Development of Photovoltaic Module using Matlab Program

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ABSTRACT: *With the help of the semi-empirical approach we have developed a photovoltaic module using Copper Indium Selenide. We have prepared the coding with matlab and checked the simulation data with real testing data using the input given by two different producers. The outcome produces the acceptance as it is able to predict the new voltage and power at a high irradiance and the voltage values are acceptable. We prove that this model is used very successfully and can to use to measure the power generation in the live scenario.*

Keywords: Copper Indium Gallium Selenide (CIGS) Photovoltaic Modules, Behavioural Model

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1. Introduction

Copper indium gallium selenide (CIGS) solar cells are extensively introduced to photovoltaic market. Their advantages include relatively high efficiency (12-15%) low fabrication costs (e.g. small number of materials used and small number of low temperature processes). The solar cells efficiency is determined by their composition. The I-III-VI CIGS is an alloy of copper indium diselenide (CIS) and copper gallium diselenide (CGS). This means that the semiconductor band gap varies from 1.0 eV for CIS to about 1.65 eV for CGS. The alloy has high absorption coefficient of solar irradiation, hence a thinner film is required (1-2μm) compared to other semiconductor materials. CIGS is one of the three main thin film photovoltaic technologies, and the other two are cadmium telluride (CdTe) and amorphous silicon. It is possible to fabricate thin films of CIGS to make them flexible and ready for deposition onto flexible substrates. In contrast to amorphous silicon technology, that is high temperature, the CIGS technology is low temperature and it is constantly improved. This will lead to higher production efficiency and lower price for the panels. For this reason, many manufacturers adopted this technology. In addition, many customers prefer this type of solar panels for mounting on roofs and building facades.

Shortcomings of CIGS cells include their lower efficiency (12 - 15%) compared with Si-based cells. With technology improvement, the efficiency is expected to increase up to 23% [1]. This is approximately 1/3 of the theoretic maximum of 28-30% efficiency for CIGS solar cells. At module/panel level the CIGS efficiency is ~ 17% [2], which can be circumvented by better design of cells and modules.

Theoretical analysis of CIGS cells relies on modified models of CdTe solar cells [3] because the structure of CIGS and CdTe cells is similar. One diode and two diode equivalent circuits could be used for modeling the dependence of I-V on temperature and illumination [4].

Since the one diode or two diode models do not describe well the efficiency of CIGS modules, behavioral model for quick estimation of efficiency and energy performance of a given module is developed. In practice, we should quickly and easily estimate the behavior of commercial CIGS solar module in real conditions (ambient temperature and irradiance).

2. Model and Equations

A simplified behavioral model for quick estimation of CIGS solar module in real conditions is presented. The model consists of semi-empirical equations coded in Matlab [5]. Block-diagrams of solar module are shown in Figure 1.

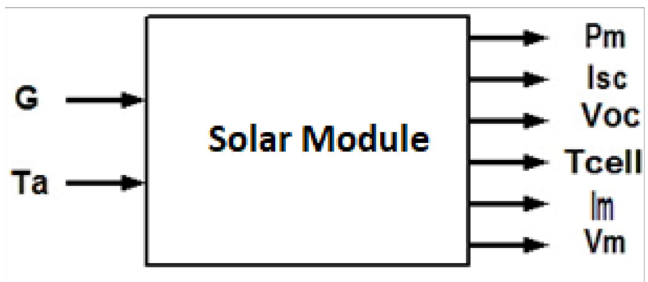

Figure 1. Solar module block-diagram

The model data input is solar irradiation (G) and ambient temperature (Ta). We are also using data from manufacturer references such as open circuit voltage (Vocr), short circuit current (Iscr), under standard testing conditions (STC), etc.

