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# MATHEMATICAL MODELING AND SIMULATION OF PHOTOVOLTAIC CONVERTER OPERATION WHEN VARYING DIFFERENT PARAMETERS

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Abstract: The paper presents a method of mathematical modelling of a solar converter using the results of full-scale testing. The advantages of analytical modelling method applied to photovoltaic systems are also presented; this is because the model parameters are directly measurable by data acquisition from the photovoltaic field consisting of photovoltaic cells type Z - (mono-crystalline photovoltaic). The model parameter also includes both the photovoltaic cell characteristics as a device (forming the photovoltaic field) and the temperature influence on the photovoltaic field performance. The results of the photovoltaic model numerical simulation (PV) to the major parameters conversion variation can also be used to design and assess the performance of low and medium - power photovoltaic systems operating in single regime (to supply the home appliances).

Keywords: photovoltaic cell, photovoltaic field, solar radiation, incidental angle.

## 1. INTRODUCTION

Since the photovoltaic conversion elements are still costly, the present researches are oriented to low and/or medium power photovoltaic systems which are capable to provide energy in single regime. In order to determine the operation parameters of a photovoltaic module it is necessary to meet the testing conditions of the real/external environment where this is positioned / located. Studies (King, 1997), (Whitaker, 1997) have shown that the best method to assess the performance of a photovoltaic module is the SOC (Specified Operating Conditions) method and enables performance estimation under any running conditions.

## 2. ANALYTICAL MODEL TO ESTIMATE THE PERFORMANCE OF A PHOTOVOLTAIC FIELD BY SOC METHOD

The photovoltaic module Z-50186 (Mono-crystalline photovoltaic) was subject to modelling by means of a set of equations (Dunea, 2002) which take into account the main parameters likely to affect its operation/performance. The most important operating parameters are expressed as:

(1) $$E_u = I_{SC}(E, T_C, AM_a, AI) / I_{SC-0}$$

(2) $$I_{mp} = C_0 + E_u[I_{mp0} + \alpha_{mp}(T_C - T_0)]$$

(3) $$V_{OC} = V_{OC-0} + C_1 \ln(E_u) + \beta_{VOC}(T_C - T_0)$$

(4) $$V_{mp} = V_{mp-0} + C_2 \ln(E_u) + C_3[\ln(E_u)]^2 + \beta_{Vmp}(T_C - T_0)$$

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$$(5)\quad I_{SC} = (E/E_0)\cdot f_1(AM_a)\cdot f_2(AI)\cdot \cdot [I_{SC-0} + \alpha_{SC-0}(T_C - T_0)]$$

where: E – sun/solar radiation in the photovoltaic field plane which depends on its incidental angle solar radiation [w/m$^2$]; $E_u$ – useful solar radiation (effective); $E_0$ – reference solar radiation, considering 1000 W/m$^2$; $f_1(AM_a)$ – empirically found function expressing the solar radiation spectrum influence on the photovoltaic conversion; $I_{mp}$ – the current provided by module PV at maximum power; $V_{mp}$ – voltage across the PV terminals corresponding to current $I_{mp}$; AI – solar radiation incidental angle to the photovoltaic module plane [degree]; $AM_a$ – absolute value of the air mass; $f_2(AI)$ – empirically found function expressing the influence of the solar radiation angle on the photovoltaic conversion; $T_C$ – temperature of the photovoltaic cell inside a photovoltaic module (PV), [$^o$C]; $T_0$ – reference temperature of a photovoltaic cell inside a PV [$^o$C]; $\alpha_{SC}$ – temperature coefficient of the current provided by PV under short circuit conditions [A/$^o$C]; $\alpha_{mp}$ – temperature coefficient of the current provided by PV under maximum power conditions [A/$^o$C]; $\beta_{VOC}$ – temperature coefficient of the current generated by PV under empty function [V/$^o$C]; $\beta_{Vmp}$ – temperature coefficient of the voltage generated by PV under maximum power transfer [V/$^o$C]; $C_i$ (i=0,…,3) – regression coefficients.

