Behavioral Model of Copper Indium Gallium Selenide Solar Module

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Abstract – **A behavioural model of Copper Indium Gallium Selenide photovoltaic modules is elaborated applying semi-empirical approach. Model equations are coded in Matlab. Model simulation results are verified against experimental data for four module data sheets from two producers. The result shows that the model very well predicts the current, voltage and power at high irradiance and it lessens the predicted values of voltage and generic power for low irradiance values. The model can be successfully used for fast estimation of generated power in real conditions – ambient temperature and irradiance.**

Keywords – **Copper indium gallium selenide (CIGS) photovoltaic modules, behavioural model**

I. 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 (1-2 μm) 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).

II. 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.

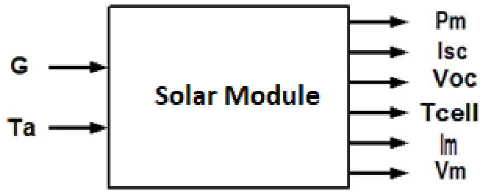

Fig. 1. Solar module block-diagram.

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 diode-model taking into account the radiation effect and temperature effect:

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

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

$$Tcell = ((NOCT - 20)*G/800) + Ta \quad (2)$$

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

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Table I

Measured data (provided by the manufacturer) vs. simulated data of Solibro modules with 115, 125 and 135 Wp .

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

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:

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

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

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

$$FFo = (vo - \log(vo + 0.72))/(1 + vo) \tag{6}$$

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

$$Rss = (Vocr/Iscr) \tag{7}$$

$$rs\_znam = Iscr.\hat{}2 \tag{8}$$

$$Rs = Rss - (Pmr/(FFo*rs\_znam)) \tag{9}$$

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

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

For the voltage at MPP is used:

$$Vmro = \log(\ Im/(Imr)) \tag{11}$$

$$Vm = Vmr + Vmro.*(Vt*(Tcell + 273)) \tag{12}$$

From here for fill factor – FF: is obtained the following

$$Fm = Vm.*Im \tag{13}$$

$$Fsoc = Voc.*Isc \tag{14}$$

$$FF = Fm/Fsoc \tag{15}$$

Finally the maximum output power Pm is

$$Pm = Vm.*Im \tag{16}$$

III. Results and Discussion

The model with data from SOLIBRO – SL2 CIGS THIN-FILM 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˚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 m^2. 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 °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.