed to the gate of a powerful MOSFET – an electronic key. In this case, pulsed measurement methods of the voltage-current characteristics are universal for all types of semiconductor devices and devices and have undoubted advantages over DC measurements. For example, specialists from Keithley, in particular, note: «Pulsed I-V testing is ideal for preventing device self-heating or minimizing charge trapping effects when characterizing devices» [4].

Most pulsed methods of measuring the voltage-current characteristics are based on the fact that the electronic key used as a field effect transistor changes its resistance in direct proportion to the voltage applied to the gate, which is expressed as a linear dependence of the drain current on the gate-source voltage [5-8,10,11]. In this case, SB is connected in parallel with the electronic key that is, short-circuited through the key. As the resistance of the electronic key changes, the position of the SB operating point (current and voltage) also changes. At the output of the SB, simultaneously with the measurement of the

voltage, its current is also measured. Thus, in the measurement circuit of the current – voltage characteristic, two independent measuring channels are used – separately for the voltage and for the SB current. The resulting data arrays are processed and displayed on the display of the device in a graphical form. In this case, the I-V Characteristic in appearance resembles an oscillogram, although it is not.

## 2. Results of researches

The proposed method for discussion allows directly display the voltage-current characteristics of a SB on the oscilloscope screen in real time. In this case, the oscilloscope can be both digital and analog. To implement the method, a simple device for linear sweep of the SB current at its short circuit is necessary. To ensure a gradual increase in current, SB, in series with an electronic key, in its load circuit includes an inductor (Fig. 1).

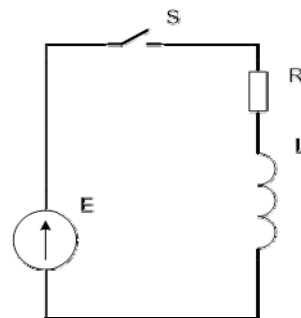


Fig. 1. Diagram of the device for linear current sweep: E – SB; S – controlled electronic key; L – inductor; R is the total resistance of the key and the additional measuring resistor

The electronic key is implemented on a powerful MOSFET and periodically closes the circuit when control pulses are applied to its gate from an external generator.

In a linear current sweep device, a transient model is implemented in an R, L circuit, through which a voltage source is short-circuited. In the case of an ideal voltage source, the current in the circuit at the end of the transition process will be set to a value that far exceeds the short-circuit current of the SB

$$E / R \gg I_{sc}$$

We show that in the area from 0 to  $I_{sc}$  the current in the device (Fig. 1) linearly depends on time. The transition

process in the R, L – chains can be described by a differential equation

$$R_i + L di / dt = U \quad (1)$$

where  $i$  – current,  $U$  – voltage,  $t$  – time.

The complete solution of equation (1) is

$$i = U / R \left( 1 - e^{-t/\tau} \right) \quad (2)$$

where  $\tau$  – time-constant,

$$\tau = L / R \quad (3)$$

Using the decomposition of formula (2) in a Taylor series at a point  $t = 0$  the condition  $t/\tau \rightarrow 0$ :

$$i = U / R \left( 1 - Rt / L + 0,5 (Rt / L)^2 + \dots \right) \quad (4)$$

We take the typical values of the parameters of the scheme  $R = 0.058 \text{ Ohm}$ ,  $L = 8.23 \text{ }\mu\text{H}$ ,  $t = 25 \text{ }\mu\text{s}$ . Then  $Rt/L = 0.176$ . The second term of the decomposition (4) is equal to 0.015 and its contribution does not exceed 1.5%.

Restricting ourselves to the first member of the expansion in a Taylor series, we get

$$i = (U / R) R t / L = U t / L \quad (5)$$

Time differentiating expression (5), we obtain the formula for the current sweep rate:

$$di/dt = U_s/L \quad (6)$$

Considering the fact of linearity of the current sweep, the voltage  $U_s$  in the formula (6) will have some constant value. Obviously, that  $U_s$  is the saturation voltage, the value of which depends on the short circuit current  $I_{sc}$  and the internal series resistance  $R_s$  of the solar battery

$$U_s = I_{sc} \cdot R_s \quad (7)$$

We estimate  $U_s$  by the real I-V Characteristic (Fig. 2). Note that the I-V Characteristic with linear current sweep are obtained in «current-voltage» coordinates, in contrast to the traditional «voltage-current» coordinate system.

