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Experimental and numerical analysis of solar cell temperature transients

István Bodnár*, Dávid Matusz-Kalász and Dániel Koós

Department of Electrical and Electronic Engineering, Institute of Physics and Electrical Engineering, Faculty of Mechanical Engineering and Informatics, University of Miskolc, H-3515 Miskolc-Egyetemváros, Hungary

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ABSTRACT

Many factors determine the efficient operation of a photovoltaic cell. These factors can be the intensity and spectral composition of illumination, the surface temperature, the ambient temperature, and the amount contaminations in the air and on the surface of the cells. The aim of the present study is to describe the effect of temperature gradient on the voltage and amperage changes, as well as the power output of a commercial solar cell through experimental methods and numerical simulations performed in MATLAB. The transient temperature investigations have allowed better understanding the time-dependent behavior of a solar cell under constant intensity illumination. Measurements prove that an increase in the surface temperature of the solar cell significantly reduces its performance. Measurements performed with the solar simulator show good conformity with simulated results.

KEYWORDS

solar cell, temperature dependence, temperature transient, MATLAB simulation, laboratory measurements

1. INTRODUCTION

The 21st Century is considered by many to be the golden age of solar power utilization. Their efficiency is increasing steadily, but it should not be overlooked that their operation is affected by several environmental factors throughout the present study, the effects of the change of the surface temperature of the solar cell on the cell's electrical parameters are investigated.

Experimental results were obtained by providing artificial illumination using an ASTM E972 (IEC 60904-9) [1], standard solar simulator. Correlations were then obtained with the help of the measurement results and the results acquired from MATLAB simulations [2]. The future development goal is to refine the established theoretical model based on the measurement results. There is a large body of literature devoted to the experimental and numerical investigation of solar cells at constant temperatures [3–5], but very few researchers [6, 7] investigate the phenomenon of transient temperature and its effects. The present study primarily contains results measured and simulated in the transient state, which also represents the novelty of the research work.

2. DEVELOPMENT OF THE SIMULATION MODEL DESCRIBING THE OPERATION OF A SOLAR CELL

2.1. Literature research, overview of solar cell models

To simulate the operation of a solar cell, the first step is to establish its electronic model. Several models of equivalent circuits of a solar cell can be found in the related literature [8–14], this study is started by reviewing them. In this chapter, without being exhaustive, the

*Corresponding author.
E-mail: vegybod@uni-miskolc.hu

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most commonly used models will be briefly described. Figure 1 shows the described models and Fig. 2 presents the experimental arrangements.

Model a) in Fig. 1 is an ideal equivalent circuit of a solar cell, consisting of a current source and a diode [9, 15]. Compared to the ideal circuit, model b) contains a series-connected resistor, which is intended to incorporate the resistance of the constructed solar cell [9]. In model c), a further extension is the resistor connected in parallel with the shunt diode [9]. Model d) is the most complex equivalent circuit of a solar cell. In this case, a double shunt diode is incorporated into the model [8, 9, 15]. This variant is considered to be the most accurate model to simulate the operation of a solar cell [8, 9, 12, 15]. The other described equivalent circuits can be derived from this one as well [16].

Some literature discusses how to compare the accuracy of different models, which can be helpful to choose the model to be applied. In this case, the model of Fig. 1c was taken as the basis of the simulation model of the solar cell. The reason for this is that, according to the literature, there is no significant difference between the accuracy of models c) and d), the calculations when using the c) equivalent circuit are, however, much simpler [8, 9, 12, 15].

2.2. Model construction

Accordingly, the photo-current (I_{ph}) provided by the current source of this model, describes the charge carrier separation occurring because of the sunlight in the p–n junction of the solar cell well; the diode of the model adequately models the processes occurring within the p–n junction [10]. The serial and parallel resistors describe the deviation from the ideal model and the individual losses of a solar cell. The series resistance (R_s) is given by the distance between the p–n junction and the metallic conductors on the surface of the semiconductor layer, and to a small extent by the resistivity of the conductors [10]. The parallel resistance (R_p) mainly occurs at the edge of the cells, and it indicates the effect of currents caused by the recombination of charges that are bypassing the p–n junction [10]. This leakage current can be minimized with proper insulation; therefore, it has a negligible impact on the operation of today's modern solar cells [3, 10, 11]. Based on the equivalent circuit is shown in Fig. 1, the following equation can be written [11, 16]:

