ACCURATE MODEL OF PHOTOVOLTAIC MODULES IN PSPICE USING ONLY ELECTRICAL PARAMETERS

Alexander Eick– alexander.eick@outlook.de
Davies William de Lima Monteiro– davies@cpdee.ufmg.br
Federal University of Minas Gerais (UFMG), Department of Electrical Engineering, OptMA Lab

Abstract.*Many currently used models to simulate the performance of photovoltaic cells and modules need physical parameters, e.g. series and shunt resistance, as input. However, these parameters are not readily shared by manufacturers on datasheets. Thus, models that use only electrical parameters, e.g. open-circuit voltage or short-circuit current, which are easily accessible, become more important. The model proposed in this paper uses only electrical parameters to accurately model the behavior of photovoltaic modules under changing operating conditions. We show that the approximation of the series resistance as a temperature dependent parameter greatly improves the model accuracy. The here described model will help researchers and companies to quickly and accurately model the expected output of their photovoltaic modules under real environmental conditions.*

Keywords:*Solar Energy, Electrical Characterization, PSPICE*

1. INTRODUCTION

In 2050 9.3 billion people will be living on Earth(Frei et al., 2013), which will naturally lead to an increase in energy demand as well. This energy can be provided by mainly using either fossil fuels, as predicted by Frei et al.(2013) in their Jazz scenario, or renewable and environmentally friendly power-generation methods, as in the Symphony scenario. From these two scenarios Symphony is more likely, since world leaders are already trying to pave the way for a global consensus to promote renewable energy sources and to stabilize the greenhouse gas concentration in the Earth´s atmosphere (Green Climate Fund, 2014; United Nations Framework Convention on Climate Change, 1998, 2012, 2014). It is predicted that electricity generation moves away from fossil fuels to renewable energy sources and fossil fuel based generationwith carbon capture and storage (CCS) capabilities. The former produced about 67% of the world´s energy needs in 2010. This will be reduced to only 18% in 2050 while renewable and green energy sources take their place. From all renewable energy source, solar energy production is predicted to increase the most, from less than 0.5% to 16% (Frei et al., 2013). This is due to environmental concerns with hydro power and the visual and noise pollution while generating energy from wind.The energy sector in Brazil is one of the least carbon intensive in world due to its large capabilities to produce energy using hydroelectric power plants or biomass (Organisation for Economic Co-operation and Development & International Energy Agency, 2013). Thus, reducing its greenhouse gas emission is not Brazil´s primary concern. However, hydroelectric power generation is vulnerable to droughts as happened recently (Barrucho, 2013) and this can severely damage the national industry as well as scare away potential investors. Therefore, a diversification of electricity generation in the country should be a major concern to its government. In this process, photovoltaic energy generation will play a major role, especially considering Brazil´s high solar potential.

To determine the best areas for the construction of photovoltaic power plants and to predict their output under different environmental conditions it is crucial to be able to model accurately the performance of solar cells, modules and strings. Many existing models use physical parameters of the photovoltaic devices. As manufacturers do not commonly share these parameters, those existing models are only of limited use. This paper will describe a new method to model photovoltaic modules using only their electrical parameters as published by the manufacturer.

A common model to simulate the operation of a photovoltaic cell is the single-diode model (Figure 1(a)). In it, a current source is used to simulate the photo-generated current (I_{ph}) and a diode and two resistors simulate parasitic effects. The diode simulates the diffusion current (defined by Shockley´s equation with a saturation current (I_{01}) and an ideality factor (n_1)), which counteracts the photo generated current. The resistors simulate series (R_s) and shunt (R_{sh}) resistive effects. Those occur due to the resistance when the generated current passes through the semiconductor material and due to atom vibrations, defects and production impurities. A more accurate model is the two-diode model (Figure 1(b)). In it, a second diode, with saturation current I_{02} and ideality factor n_2, is added to simulate recombination effects within the material. The following equation describes the two-diode model for a photovoltaic module, with (N_s) solar cells connected in series and (N_p) cell branches in parallel:

$$I = I_{ph} - N_p I_{01}\left(e^{\frac{V+IR_S}{n_1 N_S V_T}} - 1\right) - N_p I_{02}\left(e^{\frac{V+IR_S}{n_2 N_S V_T}} - 1\right) - \left(\frac{V + IR_s}{N_p R_{sh}}\right) \quad (1)$$

where V_T is the thermal voltage. This equation is also the basis for the model proposed in this paper.

