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# Measurements of thermal parameters of solar modules

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Abstract. In the paper the methods of measuring thermal parameters of photovoltaic panels transient thermal impedance and the absorption factor of light-radiation are presented. The manner of realising these methods is described and the results of measurements of the considered thermal parameters of selected photovoltaic panels are presented. The influence of such selected factors as a type of the investigated panel and its mounting manner on transient thermal impedance of the considered panels is also discussed.

#### 1. Introduction

Solar cells are more and more often used as a source of electrical energy [1]. Characteristics of these semiconductor devices strongly depend on temperature [2, 3], which also in a decisive manner influences reliability of electronic equipment [4, 5]. The internal temperature of the considered devices is higher than the ambient temperature as a result of thermal phenomena - self-heating and the energy exchange of solar radiation into heat [3, 6, 7].

In order to take into account thermal phenomena in computer analyses, electrothermal models of electronic elements are indispensable. The electrothermal model of solar cells was proposed in the paper [3]. In this model self-heating phenomenon is characterized by transient thermal impedance  $Z_{th}(t)$ , which is typically represented by the following dependence [6, 8]

$$Z_{th}(t) = R_{th} \cdot \left[ 1 - \sum_{i=1}^{N} a_i \cdot \exp\left(-\frac{t}{\tau_{thi}}\right) \right]$$
(1)

where  $R_{th}$  denotes thermal resistance, N – number of thermal time constants  $\tau_{thi}$  connected with coefficients  $a_i$ .

Methods of measuring thermal resistance of solar cells are presented, among others, in the paper [9]. However, in the real photovoltaic systems, the panels containing many solar cells connected with one another electrically and installed on the common basis are used [7]. But in literature there is no description of methods of thermal parameters measurements of such panels.

In this paper the method of measuring transient thermal impedance of photovoltaic panels and the method of estimating the absorption factor of radiation by such a panel are presented. Theoretical considerations are illustrated with the results of measurements.

## 2. Measurements method

In accordance with the well-known from the papers [10, 11] idea of measuring transient thermal impedance of semiconductor devices, the value of this parameter can be measured using the so called cooling curve. According to this idea, power of the well-known value P should be dissipated in the

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examined device until the steady state is obtained, and then after switching-off this power, the waveform of the internal temperature of the examined element  $T_j(t)$  should be measured. In the last step of the measurement the values of  $Z_{th}(t)$  are calculated using the following formula

$$Z_{th}(t) = \frac{T_j(t=0) - T_j(t)}{P}$$
(2)

where t = 0 denotes the moment of switching-off the power.

In the case of the photovoltaic panel one ought to assure the conditions of the  $Z_{th}(t)$  measurements, in which the only reason for the change of the internal temperature of the panel is self-heating. Therefore, the measurement is performed for not lighted up panel situated in the light-tight chamber. The temperature of the panel  $T_j$  is measured by means of the thermo-hunter connected with the computer, which registers the values of this temperature in the selected points of time. The power P is equal to the product of the voltage and the current of this panel measured before switching-off this power.

In turn, the absorption factor of radiation *a* is measured at the steady-state for the panel lighted up using the following formula.

$$a = \frac{1}{S \cdot p_e} \cdot \left( \frac{T_j - T_a}{R_{th}} - U_{nom} \cdot I \right)$$
(3)

where I means the current of the panel,  $U_{nom}$  - voltage at the opening output of the panel, S - the active area of the panel, while  $p_e$  is power density of radiation on the surface of the panel.

Now then, for the purpose of measuring the value of the absorption factor of radiation, one should first measure thermal resistance of the panel  $R_{th}$ , and then read the voltage  $U_{nom}$  for the lighted up panel at the zero-current; next, one should measure the value of temperature of the lighted up panel by means of the thermo-hunter at the current of the panel *I*.

The measuring-methods described above are realized in the measuring-system shown in Figure 1.



Figure 1. The measurement-system of transient thermal impedance and the absorbtion factor of radiation of the photovoltaic panel

During the measurement of transient thermal impedance the switch  $S_2$  is opened, and the voltage source  $U_{zas}$  together with the resistor  $R_{dek}$  make possible the regulation of the supply current of the examined panel DUT. In the moment t = 0 the switch  $S_1$  is opened, making possible the flow of the current through the examined panel. The temperature of the panel is measured by the thermo-hunter and registered by the PC.