$$I = I_{ph} - I_0\left(\exp\left(\frac{q(U + IR_s)}{\gamma k T_c}\right) - 1\right) - \frac{U + IR_s}{R_p}, \quad (1)$$

where I is the current [A]; U is the voltage of the cell [V]; I_{ph} is the photo-current [A]; I_0 is the saturation current of the diode [A]; q is the elementary charge [C]; γ is a cell-specific factor [–]; k is the Boltzmann-constant [8, 11, 17]. In this equation, the value of the parallel resistance R_p, based on previously discussed considerations, is chosen to be infinitely large [8]. Normally R_p would be rather difficult to determine, choosing it to represent a break does, however, not result in a significant change in the accuracy of the model [18]. Therefore, the last term of Eq. (1) is zero, so there are four variables: I_{ph}, I_0, γ, R_s [16, 18]. These variables can be determined using the solar cell characteristics given in Table 1.

When determining the variables of Eq. (1), it must be considered that the main goal of the research is to model the operation of a solar cell as a function of temperature and the irradiation [3]. To determine the four unknown parameters – taking the changes in the intensity of irradiation and temperature into account – the following equations can be devised [3, 8–11, 19]:

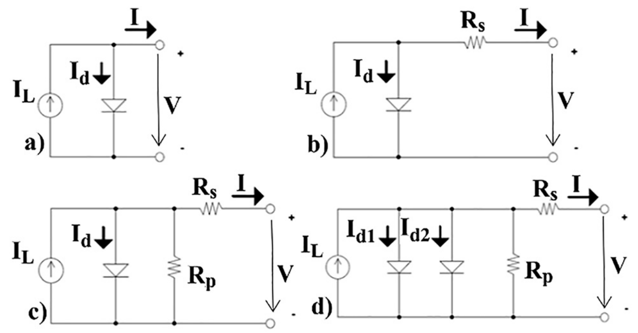

Fig. 1. The most commonly used equivalent circuits of a solar cell

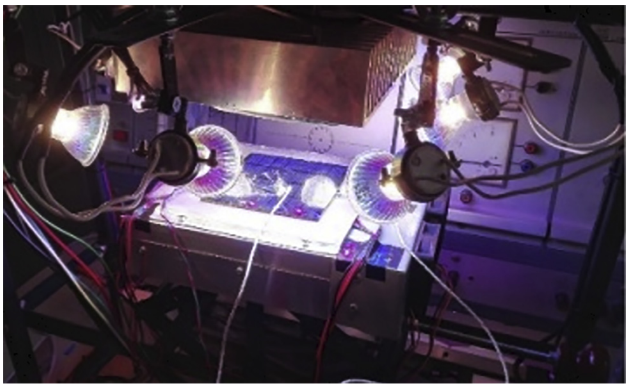

Fig. 2. The experimental arrangement

Table 1. Solar cell data used in modeling

Parameter	Symbol	Value	Measurement
Maximum power	$P_{\max}$	0.68	[W]
Short circuit current	I_{sc}	0.115	[A]
Open circuit voltage	U_{oc}	8.4	[V]
Maximum Power Point (MPP) current	I_{mpp}	0.094	[A]
Maximum Power Point (MPP) voltage	U_{mpp}	7.2	[V]
Percentage temperature coefficient for I_{sc}	μ_{Isc}	0.047	[%/°C]
Percentage temperature coefficient for U_{oc}	μ_{Uoc}	−0.32	[%/°C]
Useful surface area	A	0.01	[m^2]

$$I_{ph} = \frac{E}{E_{ref}}\left(I_{ph\_ref} + \mu_{Isc}\left(T_c - T_{c\_ref}\right)\right), \quad (2)$$

$$I_0 = I_{0\_ref}\left(\frac{T_c}{T_{c\_ref}}\right)^3 \exp\left(\frac{\varepsilon N}{q a_{ref}}\left(1 - \frac{T_c}{T_{c\_ref}}\right)\right), \quad (3)$$

$$R_s = \frac{\frac{1}{\Lambda}\ln\left(1 - \frac{I_{mpp}}{I_{sc}}\right) + U_{oc} + U_{mpp}}{I_{mpp}}, \quad (4)$$

$$\gamma = \frac{q}{\Lambda k T_c}, \quad (5)$$

where ε is the width of the band gap specific to the material of the solar cell [eV]; E is the present irradiation [W/m^2]; E_{ref} is the reference irradiation [W/m^2]; T_c is the present cell temperature [°C]; T_{c_ref} is the reference cell temperature [°C]. The reference temperature and irradiation values should be chosen in accordance with the Standard Test Conditions (STCs), which are: T_{c_STC} = 25 °C, E_{STC} = 1,000 W/m^2. The reason for this expedient choice is that the characteristic parameters given by the solar cell data are most often determined for STC.

