Modelling characteristics of photovoltaic panels with thermal phenomena taken into account

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Abstract. In the paper a new form of the electrothermal model of photovoltaic panels is proposed. This model takes into account the optical, electrical and thermal properties of the considered panels, as well as electrical and thermal properties of the protecting circuit and thermal inertia of the considered panels. The form of this model is described and some results of measurements and calculations of mono-crystalline and poly-crystalline panels are presented.

1. Introduction
Photovoltaic panels are important components of solar power stations and autonomous photovoltaic (PV) systems [1 - 7]. They consist of photovoltaic cells connected in series, in which there is conversion of solar energy into electrical energy. These devices contain a p-n junction, the properties of which strongly depend on its internal temperature $T_J$ [8, 9, 10]. This temperature increases both as a result of absorption of heat generated by the radiation source and due to self-heating [1, 8, 9, 11, 12]. Therefore, these phenomena should be taken into account while designing and analyzing solar power stations [3, 13, 14, 15].

Currently, computer programs are commonly used to design and analyze characteristics of PV panels [3, 12, 13]. In order to calculate the characteristics of such a system before its construction the model of this device should be elaborated. Unfortunately, there is a lack of papers describing the operation of PV panels, which take a thermal phenomenon into account [16]. Some of the mentioned models treat phenomena in a simplified way [12]. In these models temperature is only a parameter.

In earlier papers of the authors [13, 16] electrothermal models of solar cells, which is the main component of photovoltaic panels are proposed. However, these models omit thermal inertia of the investigated devices. In paper [13] the use of the considered models to compute dc characteristics of the photovoltaic panels is proposed. The presented in quoted paper method of calculations demands uses the dc analysis in SPICE software and additional calculations on the basis of the obtained results of computations. In neither of the quoted papers the properties of the circuit protecting the photovoltaic panel against irregular connection to the photovoltaic system are taken into account.

In this paper, the new form of the electrothermal model of PV panels taking into account electrical, optical and thermal phenomena as well as thermal inertia in the panel, is proposed. In section two the detailed description of the proposed model of a photovoltaic panel is presented. The results of experimental verification of the presented model are shown and discussed in section three.
2. The model form

The elaborated by the authors electrothermal model of the photovoltaic panel belongs to the group of compact electrothermal models, presented for many semiconductor devices e.g. in papers [14, 17, 18]. This kind of models consists of two sub-models: the electrical model and the thermal model. The electrical model describes the current-voltage characteristics of the considered devices with the influence of temperature taken into account. In turn, in the thermal model the value of the device internal temperature $T_j$ is calculated taking into account the changes of the ambient temperature $T_a$ and self-heating phenomenon.

The network representation of the elaborated electrothermal model of a photovoltaic panel is shown in Figure 1.

![Figure 1. The network representation of the electrothermal model of PV panels.](image)

In the electrical model, the controlled current source $G_1$ represents the photoelectric current, in turn, the controlled current source $G_2$ represents a component of the diffusion current of the p-n junctions, the controlled current source $G_3$ models the generation-recombination component of the p-n junctions current, whereas the controlled current source $G_4$ represents the current of the diode protecting the modelled panel against a reverse connection of this panel to the photovoltaic system. The resistor $R_R$ models the leakage current of the panel, whereas the resistor $R_S$ –series resistance of the panel at the reference temperature $T_0$. The controlled voltage source $E_{RS}$ models the temperature dependence of series resistance. The resistor $R_{SD}$ represents series resistance of the protecting diode.

In the thermal model, the controlled current source $P_{th}$ represents the sum of power dissipated in the PV panel and power of absorbed radiation, whereas $R_{th1}, \ldots, R_{thn}$ and $C_{th1}, \ldots, C_{thn}$ are thermal resistances and thermal capacitances of the panel, respectively. The voltage source $V_{Ta}$ represents the ambient temperature $T_a$.

The photoelectric current is described by the following formula [16]

$$I_1 = P \cdot S \cdot \eta \cdot x \cdot \left[ 1 + \alpha_T \cdot \left(T_j - T_0\right) \right]$$

(1)

where $P$ denotes power density of lighting radiation, $S$ - active area of the solar cell, $\eta$ – efficiency of photovoltaic conversion, $x$ - coefficient equal to 1 V$^{-1}$, $\alpha_T$ – temperature coefficient of changes of the photoelectric current, $T_j$ – internal temperature of the solar cell, $T_0$ - reference temperature.