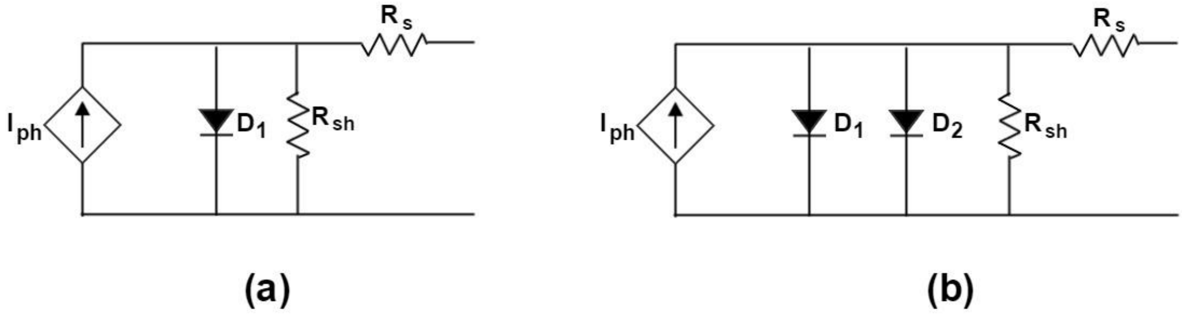

Figure 1 – Single-diode (a) and two-diode (b) solar cell model

The paper is structured into four parts. In the first, we will introduce the proposed model. The second part will describe the conducted experiments and simulations, the results of which will be presented in the third part. In the last part of the paper we will discuss the results, provide a conclusion and future recommendations.

2. PROPOSED MODEL

Castaner & Silvestre (2002) proposed a model using only electrical parameters as input, and PSPICE to simulate this model. The herein proposed model is based on their work. However, it is developed further, i.e. using the two-diode equation as basis and determining the series resistance as a temperature dependent parameter, to achieve a higher accuracy. In this newly proposed model the ideality factors of the two diodes were assumed to be $n_1 = 1$ and $n_2 = 2$ (Sah, 1991) and the two saturation currents were assumed to be equal $I_{01} = I_{02} = I_0$ as was shown by Ishaque, Salam, & Taheri(2011). Furthermore, the shunt resistance was assumed to be very large, thus reducing the magnitude of the last term on the right-hand side of Eq. (1) to a point where we can ignore it, due to its insignificance. In the simulation with PSPICE R_{sh} was set to 100 GΩ. Considering all these definitions Eq. (1) can be simplified as follows:

$$I = I_{ph} - N_p I_0 \left(e^{\frac{V+IR_S}{N_S V_T}} - e^{\frac{V+IR_S}{2N_S V_T}} - 2 \right) \tag{2}$$

Based on this equation the model can be implemented into PSPICE using voltage controlled current sources (g-devices) and a resistor. Figure 2 shows the schematic of the model in PSPICE, where Girrad calculates the photo-generated

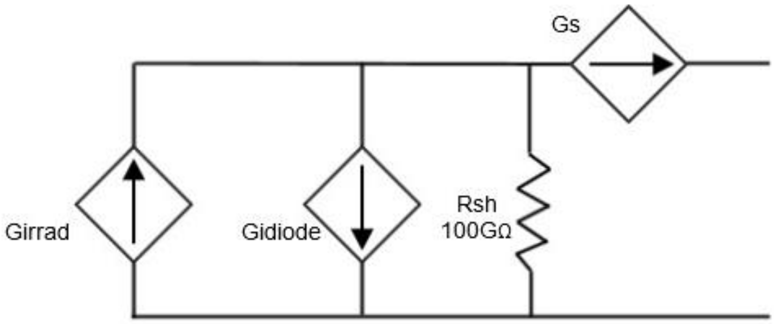

Figure 2 – Schematic of the proposed solar cell model

current, Gidiode simulates the current across both diodes and Gs represents the conductance related to the series resistance. All three g-devices are described by the following equations, which are derivatives of Eq. (2) at different operating points. However, since photovoltaic devices rarely operate under standard test conditions (STC) and manufacturers often report electrical parameters under those conditions, a conversion from STC to the real operating conditions has to be performed as well. This latter condition is denoted with a subscript r to clearly show the difference between the parameters under real operating conditions and the parameters under STC.