In turn, during the measurement of the absorption factor the switches  $S_1$  and  $S_2$  are closed. The light source lights up the examined panel, power density of radiation is measured at the steady-state by means of the photo-radiometer, and temperature of the panel is measured by means of the thermo-hunter.

#### 3. Results of measurements

The measuring methods presented in the second section were used to measure thermal parameters of the selected photovoltaic panels operating at different conditions of the power supply and cooling.

In Figure 2 waveforms of transient thermal impedance of the panel MK-240 containing 60 polycrystalline silicon solar cells connected serially are presented. This panel has the dimensions 1000 x 1681 x 50 mm, and the nominal power dissipated in this panel amounts to about 200 W. In this figure, the curve a means transient thermal impedance for the panel situated horizontally on the steel-rack, the curve b - for the panel situated on the same rack slanting at a little angle of  $30^{\circ}$  to the horizon, the curve c - for the panel situated on the same rack slanting at a little angle of  $60^{\circ}$  to the horizon, curve d - for the panel situated horizontally on the rack and separated from it with the wooden plate, while the curve e - for the panel pendant on 4 metal-brackets. The measurements were performed at dissipated power equalled to about 310 W.



Figure 2. Measured waveforms of transient thermal impedance of the panel MK-240 operating at different cooling conditions

As it is visible in Figure 2, time indispensable to obtain the steady state and the value of thermal resistance depends on the operating conditions of the panel. The steady state is obtained after 3000 - 5000 s after switching on the power supply of the panel. The least value of thermal resistance, equal to 0.0365 K/W, is obtained for the panel situated on the stand metal and slanting at an angle of  $60^{\circ}$  to the horizon, the biggest - equal to 0.045 K/W - for the panel arranged horizontally on the metal stand - and separated from it by means of the 4 mm wooden plate (of the heat conductivity coefficient equal to 0.16 W/m/K). It is worth noticing that together with an increase of the depression angle of the panel with relation to the horizon in the range from 0 to  $60^{\circ}$ , one observes a decrease of thermal resistance by even about 20%. It is also easy to notice that the mounting base, to which the panel is mounted has the essential meaning in the process of heat removal from the panel. In the case of the direct contact of the panel with this base one obtains values of thermal resistance by even about 10% lower than in the situation, when between the panel and the metal-base a material weakly conducting heat is inserted.

Dynamic properties of the process of heat removal dissipated in the panel can be characterized by spectrum of thermal time constants [8]. The spectrum of thermal time constants for the panel MK-240 are shown in Figure 3. In this figure the colours used to present this spectrum are the same as corresponding to them waveforms of transient thermal impedances denoted as curves a-e in Figure 2. Values of parameters  $a_i$  and  $\tau_{thi}$ , existing in the equation (1), were marked with the use of the algorithm described in the paper [12]. This algorithm uses measured waveforms of  $Z_{th}(t)$ .

As it can be observed, at all the considered cooling conditions at least two thermal time constants appear. Thermal time constants of values in the range from 200 to 600 s have the prevailing meaning (the corresponding to them values of parameters  $a_i$  have the biggest value). The longest thermal time constants in the range from 800 to 2300 s decide about time indispensible to obtain the steady state. Comparing the curves shown in Figure 2 and Figure 3 it can be noticed that to worse cooling conditions correspond both higher values of thermal resistance and higher values of thermal time constants.

Except the panel MK-240 the measurements of transient thermal impedance were performed also for other photovoltaic panels: the amorphous panel SG-HN-120-GG of the dimensions 1400 x 1100 x 7.1 mm and the nominal output power equal to 120 W, the monocrystalline panel SGM -250D of the dimensions 1650 x 990 x 40 mm and the nominal output power equal to 250 W and the polycrystalline panel Q.PRO-G3 250-265 of the dimensions 1670 x 1000 x 35 mm and the nominal output power equalled to 250 W.