In turn, the diffusion current of the p-n junctions is described by the equation

$$I_2 = J_0 \cdot S \cdot \left(\frac{T_j}{T_0}\right)^2 \cdot \exp\left(-\frac{U_g}{m \cdot n \cdot k / q \cdot T_j}\right) \cdot \exp\left(-\frac{v_i}{m \cdot n \cdot k / q \cdot T_j}\right) - 1$$

(2)

where $J_0$ denotes the parameter of the saturation current density, $n$ – emission factor of the p-n
junction, \( n \) – number of solar cells in the panel, \( U_{go} \) – voltage corresponding to the band-gap of silicon, \( v_1 \) – voltage on the current source \( G_2 \), \( k \) is the Boltzmann constant, \( q \) - electron charge.

The generation-recombination current is described by the formula

\[
I_3 = J_{02} \cdot S \cdot \frac{T_j}{T_0} \cdot \exp \left[ - \frac{U_{go}}{m \cdot n_1 \cdot \frac{k}{q} \cdot T_j} \right] \cdot \left[ \exp \left( \frac{v_1}{m \cdot n_1 \cdot \frac{k}{q} \cdot T_j} \right) - 1 \right]
\]

(3)

where \( J_{02} \) denotes the parameter of the generation-recombination current density, \( n_1 \) – emission factor for the generation-recombination current.

The controlled voltage source \( E_{RS} \) models the influence of temperature on series resistance of the panel by linear dependences of the form

\[
E_{RS} = V_{RSO} \cdot \alpha_{RS} \cdot (T_j - T_0)
\]

(4)

where \( \alpha_{RS} \) denotes the temperature coefficient of series resistance, whereas \( V_{RSO} \) – the voltage on the resistor \( R_S \).

The current of the protecting diode is described by the formula

\[
I_4 = I_{04} \cdot \left( \frac{T_j}{T_0} \right)^2 \cdot \exp \left[ - \frac{U_{go}}{n_4 \cdot \frac{k}{q} \cdot T_j} \right] \cdot \left[ \exp \left( \frac{v_4}{n_4 \cdot \frac{k}{q} \cdot T_j} \right) - 1 \right]
\]

(5)

where \( I_{04} \) is the parameter of the saturation current of the protecting diode, whereas \( n_4 \) is the emission factor of this diode.

In the thermal model, the current source \( P_{th} \) represents power dissipated in the panel and power of radiation absorbed by the panel. The current of the controlled current source \( P_{th} \) is described by

\[
P_{th} = P \cdot a \cdot S_1 \cdot m + (V_{out} - v_1) \cdot I_{out} + v_1 \cdot (I_2 + I_3)
\]

(6)

where \( a \) denotes the ratio of conversion of radiation energy into heat, \( S_1 \) – area of the solar cell, while \( V_{out} \) and \( I_{out} \) are the output voltage and the output current of the panel, respectively.

3. Results

The correctness of the elaborated electrothermal model of photovoltaic panels is verified experimentally for two arbitrary selected panels. First of them is a mono-crystalline panel SGM -250D of the dimensions 1650 x 990 x 40 mm, and the other is a poly-crystalline panel Q.PRO-G3 250-265 of the dimensions 1670 x 1000 x 35 mm. Both the panels consist of 60 solar cells and their nominal output power is equal to 250 W.

Using the method described in paper [16] the electrical and optical parameters of the considered panels are estimated, whereas the thermal parameters are measured using the method described in [19]. The values of parameters of the considered panels are collected in Table 1.

In Figures 2 – 7 the results of measurements (points) and calculations (lines) of the considered panels are presented. In these Figures the results obtained for the poly-crystalline panel are denoted with blue colour, whereas the results obtained for the mono-crystalline panel are denoted with red colour. All measurements are realized using the measurement system described in [13] and calculations are realized with the use of SPICE software.

Figure 2 illustrates the output characteristics of the considered panels obtained at two values of power density of lighting radiation equal to 168 W/m² and 335 W/m², respectively. Figure 3 illustrates
the dependence of temperature of the panels on the output current. As it is visible, the considered v(i) characteristics are decreasing functions. An increase in the power density of lighting radiation causes an increase in the value of the output current. For the polycrystalline panel, the obtained values of the panel output voltage are higher than for the monocrystalline panel by even about 1.5 V. Analysing the dependence $T_j(i)$, it is visible, that the output current very weakly influences the value of the panel temperature. This proves that the observed excess of the panel temperature over the ambient temperature results mostly from conversion of lighting energy into heat. This excess is even equal to about 70°C for power density of lighting radiation equal to 335 W/m$^2$.