The factor a_{ref} in Eq. (3) and the factor Λ in Eqs (4) and (5) merely simplify the expression of the equations and can be derived from the following equations [2, 3, 8, 18–22]:

$$\Lambda = \frac{\frac{I_{sc}}{I_{rz} - I_{mpp}} + \ln\left(1 - \frac{I_{mpp}}{I_{sc}}\right)}{2U_{mpp} - U_{oc}}, \quad (6)$$

$$a_{ref} = \frac{\left(\mu_{Uoc} T_{c\_ref} - 1\right) U_{oc} + \frac{\varepsilon N}{q}}{\mu_{Isc} T_{c\_ref} - 3}. \quad (7)$$

In order to solve the equation system, it is also necessary to determine the reference value of the photo current I_{F_ref} and the reference value of the saturation current of the diode I_{0_ref} [2, 8, 21, 22]. These two parameters can be expressed by substituting the open circuit and short circuit cases into Eq. (1). The values of the two parameters, after further sorting, can be expressed as follows [2, 8, 18, 21, 22]:

$$I_{ph\_ref} = I_{sc}, \quad (8)$$

$$I_{0\_ref} = I_{sc}\exp(-\gamma U_{oc}). \quad (9)$$

With the help of the described Eqs (2)–(9), the main Eq. (1) of the equivalent circuit of the solar cell becomes implicitly solvable, hence the curve of the solar cell can be determined as a function of temperature and irradiation by the model [11, 12, 20]. So far, the effect of the temperature of the solar cell was only considered, but in practical applications it is useful to determine the relationship between the temperature of the solar cell and the ambient temperature [20, 22]. The basis is the following solar energy balance (Electric energy is equal to the difference of adsorbed and dissipated energy) [23]. Energy balance can be expressed reduced to a unit surface of the solar cell as follows:

$$E\eta = E\tau a - U_L(T_a - T_c), \quad (10)$$

where E is the irradiation [W/m^2]; η is the efficiency of the solar cell [%]; τ is the transmission coefficient of the solar cell [-]; a is the emission coefficient of the solar cell [–]; U_L is the heat transfer coefficient of the solar cell [W/m^{2}K]; T_a is the ambient temperature [°C]; T_c is the cell temperature [°C]. By rearranging Eq. (10), the cell temperature can be expressed as a function of ambient temperature [20, 22]:

$$T_c = T_a + \frac{E\tau a}{U_L}\left(1 - \frac{\eta}{T_a}\right). \quad (11)$$

There are several unknown variables in Eq. (11), of which the product of τa is chosen to be 0.9 as recommended by the literature. As it can be seen, the efficiency of a solar cell depends on the temperature, so accurate determination can only be achieved using an iterative approach. By executing the calculations with efficiency valid for Maximum Power Point (MPP), the equation can be written as follows [24]:

$$\eta_{mpp} = \frac{I_{mpp} U_{mpp}}{EA}. \quad (12)$$

The last missing parameter, namely the heat transfer coefficient of the solar cell (U_L), is determined by the help of the so-called Nominal Operating Cell Temperature (NOCT), which is found among the solar cell data. The required equation can be written as follows:

$$U_L = \frac{E_{NOCT}\,\tau a}{T_{c\_NOCT} - T_{a\_NOCT}}, \quad (13)$$

where E_{NOCT} is the solar irradiation in case of NOCT, usually 800 W/m^2 – 1,000 W/m^2; T_{a_NOCT} is the ambient temperature in case of NOCT, usually 20 °C; T_{c_NOCT} is the cell temperature in case of NOCT, usually 40–50 °C; and in case of NOCT a wind speed of 1 m/s on the solar cell surface is also assumed [9, 10, 24].

