Temperature Influence on Conversion Efficiency in the Case of Photovoltaic Cells

Corina MARTINEAC, Mihai HOPÎRTEAN, Gilbert DE MEY, Vasile ȚOPA, Silviu ŞTEFĂNESCU
Technical University of Cluj-Napoca
Utrecht University, Gent University
str.George Baritiu nr.26-28, 400027 Cluj-Napoca, ROMANIA
Heidelberglaan 2, 3584CS Utrecht, THE NETHERLANDS
Sint-Pietersnieuwstraat 41, B-9000 Gent, BELGIUM
Corina.Martineac@eps.utcluj.ro, M.I.Hopirtean@students.uu.nl, Demey@elis.ugent.be, Vasile.Topa@et.utcluj.ro, Silviu.Stefanescu@eps.utcluj.ro

Abstract — **The following paper presents concisely the operation principles of photovoltaic cells and their main parameters. The heat transfer process for a PV cell is described in order to analyze the PV cell temperature variation during operation. The aim of the paper is investigating temperature's influence on the conversion efficiency of solar energy into electricity. Temperature measurements have been done to provide PV cells' actual operation temperatures and also to ease an analysis on their effect on the conversion process.**

Index Terms — **Conversion efficiency, Photovoltaic cells, Photovoltaic cell thermal factors, Solar energy, Solar radiation.**

I. INTRODUCTION

In the past two decades, photovoltaic cells (PV cells) production and demand have rapidly increase due to both the concern of fossil fuels depletion and cleaner, non-polluting ways of energy production. [1] Based on converting solar energy into electricity, photovoltaic modules comply with both requests, having no net CO_2 emissions.

Energy policies throughout the world have had a big impact on solar power plants development, leading to a constant increase in the use of PV technology. However, the main limitation in the power output of photovoltaic cells resides in the conversion efficiency. Physical limitations, such as the available wavelength spectrum for conversion, lead to a maximum theoretical efficiency achievable for each type of photovoltaic cell. Another factor which lowers their efficiency is the cell's operation temperature.

This paper aims at understanding how temperature influences PV cells conversion efficiency. This is done by describing the heating process of a PV cell and the correlation between temperature increase and efficiency drop.

II. PHOTOVOLTAIC CELL FUNCTIONING AND MAIN PARAMETERS

PV cells are semiconductor devices with an internal structure similar to the one of diodes. Several types of junctions have been developed in PV cells manufacturing (single-junctions, heterojunctions, multijunctions, metal-semiconductor junctions, electrolyte-semiconductor junctions); the goal of researching several possibilities of manufacturing is an increase in efficiency and also lowering production costs. This part of the paper describes the functioning of an idealized single-junction PV cell, emphasizing its main parameters and the relation between these parameters and temperature.

The characteristic equation for a PV cell is:

$$I = I_{sc} - I_s \cdot \left(e^{\frac{q \cdot V}{k \cdot T}} - 1 \right) \tag{1}$$

In which I is the current flowing through the cell and Isc is the short-circuit current.

The reverse-bias current, Is, is also temperature dependent, as the following equation describes it [2]:

$$I_s = C \cdot T^3 \cdot e^{\frac{-q \cdot E_g}{k \cdot T}} \tag{2}$$

C being a constant in the previous equation.

Two important parameters of a PV cell can be derived from equation (1): the short-circuit current, Isc, value obtained when the cell's terminals are interconnected, and the open circuit voltage, Voc, which is obtained when the cell's terminals are not connected to an external load.

$$I_{sc} = I \tag{3}$$

$$V_{oc} = \frac{k \cdot T}{q} \cdot \ln\left(\frac{I_{sc}}{I_s} + 1 \right) \tag{4}$$

Figure 1 depicts the I-V curve of a PV cell and also the corresponding power output.