We assume that the photo-generated current is nearly equal to the short-circuit current (I_{sc}), which can be calculated from the reported I_{scr} and the temperature coefficient of the short-circuit current (α_{Ir}) together with the module temperature (T_{mod}) and the Irradiance (G):

$$I_{sc} \cong I_{ph} = \frac{G}{1000} * [I_{scr} + \alpha_{Ir}(T_{mod} - 25)] \tag{3}$$

Eq. (3) determines the current output of the g-device Girrad in Figure 2. Using the same approach the current at the maximum power point (I_m) is approximated:

$$I_m = \frac{G}{1000} * [I_{mr} + \alpha_{Ir}(T_{mod} - 25)] \tag{4}$$

The open-circuit voltage (V_{oc}) is calculated similarly. Obviously, we need to use the temperature coefficient of the open-circuit voltage (α_{Vr}) to specify the effects the temperature has on V_{oc}. Furthermore, it is not linearly proportional to the irradiance, as the short-circuit current is, but logarithmically proportional. Castaner & Silvestre (2002) derived the following equation:

$$V_{oc} = V_{ocr} + \alpha_V(T_{cell} - 25) + N_S V_T \, ln \frac{I_{sc}}{I_{scr}} \tag{5}$$

The g-device Gidiode uses the second term on the right-hand side of Eq. (2) to determine the current through the recombination and diffusion diodes. I_0 is determined by the following equation:

$$I_0 = \frac{I_{sc}}{N_P\left(e^{\left[\frac{V_{oc}}{N_S V_t}\right]} + e^{\left[\frac{V_{oc}}{2N_S V_t}\right]}\right)} \tag{6}$$

Eq. (6) is achieved by solving Eq. (2) for I_{ph} under open circuit conditions, i.e. $V = V_{oc}$ and $I = 0$, and substituting it into Eq . (2) under short circuit conditions, i.e. $V = 0$ and $I = I_{sc}$.

Green (1982) proposed an equation which relates the fill factor (FF) to the ideal fill factor (FF_0). Using this equation we found that R_s can be calculated using the following equations:

$$R_s = \frac{2.7V_{oc}\left\{1.1FF_0 - \sqrt{\left[1.21{FF_0}^2 + \frac{20}{27}\left(\frac{I_m V_m}{I_{sc}V_{oc}} - FF_0\right)\right]}\right\}}{I_{sc}} \tag{7}$$

$$FF_0 = \frac{\frac{V_{oc}}{N_S V_T} - \ln\left(\frac{V_{oc}}{N_S V_T} + 0.72\right)}{1 + \frac{V_{oc}}{N_S V_T}} \tag{8}$$

Where the voltage at the maximum power point (V_m) is assumed to be scaleproportional to V_{oc}, thus Eq. (5) can be used for this approximation where V_{ocr} is replaced by V_{mr}. Eq. (7) is as well used to determine the behavior of the last g-device in Figure 2, i.e. Gs. However, as mentioned before Gs simulates a conductance, which is determined by $1/R_s$.

The assumption of scale proportionality of V_m is a valid approximation for the calculation of the series resistance, however, to locate the maximum-power point it is duly more accurate to evaluate Eq. (2) at the maximum power point, i.e. $V = V_m$ and $I = I_m$. When rearranging this equation and combining it with Eq. (6) we arrive at:

$$V_m = N_S V_T \, ln\left[\frac{I_{sc} - I_m}{I_{sc}}\left(e^{\left[\frac{V_{oc}}{N_S V_t}\right]} + e^{\left[\frac{V_{oc}}{2N_S V_t}\right]}\right)\right] - I_m R_s \tag{9}$$

Implementing Eq. (2) through to Eq. (9) in PSPICE we are able to simulate the behavior of a photovoltaic module and extract the critical electrical parameters under a variety of irradiance and temperature conditions. This model is thus used with parameters of the Kyocera KD140SX-UFBS photovoltaic module. The results of the simulations are then compared to experimental data obtained with the same solar module and to the simulation results obtained from Castaner & Silvestre´s(2002) model.