Therefore, based on the equations and considerations described above, a correlation between the cell temperature and the ambient temperature can be established [9, 10, 15, 19, 24]:

$$T_c = T_a + \left(\frac{E(T_{c\_NOCT} - T_{a\_NOCT})}{E_{NOCT}} - \frac{(T_{c\_NOCT} - T_{a\_NOCT}) I_{mpp} U_{mpp}}{0.9 E_{NOCT} A}\right). \quad (14)$$

2.3. Implementing the simulation program

The program is structured into several blocks, which are [2, 3, 8, 12, 17, 20, 22, 24–26]:

- specification of solar cell properties (solar cell data);
- requesting environmental factors (temperature, solar irradiation);
- setting reference values for each variable;
- adjusting the reference values for each variable based on the current temperature and light intensity values;
- solving the implicit equation for the current at the end points of the solar cell within the respective voltage range.

The first four blocks of the program are unambiguous and merely involve substitution into the equations that were described along with the model. To solve the implicit equation of the current, the following are required: create a target function from Eq. (1) (Eq. (15)) and look for the zero value (or root) of this function where I is the variable. Using MATLAB's 'fzero' command the root of a target function can be found rather easily [2, 12, 22, 24]:

$$f = I - \left[I_{ph} - I_0 \exp\left(\frac{q(U + IR_s)}{\gamma k T_c} - 1 \right) \right]. \tag{15}$$

To determine the voltage-current curve of a solar cell, the output current (I) needs to be determined for the entire voltage range 0–U_{oc}. To solve this problem numerically, it is sufficient to define a cycle which repeatedly searches for the root of Eq. (16) at a given resolution (U step), and registers the amperage for that given voltage [2, 3, 8, 10, 15, 17, 22, 24, 27, 28].

Since the behavior of the solar cell's electronic parameters is also investigated during the transient temperature stage, it becomes necessary to use the simulation model in this way as well. During the transient temperature measurements, the illumination is constant [3]. The U_{oc} and the I_{sc} of the unloaded solar cell are recorded with varying temperatures. With the help of the mathematical correlations stated above this phenomenon can easily be described. To be able to do that Eq. (1) just needs to be rearranged for the short-circuit and the open-circuit cases. The equations for the U_{oc} and the I_{sc} can be written as [8, 24]:

$$I_{sc} = I_{ph}, \tag{16}$$

$$U_{oc} = \frac{\gamma k T_c}{q} \ln\left(\frac{I_{ph}}{I_0} + 1 \right). \tag{17}$$

The previously stated correlations can be used to solve the described equations, with which the photoelectric current I_{ph}, and the saturation current I_0 of the diode can be calculated while considering the effect of temperature [2]. The transient temperature calculation method is also built in MATLAB environment. Along with the already requested solar cell properties and irradiation values, the program also requests temperature values, with which it solves Eqs (16) and (17) for each temperature value. This task is feasible by implementing a 'for loop' to the program code. The transient temperate simulating program did not receive a unique graphical interface [2, 8].

As a result of computer simulations, in addition to voltage and current values, theoretical and real power values are also determined. The theoretical performance of a solar cell is calculated from Eq. (18), and the real power of a solar cell is given by Eq. (19) [8].

$$P_{th} = I_{sc} U_{oc}, \tag{18}$$

$$P = IU. \tag{19}$$

During the investigation of the transient phenomenon, the correlation between theoretical power and temperature is determined from Eq. (18). In addition to the voltage-current characteristic of a loaded solar cell, the voltage-power characteristic can also be plotted by the cyclic solution of Eq. (19).

3. THE EXPERIMENTAL COMPOSITION

As a precursor to this research, a standard solar simulator was developed. Requirements for solar simulators are managed by *American Standard for Testing and Materials* (ASTMs) E972 (IEC 60904-9) [1]. The solar simulator implemented in the current research is a standard Class C, so both spatial non-uniformity and temporal non-uniformity are below 10%. The light intensity distribution of our sun simulator has a 9.96% inhomogeneity, which means the device complies with the standard.

The temperature of the solar cell is controlled by a cooling module made using Peltier modules [1]. The temperature of the solar cell is measured by a Voltcraft PL-125-T4 four-channel digital thermometer, furthermore current and voltage measurements are performed by two METEIX MX 59H digital multimeters. Figure 2 shows the experimental arrangements.