The objective is to determine the solar module parameters for short circuit current (Isc), open circuit voltage (Voc), power (Pm) at maximum power point (MPP), cell temperature (Tcell), current at MPP (Im), voltage at MPP (Vm). The short circuit current equation is derived from the standard diodemodel taking into account the radiation effect and temperature effect:

$$Isc = (Jscr*A*G/1000) + (DIFJscT)*(Ta - Tr) \tag{1}$$

where Jscr - current density, A - area of the module, DIFJscT - temperature coefficient of short circuit current, Tr - reference temperature.

$$Tcell = ((NOCT\ 20)*G/800) + Ta \tag{2}$$

where NOCT nominal operating conditions temperature.

Different equations can be used for Voc. Most of them show that Voc is proportional to the thermal potential *Vt*, but non-ideality factor (n) need to be accounted for as well as the voltage temperature coefficient [V/ °C] (DIFVocT):

$$Voc \sim n*(DIFVocT)*Vt \tag{3}$$

The output results do not fulfil the standard deviation requirements. Hence, the next semi-empirical equation is derived:

$$Vocc = \log((Isc)/(Iscr)) \tag{4}$$

PERFORMANCE AT STANDARD TEST CONDITIONS (1000 W/m2, 25˚C, AM 1.5 G SPECTRUM)							
SOLIBRO		Data	model	Data	model	Data	model
Minimum Power *Pm*	[W]	115	115,02	125	124,95	135	134,96
Short Circuit Current *Isc*	[A]	1,75	1,75	1,78	1,78	1,81	1,81
Open Circuit Voltage *Voc*	[V]	97,3	97,3	100,2	100,2	102,6	102,8
Current at MPP *Im*	[A]	1,49	1,47	1,56	1,57	1,63	1,61
Voltage at MPP *Vm*	[V]	77,2	77,2	80,1	80,1	82,8	82,8
PERFORMANCE AT NOMINAL MODULE OPERATING TEMPERATURE (800 W/m2, NMOT, AM 1.5 G SPECTRUM)							
Minimum Power *Pm*	[W]	85,6	85,1	92,8	92,7	100,6	100,4
Short Circuit Current *Isc*	[A]	1,4	1,42	1,43	1,44	1,45	1,44
Open Circuit Voltage *Voc*	[V]	91,3	91,8	94,1	94,7	96,5	97,1
Current at MPP *Im*	[A]	1,19	1,2	1,24	1,27	1,3	1,29
Voltage at MPP *Vm*	[V]	71,9	71,3	74,8	74,3	77,4	77,3

Table 1. Measured Data (Provided By The Manufacturer) Vs. Simulated Data Of Solibro Modules With 115, 125 And 135 Wp

$$Voc = Vocr + n*(DIFVocT)*Vocc*(Vt*(Ta + 273)) \quad (5)$$

The *vo* parameter below is the normalized value of the open circuit voltage to the thermal potential *Vt.* The value of the fill factor for the ideal solar cell without resistive effects *FFo* is

$$FFo = (vo - \log(vo + 0.72))/(1 + vo) \quad (6)$$

The series resistance *Rs* can be calculated from the fill factor:

$$Rss = (Vocr/Iscr) \quad (7)$$

$$rs\_znam = Iscr.\string^2 \quad (8)$$

$$Rs = Rss - (Pmr/(FFo*rs\_znam)) \quad (9)$$

In reality, the series resistance is also affected by irradiation and temperature. The current at MPP is calculated in the same manner as *Isc*:

$$Im = Imr*(G/Gr) + DIFJscT*(Ta - Tr) \quad (10)$$

For the voltage at MPP is used:

$$Vmro = log(Im/(Imr)) \quad (11)$$

$$Vm = Vmr + Vmro.*(Vt*(Tcell + 273)) \quad (12)$$

From here for fill factor FF: is obtained the following

$$Fm = Vm.*Im \quad (13)$$

$$Fsoc = Voc.*Isc \quad (14)$$

$$FF = Fm/Fsoc \quad (15)$$

Finally the maximum output power *Pm* is

$$Pm = Vm.*Im \quad (16)$$

3. Results and Discussion

The model with data from SOLIBRO SL2 CIGS THINFILM MODULE, Generation 2.1 | 115-135 Wp [6] is tested first. The model is verified for three panels with power at MPP for 115, 125 and 135 Wp respectively; these panels operate at standard test conditions (1000 W/m^2, 25^0 C, AM 1.5 G SPECTRUM) and at nominal module operating temperature (800 W/m^2, NMOT, AM 1.5 G SPECTRUM). The area of the three panels is equal to 0.94 m2. The results are in Table 1.