Figure 3. Spectrum of thermal time constants of the panel MK-240 operating at different cooling conditions

Figure 4 presents the measured waveforms of transient thermal impedance of the considered panels at worse cooling conditions (the panel situated horizontally on the rack and separated from it with the wooden plate), whereas Figure 5 - at the optimum cooling conditions (the panel situated on the same rack slanting at a little angle of 60° to the horizon). In these figures curves a correspond to the panel MK-240, curves b - the panel SG-HN-120-GG, curves c - the panel SGM-250D, whereas curves d - the panel Q.PRO-G3 250-265.

As one can notice, higher differences between the waveforms of transient thermal impedance are obtained at worse cooling conditions. For all the considered panels time indispensable to obtain the steady state equals 2 hours. Values of thermal resistance obtained for panels SG-HN-120-GG and Q.PRO-G3 250-265 differ by over 25%. The panel SG-HN-120-GG differs constructively from other panels, ie. it does not possess the aluminium-frame, but it is situated on the glass basis.



Figure 4. Measured waveforms of transient thermal impedance of the selected panels situated horizontally on the rack and separated from it with the wooden plate

In turn, the visible in Figure 5 waveforms  $Z_{th}(t)$  prove that the use of the metal rack bracket under the large angle to the horizon assures essential improvement in the cooling efficiency of the

considered panels. It is worth noticing that in the considered case differences are visible in heat capacitances of each panel appearing at different times indispensible to obtain the steady state. Simultaneously one observes small differences in the value of thermal resistance of each panel. These differences exceed 15%. The time indispensable to obtain the thermally steady state in the investigated panels reaches even 6000 s.



Figure 5. Measured waveforms of transient thermal impedance of the selected panels situated on the rack slanting at a little angle of 60° to the horizon

In Figure 6 the spectrum thermal time constants corresponding to the waveforms of transient thermal impedances shown in Figure 5 are presented. It is easy to observe large divergences in values of thermal time constants characterizing each of the considered panels. Values of the longest thermal time constants, decisive about time indispensable to obtain the thermally steady state of the investigated panels, accept values from the range from 1000 s for the panel MK-240 to 5000 s for the monocrystalline panel SGM -250D. The transient thermal impedance of the amorphous panel, as the only one of the investigated panels, is described by means of only one thermal time constant. Thermal proprieties of all the remaining panels are characterized by two thermal time constants.



**Figure 6**. Spectrum of thermal time constants of the considered panels situated on the rack slanting at a little angle of 60° to the horizon

Using the method described in the second section, the absorption factor of radiation is measured for the selected photovoltaic panels. During the measurements power density of radiation on the surface of the examined panel amounted to about  $175 \text{ W/m}^2$ . The load current of the panel amounted to about 3 mA. The panel was pendant on 4 metal-brackets. Time indispensable to obtain the steady state exceeded 2 hours. In accordance with the equation (3) the values of the absorption factor of radiation are obtained and they equal 2.99 for the polycrystalline panel MK-240 and 2.405 for the monocrystalline panel SGM-250D. The obtained values of the considered parameter mean that the

absorption of solar radiation can cause the excess of the panel internal temperature over the ambient temperature equal to even 200 K at the maximum allowable value of the power density of solar radiation (1000  $W/m^2$ ).

# 4. Conclusions

In the paper the methods of measuring thermal parameters (transient thermal impedance and absorption factor of radiation) of photovoltaic panels are presented and some results of measurements of these parameters for the selected panels operating at different conditions of their mounting are shown. The presented results of measurements confirm usefulness of the worked out measuring-methods. The investigations were performed by means of the worked out methods. The influence of the manner of mounting photovoltaic panels on their transient thermal impedance confirmed that among others the attack angle of the panel in relation to the horizon and thermal conductance of material situated between the panel and the mounting-base had the essential meaning.

The obtained waveforms of transient thermal impedance of the panels and the measured values of the absorption factor of radiation show that for the nominal value of the output power of the examined panels and for the power of sun lighting observed in Poland an increase in temperature of the panel above the ambient temperature can exceed tens kelvins. Such a large increase of temperature can cause essential depreciation of the output voltage and the output power [3]. Therefore, optimization of cooling conditions of photovoltaic panels can cause an increase in their efficiency.

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