The model of the photovoltaic field can be validated by numerical simulation if the initial values of the main parameters are known. These initial values used in researches (Dunea, 2002) are:

$$I_{SC-0} = I_{SC}(E, T_C, AM_a, AI);\ AM_a = 1{,}5;\ AI = 0^o$$

$$I_{mp-0} = I_{mp} = I_{mp}(E_0, T_C);\ E_0 = 1000W/m^2$$

$$V_{0C-0} = V_{0C}(E_0, T_C); T_C = T_0[^oC]$$

$$V_{mp-0} = V_{mp}(E_0, T_C)$$

Equations (1), (2), (3), (4) express the direct dependence of the parameters characterizing the photovoltaic conversion on the PV module technological performance. The effect of the spectral distribution and the solar radiation incidental angle can be compensated for by adjusting the current $I_{SC}$ I from equation (1).

The effective solar radiation comprises the spectral components such as wave length of the solar spectrum which the photovoltaic cells convert into electrical energy.

## 3. ESTIMATION OF THE PHOTOVOLTAIC MODULE (PV) PERFORMANCE MODEL TO ESTIMATE THE PERFORMANCE

The performance of a photovoltaic field strongly depends on an as accurate as possible measurement of the PV module performance. This implies measurements and calculations made in the sequence given below:

### *3.1. Estimation of the solar radiation*

The total solar radiation, also called global incidental radiation, has three components illustrated in figure 1.

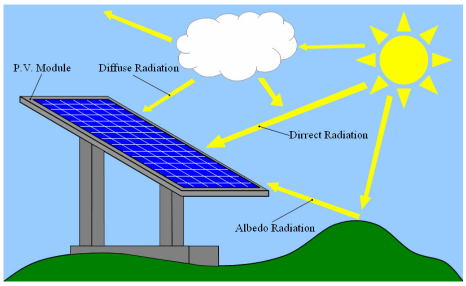


Fig.1. Distribution of the solar radiation into atmosphere

The direct solar radiation is that part of the global radiation which is not reflected or spread. Diffuse solar radiation is part of the global radiation which is spread by the clouds and atmosphere particles but reaches the PV module surface; Albedo radiation - part of the global radiation which reaches the PV module surface due to the ground reflection of some parts of the direct or diffuse radiation.

The standard value of the global incident solar radiation at ground level is considered 1000 w/m$^2$. The spectral distribution of this standard radiation according to (Castaner, *et al.,* 2002) is 1,5 AM (global air mass) which implies that the solar rays forming together the direct radiation run 1,5 times the thickness of the Earth atmosphere. To design the photovoltaic fields (determining the number of PV modules in the field), the necessary part generated by the PV field being known, it is necessary to know the solar radiation integrated over a period of time, also called daily sunny. According to researchers (Quaschning, *et al.,* 1997) the daily sunny per area unit above the earth atmosphere is give only by the direct solar radiation and it is calculated by the relation:

$$(6)\quad B_0 = \frac{24}{\pi}\cdot S\cdot\left[1+0{,}033\cdot\cos\left(2\pi\frac{n_z}{365}\right)\right]\cdot \cdot(\cos\varphi\cdot\cos\omega_s + \omega_s\sin\varphi\cdot\sin\delta)$$

where: S – solar constant = 1.367 kw/m$^2$; $n_z$ – number of days in a year (from 365); φ – latitude (at which module PV is located); $\delta$ – solar declination; $\omega_S$ – sun hour angle.

The clarity index is calculated (attenuation degree of the solar radiation upon breaking through the atmosphere) for the geographic location of PV module, in a month as established for the experiment, acc to the relation:

$$(7)\quad K_T = R_G / B_0$$

Where $R_G$ is the global radiation measured experimentally in the horizontal plane of PV module. Diffuse solar radiation is approximated, as per (Whitaker, 1997), by:

$$(8)\quad R_d = R_G(1-1{,}13K_T);\ [kwh/m^2]$$

$$(9)\quad R_D = G_G - R_d;\quad [kwh/m^2]$$

The Albedo solar radiation is negligible.