The results from Table 1 clearly show that the model well describes the behavior at STC and NOCT. The accuracy for current, voltage, and power is under 1%. Unfortunately, the manufacturer has given insufficient information for module behavior at different temperatures and irradiation - only IV characteristic for irradiation of 1000, 500 and 200 W/m^2 and 25 and 50^0 C. We tested the model at these conditions and obtained good description for the current at different conditions but poor description for voltages at low irradiation.

In Table 2 the variation of voltage at different temperatures and irradiations is shown.

SOLIBRO 135Wp	Tcell= 25			Tcell = 50		
G [W/m^2]	data [V]	model [V]	error %	data [V]	model [V]	error %
1000	102,6	102,8	0,19	96	102	6,25
500	99	88	-11,11	91	86	-5,49
200	93	67	-27,96	85	64	-24,71
average			-12,96			-7,98

Table 2. Voc Vs. Irradiation of Solibro 135 Wp Module

In Table 2 is seen that the model underestimates the voltage at low irradiation but the average error at different temperatures is between 8 13%., which is close to the tolerance given by the manufacturer (10%) [6]. As expected, the power is also underestimated.

For better verification of the model, other data sheets are used SOLAR FRONTIER [7] (SF170-S 170 W Module with area of 1.23 m^2). Experimentally obtained characteristics for the current, voltage, and power at different irradiation are shown in Figure 2. In Figure 3 we show the simulated dependence of Pm on irradiation.

In Table 3 are psoted the results of manufacturer provided data, the simulated model data and the accuracy of simulation. Similarly to the previous simulations, the model well describes the current, voltage and power for high values of irradiation but the accuracy for the voltage and power worsens for low values of irradiation.

The model well describes the values for the current at 1000 W/m^2 irradiation - the error is 0%. A small increase of the error at low irradiation values is observed - 2.22%. The averaged error is under 1%, which is much less than the 10% tolerance given by the manufacturer.

In the simulation results for the voltage vs. irradiation, it is observed the same dependence as in the case of SOLIBRO 135Wp module the error increases with decreasing the irradiation. At 400 W/m^2 the irradiation reaches maximum deviation for the voltages 5%. Nevertheless, we still remain in the range of the manufacturer tolerance of 10%.

It is reasonable to expect that the accuracy of the power vs. experimental data will be maximal. At irradiation of 400 W/m^2 the accuracy is 15%. The average accuracy for the power is 7.23%, which is in the range of manufacture provided tolerance of 10% [7]. The same model was applied for simulation of polycrystalline PV modules and the calculated accuracy was in the same range [8].