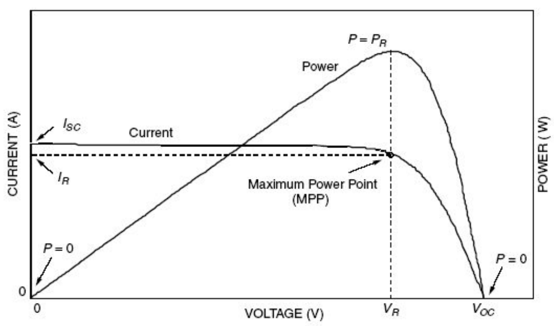

Fig. 1. I-V and P-V curves for an idealized solar cell. [5]

The maximum power delivered by the PV cell has corresponding current and voltage values, I_R and respectively V_R. V_R is the solution of the transcendental equation obtained by derivation of equation (5) with respect to the voltage. The resulting equation (6) is transcendental and its solution can be found by using adequate computer software.

$$P_R = V_R \cdot I_R = V_R \cdot I_{sc} - V_R \cdot I_s \cdot \left(e^{\frac{q \cdot V_R}{k \cdot T}} - 1 \right) \tag{5}$$

$$\frac{dP_R}{dV_R} = 0 \Rightarrow I_{sc} - I_s \cdot \left(e^{\frac{q \cdot V_R}{k \cdot T}} - 1 \right) - V_R \cdot I_s \cdot e^{\frac{q \cdot V_R}{k \cdot T}} = 0 \tag{6}$$

The (conversion) efficiency of a PV cell is defined as the ratio between the maximum power output (peak power output) P_R that can be delivered by the cell under Standard Test Conditions (T=298.16 K, an irradiance P_s=1000 W·m^{-2} and an air mass (AM) 1.5 spectrum.) and the solar irradiance P_S:

$$\eta = \frac{P_R}{P_S} = \frac{I_R \cdot V_R}{P_S} \tag{7}$$

III. HEAT TRANSFER AND PV CELL HEATING

This paragraph describes the heat transfer to which a PV cell is subject under sunlight exposure. For a better understanding of the mechanism, a heat transfer model similar to an electric circuit has been depicted in Figure 2. The general equations for heat transfer are applied to the specific case of the cell and in accordance to the model, resulting in the equation which describes the cell's temperature variation over time.

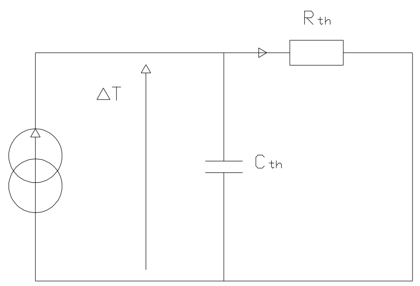

Fig. 2. Heat transfer model for a PV cell.

The model assumes a constant source of irradiance (the Sun) which is equivalent to a current source. This delivers heat to the PV cell, represented in the form of a thermal resistance (the property of increasing the temperature when exposed to a heat flux) and a thermal capacitance (the property of storing heat). The potential difference is thus replaced by the temperature difference ΔT which is the difference between the cell's temperature T and the ambient temperature T_0: $\Delta T = T - T_0$.

Heat transfer in the case of a PV cell is done through thermal radiation and convection, the effect of heat conduction being limited and thus is not accounted for in the present paper. Having this in mind, the thermal resistance of a PV cell is [2]:

$$R_{th} = \frac{1}{\left(h_{conv} + h_{rad}\right) \cdot A_s} \tag{8}$$

The thermal capacitance of the PV cell is defined by the following relation [2]:

$$C_{th} = c_v \cdot \rho \cdot d \cdot A_s \tag{9}$$

The thermal time constant for the PV cell heating is the necessary time for the cell's temperature to reach 63.2 % of the equilibrium temperature and is defined by [2]:

$$\tau_{th} = R_{th} \cdot C_{th} \tag{10}$$

Having all the required parameters and the model, the equation which describes the cell's temperature's variation over time due to heat transfer is:

$$C_{th} \cdot \frac{d(\Delta T(t))}{dt} + \frac{1}{R_{th}} \cdot \Delta T(t) = P_s \tag{11}$$