### Table 1. The estimated values of model parameters of the considered panels

| parameters | $S$ [m$^2$] | $S_1$ [m$^2$] | $\eta$ | $\alpha_T$ [K$^{-1}$] | $J_0$ [A/m$^2$] | $\theta_2$ [A/m$^2$] | $I_{b1}$ [A] |
|------------|-------------|-------------|--------|----------------------|----------------|---------------------|-----------|
| poly-crystalline | 0.0231 | 0.024 | 0.5952 | 2.51x10$^{-3}$ | 9.44x10$^{-12}$ | 1.51x10$^{-5}$ | 10$^4$ |
| mono-crystalline | 0.0231 | 0.024 | 0.588 | 2.34x10$^{-3}$ | 9.44x10$^{-12}$ | 1.51x10$^{-5}$ | 70 |

| parameters | $n$ | $n_1$ | $n_4$ | $m$ | $U_{go}$ [V] | $\alpha_{RS}$ [K$^{-1}$] | $R_s$ [Ω] |
|------------|----|-----|-----|-----|---------|-----------------|---------|
| poly-crystalline | 0.95 | 2.72 | 1.3 | 60 | 1.206 | 0.00279 | 0.186 |
| mono-crystalline | 0.98 | 2.82 | 1.8 | 60 | 1.206 | 0.00293 | 0.234 |

| parameters | $R_{SD}$ [Ω] | $R_s$ [Ω] | $R_{h1}$ [K/W] | $C_{th1}$ [J/W] | $R_{h2}$ [K/W] | $C_{th2}$ [J/W] | $a$ |
|------------|-------------|-------------|----------------|--------------|----------------|--------------|-----|
| poly-crystalline | 0.08 | $10^4$ | 0.0106 | 3.18x10$^5$ | 0.03083 | 3.474x10$^4$ | 3.25 |
| mono-crystalline | 0.135 | $10^4$ | 0.0166 | 1.57x10$^5$ | 0.0234 | 3.54x10$^4$ | 3.41 |

**Figure 2.** The calculated and measured output characteristics of the lighted up panels.
Figure 3. The calculated and measured dependences of the temperature of the considered panels on their output current.

In Figure 4 the output characteristics of the considered panels operating without lighting up are presented, whereas in Figure 5 – corresponding to them dependences of temperature of these panels on the panel output current.

Figure 4. The calculated and measured output characteristics of the non lighted up panels.

Figure 5. The calculated and measured dependences of the temperature of non lighted up panels on the output current.
As it is seen, the forward current of the considered panels is an exponentially increasing function of the forward voltage. This voltage assumes higher values for the mono-crystalline panel. In turn, the temperature of the panel linearly increases with an increase of the forward current. It is worth noticing, that for the maximum allowable value of the panel forward current (equal to 8 A), a self-heating phenomenon causes an increase in the panel temperature value equal only by 12°C.

The characteristics presented in Figures 2-5 correspond to operation of the considered panels at the steady state. In Figure 6 a waveform of temperature of non lighted up panels obtained at rectangular pulses train of their output current of the low value equal to 0 and the high value equal to 8 A is presented. The pulse width and period are selected in order to obtain the steady state in the panel during each pulse of the current. It is worth noticing that the steady state is obtained in the considered panel after about 3 hours (10000 s).

Figure 7 illustrates the characteristics of the non lighted up panels operating at the reverse biasing voltage.

It is easy to observe that the reverse voltage of the poly-crystalline panel is higher than this voltage of the mono-crystalline panel. Power dissipated in the protecting diodes is very small and therefore, an increase of the panel temperature is not observed.

Figure 6. The calculated and measured waveforms of panels temperature by stimulation with the rectangular current pulses train.

Figure 7. The calculated and measured characteristics of the protecting diodes.

4. Conclusions
In the paper the new electrothermal model of photovoltaic panels is proposed. This model takes into account optical, electrical and thermal properties of the considered panels. Apart from properties
of solar cells included in the considered panels, the characteristics of protecting diodes are taken into account in this model. In the thermal model of the panel, thermal inertia is included.

The correctness of the model was tested by examining characteristics of mono-crystalline and poly-crystalline solar panels for different values of power of lighting radiation and different biasing conditions. For all the considered operating conditions the good agreement between the results of calculations and measurements was obtained.

The presented model can be useful for designers of solar energy generation systems, as well as for designers of electronics systems supplied with solar panels.

5. References

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