3. EXPERIMENT AND SIMULATIONS

Thedatasheet parameters of the Kyocera KD140SX-UFBS photovoltaic module fed the model herein proposed. The simulation results where then compared to experimental data obtained with the module, and to simulation results yielded by theCastaner & Silvestre´s (2002) model. The experimental data was obtained on the 4th of November 2014, a sunny spring day, in Belo Horizonte, Brazil (19.8693 S, 43.9617 W). The module was facing northeast with an azimuth of 27°

and an angle of 33°. The I-V curves were extracted using the Solmetric PVA-600 PV Analyzer, which simultaneously measured the module temperature (T_{mod}) and the irradiance (G). Three datasets from the experimental data were chosen, i.e. Dataset 1(G = 904 W/m^2& T_{mod} = 54.4 °C), Dataset 2 (G = 667 W/m^2& T_{mod} = 52.77 °C), and Dataset 3 (G = 423 W/m^2& T_{mod} = 49.44 °C), and the simulations were then performed in PSPICE under those same environmental conditions.

Unfortunately the PVA-600 PV extractsmost measurement points concentrated around the V_{oc} point, which leads to a cluster around this point (blue marks in Figure 3). To obtain a clear I-V curve the data is imported into MatLab and

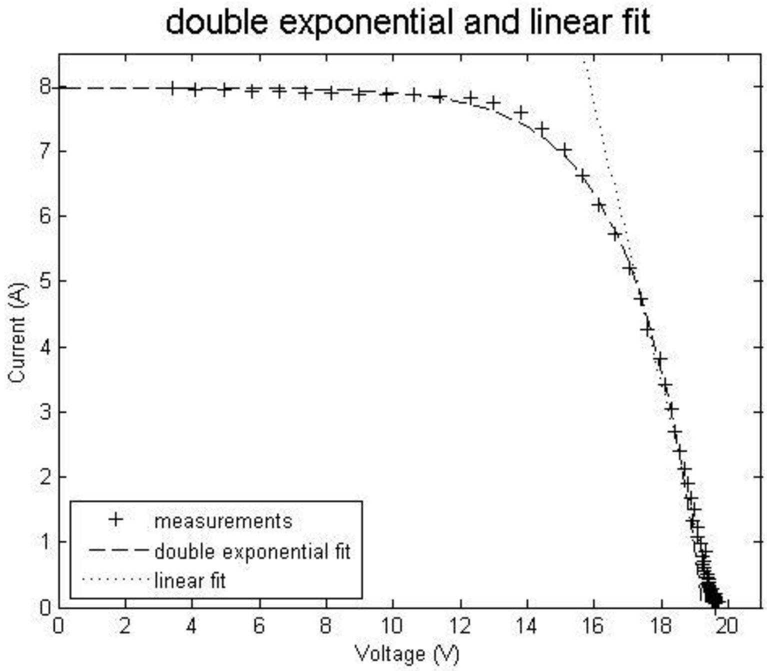

Figure 3 – measurement point together with the double exponential and the linear fit

the curve fitting tool is used to fit a double exponential curve (green line in Figure 3) through the measurements. Due to the large number of points at the far right of the measurements, the fitted curve exhibits an inaccurate fit. Thus, the measurements around the V_{oc} point werenot used to determine the double exponential fit. Instead, a linear curve (red line in Figure 3) was fitted through those points. This is valid since every I-V curve exhibits a linear behavior around the open circuit voltage. The combination of both the double exponential, for the region on the knee and left of it, and the linear curve results in the best fitting curve for the present data. This fitting curve was then evaluated at regular voltage intervals (0.1 V) to generate a dataset compliant to the simulation data generated by PSPICE.