The I-V Characteristic (Fig. 2) was obtained with the following parameters of a SB and a device for linear current sweep: rated power 30 W; no-load voltage 22.8 V; short circuit current in conditions of incomplete illumination 0.36 A; inductance in the circuit of the current sweep 17.7  $\mu$ H; the frequency of the control pulses 2662 Hz; pulse duty cycle 10; the voltage across the gate of the MOSFET is 10 V; type of transistor – IRF1010N;

resistance in the switching circuit 55 milliohm; horizontal scan scale of 1  $\mu$ s by grid division; the vertical scale is 5 V per grid division.

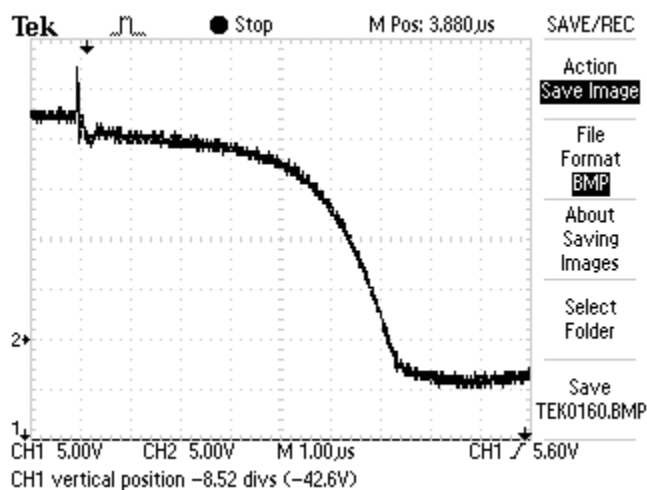


Fig. 2. I-V Characteristic SB of monocrystalline silicon

The sweep time  $T_s$  of the I-V Characteristic (Fig. 2) is 6.3  $\mu$ s. With a short-circuit current of 0.36 A, the sweep speed will be A /  $\mu$ s. Then the saturation voltage  $U_s$  in accordance with (6) is

$$U_s = L \cdot di / dt \quad (8)$$

For the above values  $U_S = 17.7 \cdot 0.057 = 1.01 \text{ B}$ . The saturation voltage  $U_S$  lies near the short-circuit point of the SB ( $I = I_{sc}$ ,  $U = 0$ ). This means that the SB has completely switched to the current source mode and the current is constant and equal  $I_{sc}$  in the section where the voltage changes from  $U_S$  to zero. Thus, when measuring the I-V Characteristic, it is important to ensure the minimum error within the range of voltage variation from the value  $U_{os}$  (idle mode) to saturation  $U_S$ . Note also that in the above calculation we neglected the resistance  $R$  in the sweep circuit (Fig. 1), because

$$R \ll R_s \quad (9)$$

The linear dependence of the current by time is also confirmed by an oscillogram on the measuring resistor (Fig. 3).

In accordance with (7), the saturation voltage  $U_s$  linearly depends on the short circuit current  $I_{sc}$ . This allows for the family of the I-V Characteristic measured at different illuminances of the SB surface and, as a result, at different values of the short-circuit current (Tab. 1), to calculate the saturation voltage  $U_s$ .

Table 1.

Calculation of the saturation voltage SB at various short circuit current

ISC, A	0.82	0.68	0.57	0.42	0.34	0.19	0.11
Sweep duration $\tau$ , $\mu$ s	16.8	18.0	16.4	14.4	13.2	12.0	10.4
Sweep speed $di/dt$ , A/ $\mu$ s	0.049	0.038	0.035	0.029	0.026	0.015	0.010
Saturation voltage $U_s$ , V	2.295	1.775	1.635	1.37	1.21	0.745	0.50