*3.2. Determining the solar incidental angle*

The short-circuit current $I_{SC}$ of the PV module depends on the solar incidence by function $f_2$ while the solar incident angle (AI) is calculated, as in (Whitaker, 1997), by relation:

$$(10)\quad AI = \cos^{-1}[\cos(T_m)\cdot\cos(z_s)+\sin(T_m)\sin(z_s)\cos(AZ_s - AZ_m)]$$

in which: AI – the solar incidence angle; $T_m$ – PV module inclination angle with respect to the horizontal plane at [degree]; $Z_s$ – sun zenith angle [degree]; $AZ_m$ – PV module azimuth (North = $0^o$, East = $90^o$); $AZ_s$ – sun azimuth (North = $0^o$, East = $90^o$);

Function $f_2$ (AI) is calculated by relation:

$$(11)\quad f_2(AI) = \frac{I_{SC}(AM_a,T) - C_2\cdot E_{dif/1000}}{C_1\cdot E_{dir/1000}\cdot\cos(AI)}$$

For a typical PV module, the dependence $f_2$(AI) (expressed in relative values) on the incidental angle appears, acc. to (Dunea, 2002), as illustrated in figure 2. It can be noticed that for incidental angles within the interval (25 - 45) the values $f_2$(AI) are max. and cause an increase in the short-circuit current of PV module.

The PV module short-circuit current is determined by equation (5) where the value of function $f_2$ (AI) from equation (11) is introduced:

$$(12)\quad T_c - T_r = \frac{V_{oc}/N - V_{ocr}/N - (nkT_c/q)\cdot\ln(I_{sc}/I_{scr})}{\beta_{voc}}$$

where: N – total number of PV cells forming the PV field; $I_{SC}$ – short-circuit current generated by the field PV, [A]; $I_{SCr}$ – value of the short-circuit current $I_{SC}$ at reference temperature, [A]; $V_{ocr}$ – value of the idle voltage at reference temperature, [V]; $T_C$ – PV cell temperature inside the module, [k]; $T_r$ –Tr- reference temperature, [k]; $\beta_{voc}$ – temperature coefficient for $V_{oc}$ given for a single PV cell, [v/$^o$C]. n = 1, factor associated with Si diodes; K–Boltzman constant.

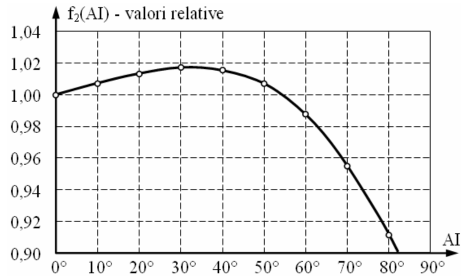


Fig.2. The incidental angle, AI [degree]

## 4. MODEL VALIDATION BY NUMERICAL SIMULATION USING A LOW-POWER PHOTOVOLTAIC CONVERTER

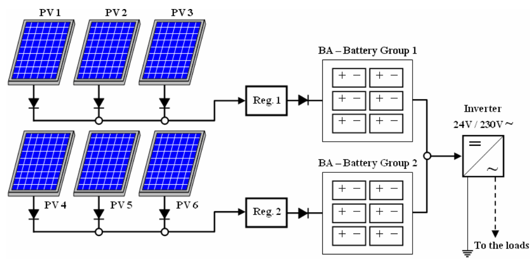


Fig.3. The structure of the photovoltaic converter

The rated (nominal) voltage at the maximum power transfer point, 28V, and a current of 16A. The PV modules have been located at 80 height, their inclination being 45 degree, South – East orientation, and their measured incident global radiation, 735 W/m$^2$. By substituting the numerical values in eqs. (2) and (4), under STC (Standard Test Conditions), the values of the PV field parameters were obtained:

$$(13)\quad I_{mp} = 12{,}685\,E_u$$

$$(14)\quad V_{mp} = 25{,}46 - 0{,}005\,[\ln(E_u)]^2 + 0{,}092\ln(E_u)$$

Figures 4 and 5 illustrate the simultaneous variations (continuous line) and measured (*) of parameters $I_{mp}$ and $V_{mp}$ for the given relative values of the useful radiation $E_u$ and ln ($E_u$) respectively. From figures 4 and 5 it can be seen that for a measured value of the useful solar radiation, $E_u$ = 735w/m$^2$ (experiment performed in April 2007), the power generated by a converter PV is $P_{mp1} \cong 216$W, while the maximum power ($P_M \cong 322$W) is obtained when the useful radiation reaches the value , $E_u$ = 1000 W/m$^2$. The results obtained by analytical modeling described above have not taken into account the effects of the variation of some essential parameters such as, the serial resistance of the PV converter, the shunt resistance and the temperature of the working environment. Below are studied the effects of the parameter variation on the converter generated power by numerical simulation using the model *PSpice*.