Equation (12) is the result of introducing the time constant in equation (11):

$$\frac{d(\Delta T(t))}{dt} + \frac{1}{\tau_{th}} \Delta T(t) = \frac{P_s}{C_{th}} \tag{12}$$

The solution of the differential equation (12) is given by:

$$\Delta T(t) = P_s \cdot R_{th} + C \cdot e^{-\frac{t}{\tau}} \tag{13}$$

Taking into account that ΔT(t) stands for the variation in time of the difference between the cell's temperature and the ambient temperature, equation (13) can be rewritten:

$$T(t) = T_0 + P_s \cdot R_{th} + C \cdot e^{-\frac{t}{\tau}} \tag{14}$$

The equilibrium temperature is the maximum temperature reached by the PV cell and it can be found by converting (14) into a limit with respect to time:

$$T_{eq} = \lim_{t \to \infty} T(t) = T_0 + P_s \cdot R_{th} \tag{15}$$

IV. THE HEAT TRANSFER PROCESS: MEASUREMENTS AND CALCULATIONS

A PV module made of poly-crystalline silicon cells manufactured by AEG Telefunken has been used for measurements.

All values used for calculations are summarized in Appendix A.

When calculating the thermal resistance of the module, it is of high importance to take into account that only one side of the module is being exposed to sunlight. A value of R_{th}=0.05 K·W^{-1} has been found. For calculating the thermal capacitance of the module, attention must be paid as the silicon layer is lain between two layers of glass, so a factor 2 must be applied to equation (9). The thermal capacitance value is C_{th}=9600 J·K^{-1}. The thermal time constant is according to equation (10) τ_{th}=480 s. By substituting these values in (14) we can find the equation which describes the module's temperature variation (in degrees Celsius) over time:

$$T(t) = 62 + C \cdot e^{-\frac{t}{480}} \qquad (16)$$

From equation (16) and by placing the condition $t \to \infty$ we can see that the maximum temperature of the module under idealized conditions (no ventilation) would be 62 ºC.

The module was exposed to sunlight and a Steinel ThermoCheck infrared thermometer was used to record the temperature variation of the PV module with a time step of 15 s. The graph representing this variation is presented below, in Figure 3.

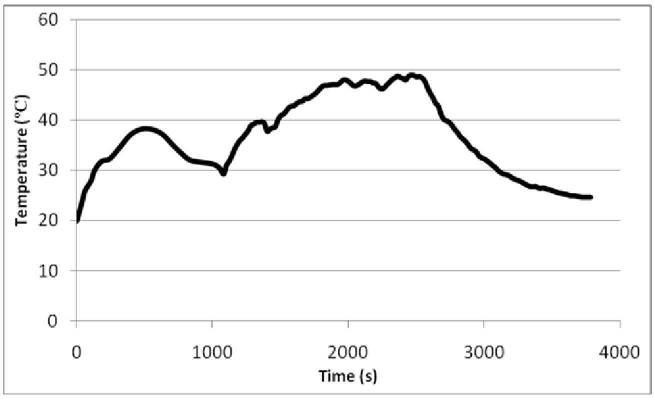

Fig. 3. Temperature variation of the PV module.

The graph can be divided into four sections: the first one in which the temperature rises steeply up to about 38 ºC, the second section in which due to nebulosity the module's temperature decreases down to almost 29 ºC, the third section depicts the temperature increase under clear skies and a variation in its final points, variation which occurs due to ventilation; natural ventilation (wind) is also the reason for which the maximum achievable temperature of 62 ºC is not reached (the maximum temperature reached was 49 ºC). The last section depicts the module's cooling after removing it from sunlight exposure; the final temperature recorded is 24.7 ºC.

Using adequate software for modeling the temperature variation, the thermal time constant can be calculated. Two sections of the graph, in which the heat transfer process was not disturbed by external factors, were used for this: the first section in which the temperature rises giving a result of τ_{th1}=442 s and the last section in which the module cooled gave a result of τ_{th2}=461 s. The difference between these two values for the thermal time constant and between these values and the value of the theoretical time constant previously calculated is explained by the simplifying assumptions that were made in treating the heat transfer in the present paper: no ventilation (which is, of course, not occurring in real life) and no heat conduction.