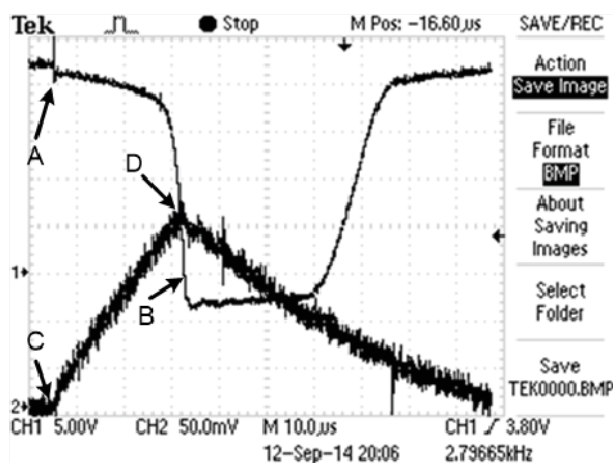


Fig. 3. Oscillograms of linear current sweep SB: channel 1 – current measurement on resistor R, channel 2 – voltage measurement of SB, A – starting point (idle) I-V characteristic, B – end point I-V characteristic (short circuit), C – start of current sweep, D – the end of the current sweep

The dependence of the saturation voltage  $U_s$  on the short circuit current  $I_{sc}$  is shown in Figure 4.

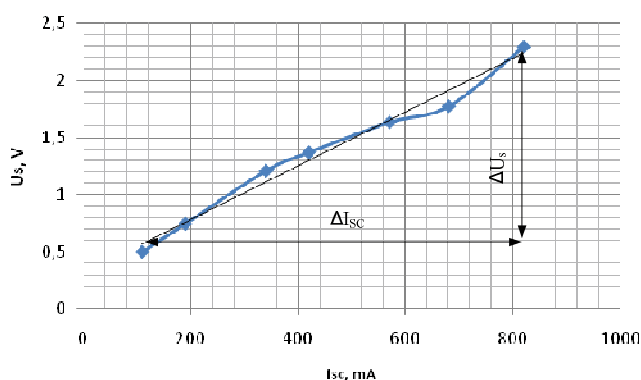


Fig. 4. The dependence of the saturation voltage  $U_s$  on the short circuit current  $I_{sc}$

Next, we define the series resistance of SB by the formula

$$R_s = \Delta U_s / \Delta I_{sc} \quad (10)$$

In accordance with Figure 4 graphically determine the  $R_s = 1.65 / 0.7 = 2.36$  Ohm.

Measurement of the series resistance according to the above method can serve as an alternative to the measurement method according to the family of power curves for the solar elements SE and SB [4,12-15].

Continuing the analysis of I-V Characteristic, we note that at the beginning of the current sweep (point A, Fig. 3), a characteristic voltage jump is observed, caused by the occurrence of a counter-EMF on the inductor when current flows through it. Power surge is:  $(di/dt)L$  or, in accordance with (8)  $U_s$ . Thus, the I-V Characteristic of the SB throughout the entire linear sweep section of the current is shifted down along the ordinate axis by the value of the saturation voltage  $U_s$ . In this case, the value  $U_s$  can be easily determined from the magnitude of the jump in the I-V Characteristic at the beginning of the current sweep. According to Figure 3  $U_s = 1.0$  V, which is consistent with the previously calculated value of 1.01 V.

The linear character of the conversion of the I-V Characteristic in the form of a shift along the ordinate axis allows one to avoid additional mathematical transformations when obtaining the true I-V Characteristic of the SB. For this it is enough to add a value equal to  $U_s$ .

In Figure 5 shows a block diagram of a test bench for measuring the current-voltage characteristics of an SB using the linear current sweep method. The stand allows to control the SE and SB of various types and sizes, including a power of 240 W and an area of up to 2 m<sup>2</sup>.