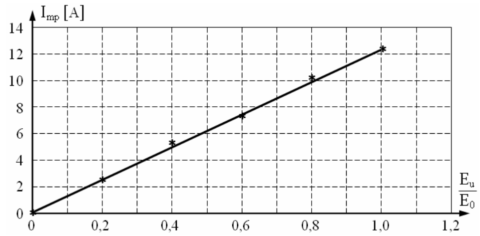


Fig.4. Curent $I_{mp}$ vs. $E_u$

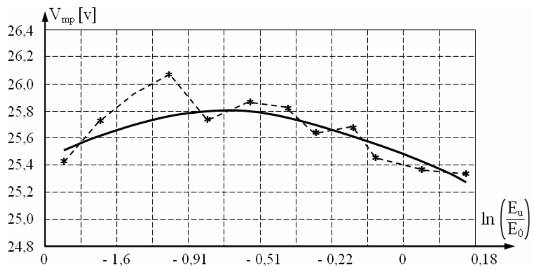


Fig.5. Voltage $V_{mp}$ vs. $\ln(E_u)$

## 5. THE EFFECTS OF THE MAIN PARAMETERS VARIATION ON THE PV CONVERTER GENERATED POWER

### *5.1. Effects of the serial resistance*

$$(15)\quad I_{SC} = L_L - I_0 \cdot \left[\exp\left(I_{SC} R_S / n \cdot v_T\right) - 1\right]$$

with numerical values which known: $I_{SC}$ – short circuit for Rs = 0; n - number of PV cell; $v_T$ – potential at the working temperature; $I_L$ – current under charge; $I_0$ – current at idle operation with known values. It can be noticed that for serial resistance values higher than 0,01 Ω, the short-circuit current is kept constant, while for higher values ($R_S \leq$ 0,1Ω) the short-circuit values and the filling factor decrease unacceptably thus decreasing drastically the PV module generated power. The idle operation voltage ($v_0$) is kept constant, because all the characteristics I(v) meet in point $v_0$ ( $v_0 \cong 47\text{V}$ ).

### *5.2. Effects of the working temperature*

$$(16)\quad J_0 = BT^{XTI} \cdot e^{-E_g/kT}$$

The effects of the temperature T on the PV module generated power can be estimated by numerical simulation if the *PSpice* model is applied to equation (16) where: B – a constant independent from temperature, XTI is a *PSpice* parameter independent from temperature and $E_g$ is a parameter known from the semiconductor material (the energy for the forbidden band). Figure 7 gives the characteristics I(V) affected by the variation of the working temperature.

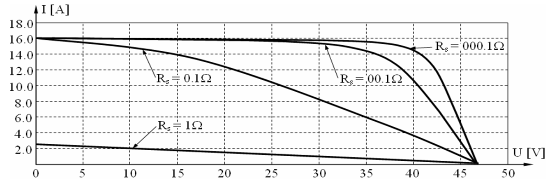


Fig.6. Effects of the serial resistance ($R_s$) on the characteristics I(v).

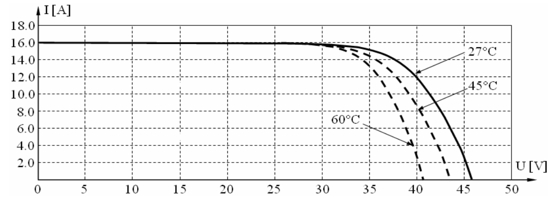


Fig.7. Effects of the working temperature on the characteristics I(V)

## 6. CONCLUSIONS

Estimation of the performance of a PV converter by means of analytical model is closer to reality in spite of the large amount of work required.

The main parameters that significantly modify the PV converter generated power are: useful radiation ($E_u$), the radiation incident angle (AI), orking temperature (T), serial resistance (R) of PV converter.

Simulation of the operating regimes by *PSpice* method, with a PV converter, allows for the estimation of its performance with low time consumption – when a low power PV field for domestic consumers/appliances is designed.

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