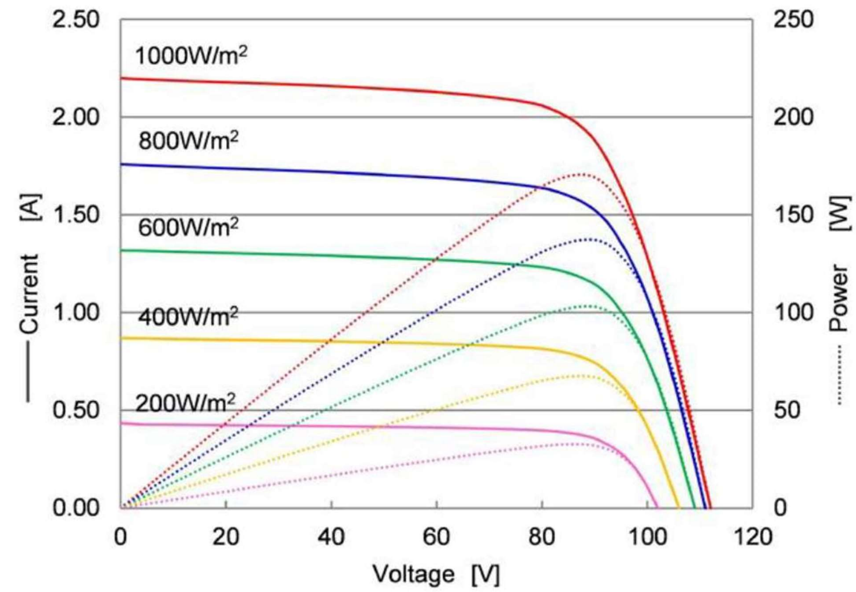

Figure 2. Experimental data (manufacturer data) *I-V* and *Pm-V* characteristics dependent on irradiation *G*

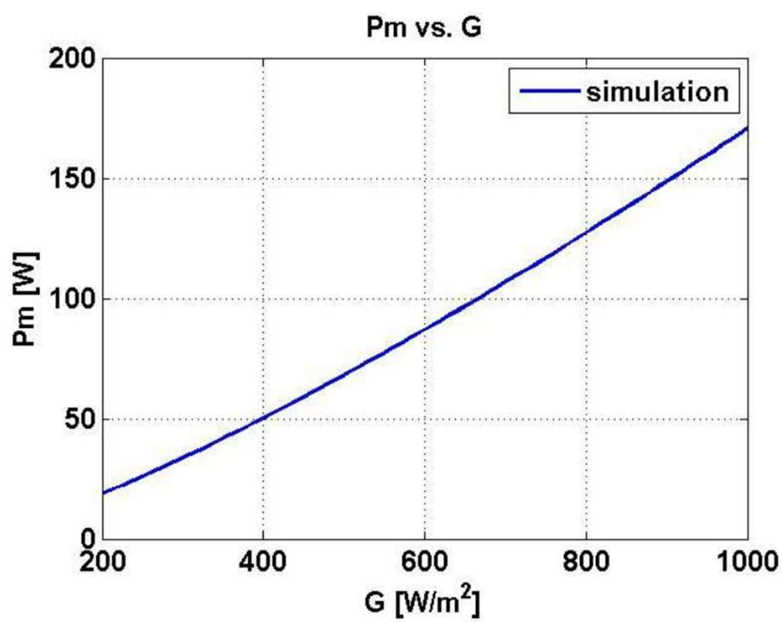

Figure 3. Modeled relation of power (*Pm*) vs irradiation (*G*)

SOLAR FRONTIER SF170-S 170 W Module									
G [V/m2]	Isc data [A]	Isc model [A]	error %	Voc data [V]	Voc model [V]	error %	Pm data [W]	Pm model [W]	error %
1000	2,2	2,2	0,00	112	112	0,00	170	170,7	0,41
800	1,76	1,75	-0,57	110	110,5	0,45	126	125,5	-0,40
600	1,29	1,3	0,78	107	108	0,93	101	92	-8,91
400	0,92	0,9	-2,17	105,5	100,5	-4,74	61	52	-14,75
200	0,45	0,44	-2,22	102	99,5	-2,45	24	21	-12,50
average			-0,84			-1,16			-7,23

Table 3. Measured Data (Provided by the Manufacturer) Vs. Simulated Data of Solar Frontier SF170- S170 W Module

4. Conclusion

The developed simplified behavioral model for quick estimation of CIGS module operation proves its applicability in real conditions. The test show that the model very well predicts the current, voltage and power at the big values of solar irradiance and decrease the values of voltage and power as decreasing of irradiance but the average error from model is in a good similarity with the tolerance of the experimental data producers.

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