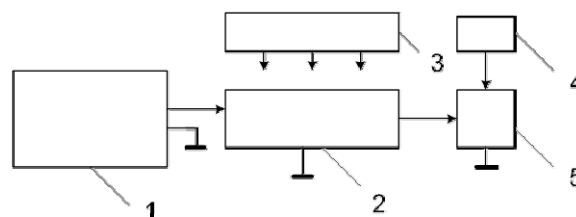


Fig. 5. Structural scheme of the stand for measuring the current-voltage characteristics of an SB: 1 – oscilloscope; 2 – SB; 3 – solar radiation simulator; 4 – control pulse generator; 5 – electronic key on a powerful MOSFET [6,9,16]

The stand works in the following way (Fig. 5). The generator (4) generates continuous or single control pulses that go to the gate of the powerful MOSFET key (5). An inductor coil and a resistor for measuring the current of the SB current are included in the source circuit of the key (2). The generator is implemented on CMOS-logic elements, which allows using a wide supply voltage range – from 3 to 15 V. Power supply for the generator circuit can be supplied both from an external source and from the solar battery itself with its continuous illumination. When a pulse arrives at the gate, the MOSFET starts flowing through the circuit: SB – drain MOSFET – source MOSFET – inductance – measuring resistor – ground. Thus, a short-circuit current of SB flows through the circuit, which increases linearly (with an error of 1%) due to the presence of inductance. As a result, we provide a linear current sweep SB. During the action of one pulse from the generator on the oscilloscope screen (1), we obtain the voltage-current characteristic of the SB. A feature of the IVC is that the abscissa axis we have a current in amperes, and the ordinate axis – the voltage in volts. The second channel of the oscilloscope on the resistor in the source circuit MOSFET measure the current. The solar simulator (3) is based on halogen-tungsten incandescent lamps and illuminates the surface of the solar panel in a continuous mode. Note that the emission spectrum of these lamps is closest to the solar spectrum.

In the test bench, a solar radiation simulator on tungsten-halogen incandescent lamps was used (Fig. 6). In this case, the irregularity of the energy illumination at different points of the irradiation surface is within  $\pm 8\%$ , and the minimum value of illumination is  $1000 \text{ W/m}^2$ , which corresponds to the standard for atmospheric mass AM 1.5.



Fig. 6. Solar radiation simulator: 21 incandescent bulbs of 0.5 kW each were used

Lighting lamps simulator SB of monocrystalline silicon panel with a nominal power of 140W is presented in Figure 7.

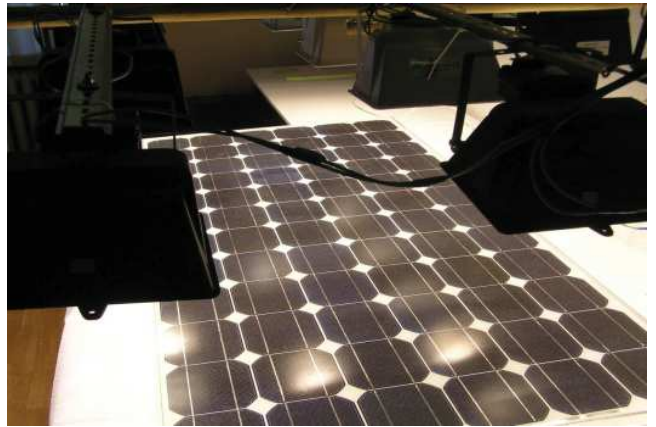


Fig. 7. Radiation of SB with light from the simulator: some of the lamps were not activated, the magnitude of the short-circuit current was 5.8 A

### 3. Conclusions

1. The method of measuring the I-V Characteristic of a SB based on a linear current sweep is theoretically justified.
2. Practically it is proved that within the duration of a single pulse of  $40 \mu\text{s}$ , it is possible to measure the I-V characteristic of an SB with a short-circuit current of up to 5.8 A.
3. A parameter was also introduced that determines the current sweep rate, the saturation voltage of the SB, at which the battery fully switches to the current source mode.
4. It is shown that on the basis of measuring the family of the I-V characteristic for different magnitudes of short-circuit current, which is ensured by SB illumination at different energetic illumination, it is possible to calculate the series resistance of SB.
5. It is shown that the jump in the I-V characteristic at the beginning of the current sweep, caused by the back-EMF in the inductance coil of the sweep device, is numerically equal to the saturation voltage of the SB.
6. It is shown that the I-V characteristic of a SB has a linear shift down along the ordinate axis by the value of the saturation voltage over the entire portion of the linear current sweep.

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