V. EFFICIENCY OF CONVERSION

For the measurement of I_{sc} and V_{oc} the Standard Test Conditions were not fulfilled; all conditions and values necessary for calculations are summarized in Appendix A. The values found were I_{sc}=2 A and V_{oc}=0.5 V. The reverse-bias current must be calculated; the value was found to be $I_s=1.226 \cdot 10^{-9}$ A.

By substituting these values in equation (1) and varying the temperature between 20 ºC and 75ºC a set of I-V curves was found; this is depicted in Figure 4. The temperature for each curve is (from left to right): 75 ºC, 60 ºC, 40 ºC, 25 ºC and 20 ºC. From these values, only the last three were recorded during temperature measurement; the first two are used for further emphasizing temperature's influence on efficiency.

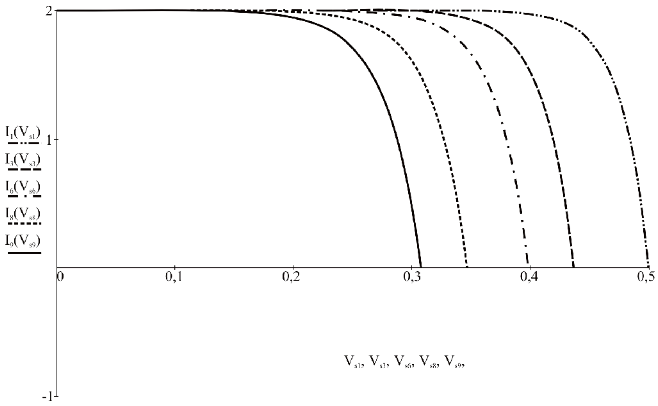

Fig. 4. Set of I-V curves for a polycrystalline silicone cell. (Values on X axis in Volts; values on Y axis in Amperes)

From this graph, it can be seen that the value of V_{oc} increases with the decrease of temperature; or interpreting it differently, the value of V_{oc} decreases when the cell's temperature increases. Figure 5 depicts a set of P-V curves for the same set of temperatures and the implications on the peak power output are visible. The curves result from equation (17) in which I was substituted from (1):

$$P = V \cdot I = V \cdot I_{sc} - V \cdot I_s \cdot \left(e^{\frac{q \cdot V}{k \cdot T}} - 1 \right) \qquad (17)$$

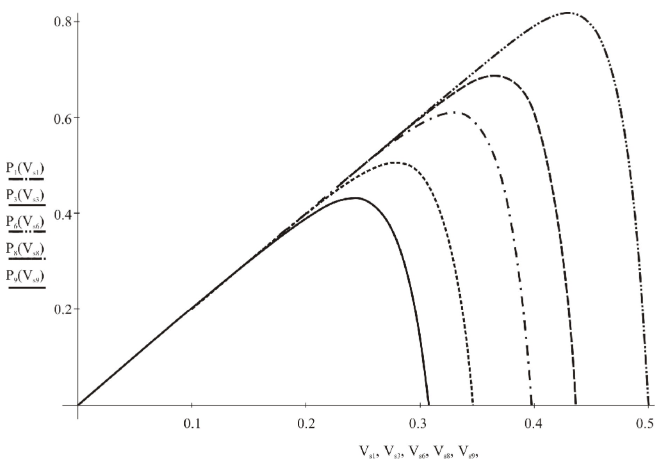

Fig.5. Set of P-V curves for a poly-crystalline silicon cell. (Values on X axis in Volts; values on Y axis in Watts)

The peak power output of the PV cell decreases (from right to left) as the temperature increases. The effect on the conversion efficiency is summarized in Table 1. This was done considering a constant irradiance (also taking into account the cell's surface area A_s) and using the calculated values for the peak power output (equations (5) and (6)).