This is reasonable as the cell in the investigation area is illuminated by 36 LED units in addition to the 8 halogen lamps. With an average irradiation of 1,000 W/m^2, the cell temperature steadies at 88 °C. The whole investigation is carried out over a period of roughly 20 minutes, since steady-state temperature values are obtained at each of the three measurement points by then.

4. COMPARISON BETWEEN EXPERIMENTAL AND NUMERICAL RESULTS

The results of the simulations are plotted against the experimental results so that the difference between the measured and the simulated values is shown, thus showing the correctness of the simulation. The temperatures recorded during the measurements are used to calculate the temperature transient. Parameters used during the simulations are obtained from the solar cell's product data sheet. Open-circuit voltage, short-circuit current, and theoretical performance are plotted against time/temperature in case of three different heating curves (no cooling, half cooling, full cooling). The graphs show measured and simulated data simultaneously under STCs.

Figure 3 shows that under STC conditions and without cooling the cell surface temperature reached steady state at 70 °C [20]. In case of half cooling, the maximum steady-state temperature of the cell was reduced by 10 °C, and by 18 °C under full cooling. The experiments and simulations were also performed under Non-Standard Test Conditions (NSTCs) conditions, in which case similar results were obtained. Many other researchers received similar results, for example Singh et al. [29], Wood et al. [30] and Malik et al. [31].

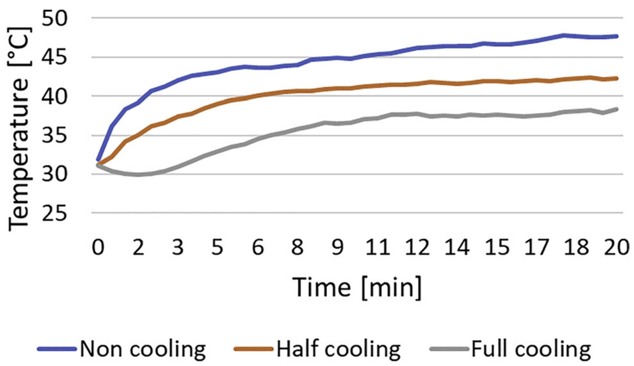

Fig. 3. Temperature versus time

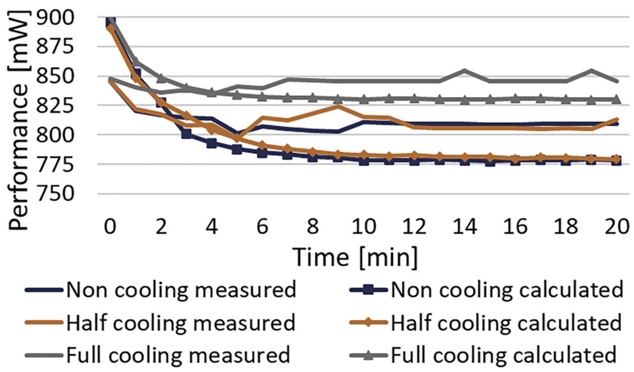

Fig. 4. Short-circuit current versus time

Observing graphs in Fig. 4, it can be concluded that the results of the transient investigations are in good agreement with experimental results [30]. It can be observed in both the simulation and the measurement results, the curves of the chilled and non-cooled solar cell cross each other, just like in case of other researches: Chantana et al. [23], Singh et al. [29] and Malik et al. [31].

5. CONCLUSION

In summary it can be stated that the activity in matter of solar cell simulation and measurement results in a mathematical model based on the study of the relevant literature that can describe the operation of the solar cell. The correct operation of the model implemented in MATLAB was based on the results of our measurements. The model validation was performed by comparing the measured and simulated results. Validation can be said to be successful, but it should be mentioned, that while transient examinations showed excellent agreement, the simulations of the loaded solar cell worked with greater error compared to the measurement. There may be two reasons for this, on the one hand, the measurements have errors as well, and on the other hand the calculations of the loaded solar cell required more complicated solutions and influenced the upshot with larger errors. The main goal of the cooling is to improve the solar cell's energetic efficiency and to increase its lifetime.

The results of the experimental and simulation examinations clearly reflect that the cooling changes the solar cell power in a positive direction, so the basic assumption is correct.

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