TABLE I. VALUES FOR THE MODULE'S MAIN PARAMETERS AT THE CONSIDERED SET OF TEMPERATURES

t [ºC]	V_R [V]	I_R [A]	P_R [W]	η [%]
20	0.379	1.876	0.711	8.46
25	0.366	1.871	0.685	8.15
40	0.329	1.845	0.607	7.22
60	0.279	1.810	0.505	6.01
75	0.242	1.777	0.43	5.12

Figure 6 plots the drop of the module's efficiency against the temperature. It can be seen that there is a linear trend in the drop, so a linear regression was used to find a relation between the efficiency and the temperature. The equation displayed in the graph suggests that at t=0 ºC the efficiency would be 9.66 % with a drop of 0.0608 % for each increase of 1 ºC in the module's temperature.

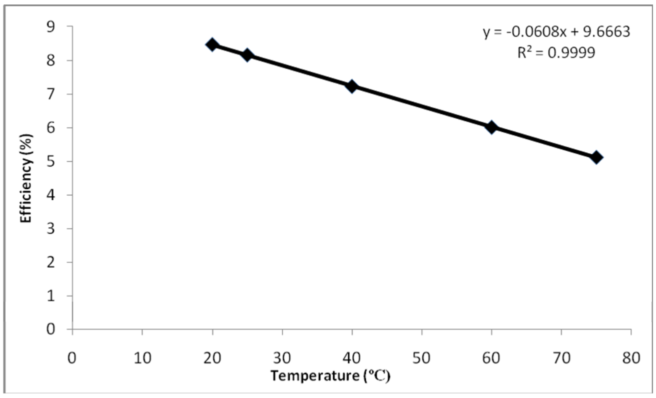

Fig. 6. Conversion efficiency variation with temperature.

VI. CONCLUSIONS

The simplifying assumptions regarding the heat transfer mechanism made in this paper led to differences between the theoretical results and the experimental measurements. However, the differences are within reasonable limits.

The theoretical maximum temperature (62 ºC) was not reached during measurements; the module's maximum recorded temperature was 49 ºC. The theoretical thermal time constant of the cell was calculated to be 480 s; the calculated values from the experimental data were 442 s during the heating process and 461 s during the cooling process of the module.

As temperature increases, the value of the open-circuit voltage drops. Consequently, the maximum power delivered by the module drops while the irradiance can remain at a constant value. The results show that the efficiency for the considered cell would be 9.66 % at t=0 ºC with a drop of 0.0608 % for each increase of 1 ºC in the module's temperature.

APPENDIX A

Symbol	Description	Value	Unit
K	Boltzmann constant	$1{,}38\cdot10^{-23}$	$m^2\cdot kg\cdot s^{-2}\cdot K^{-1}$
E_g	Energy bandgap	-	V
q	Elementary charge	$1.6\cdot10^{-19}$	C
T	Absolute temperature	-	K
T_0	Ambient temperature	293.15	K
P_s	Irradiance	840	$W\cdot m^{-2}$
$h_{conv}+h_{rad}$	Global heat transfer coef. glass	10	$W\cdot m^{-2}\cdot K^{-1}$
c_v	Specific heat	-	$J\cdot kg^{-1}\cdot K^{-1}$
ρ	Glass density	-	$kg\cdot m^3$
d	Glass thickness	0.002	m
ρd	Specific volumetric heat	2.4	$MJ\cdot m^{-3}\cdot K^{-1}$
A_s	Cell surface area	0.01	m^2

REFERENCES

[1] K. Blok, Introduction to Energy Analysis, Techne-Press, 2007
[2] Y.A. Cengel, Introduction to Thermodynamics and Heat Transfer, 2nd Edition, McGraw-Hill, 2008
[3] S. Darie and I. Vadan, Producerea, Transportul si Distributia Energiei Electrice. Vol. I Instalatii pentru Producerea Energiei Electrice, UTPRESS, 2000
[4] A. Luque and S. Hegedus, Handbook of Photovoltaic Science and Engineering, John Wiley & Sons, 2003
[5] G. M. Masters, Renewable and Efficient Energy Power Systems, John Wiley & Sons, 2004
[6] C. J. Winter, Solar Power Plants. Fundamentals, Technology, Systems, Economics, Springer-Verlag, 1991