For both, the proposed and Castaner´s model, the mean absolute deviation percent (MADP) and the Nash-Sutcliffe model efficiency coefficient (E) are then calculated so that a comparison between the two models can be performed.

4. RESULTS

The results of the measurements and the simulations for Dataset 1 can be seen in Figure 4. Both models exhibit good approximations of the measured curve (blue) around the short-circuit and open-circuit conditions. However, around the knee and thus at the maximum power point the errors seem to be large for both models. The simulation results deviate more from each other for Datasets 2 and 3 (Figure 5&6). Here the proposed model clearly outperforms Castaner´s model, as it overall simulates the I-V curve more accurately, especially around the open-circuit voltage. For Dataset 2 it can be seen, that both, the proposed and the Castaner´s model, simulate the short-circuit current as too high. Since that cannot be observed for the other datasets it is possible that some undetected external parameter, e.g. clouds or partial shade influenced the measurements at this time. Table 1 shows the mean absolute deviation percent and the Nash-Sutcliffe model efficiency coefficient of both, the proposed model and Castaner´s model. Moreover, the measurement and simulation results of the key photovoltaic module parameters are shown together with their respective relative errors. Table 1 proves what was already suggested by Figure 4 – 6, namely that the proposed model outperforms Castener´s model for environmental conditions far from STC. For environmental conditions close to the STC, e.g. Dataset 1, both models perform nearly equal, as can be expected since Castaner´s model determines the series resistance under STC conditions and thus the closer the environmental conditions are to STC the more accurate Castaner´s model is.

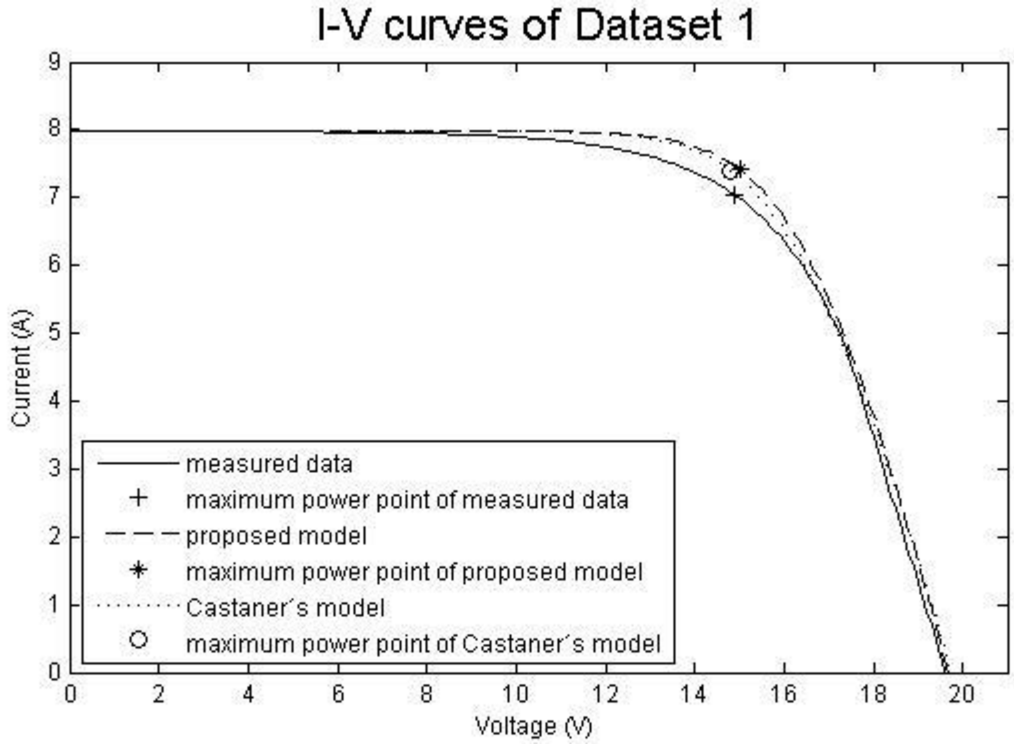

Figure 4 – I-V curves for Dataset 1

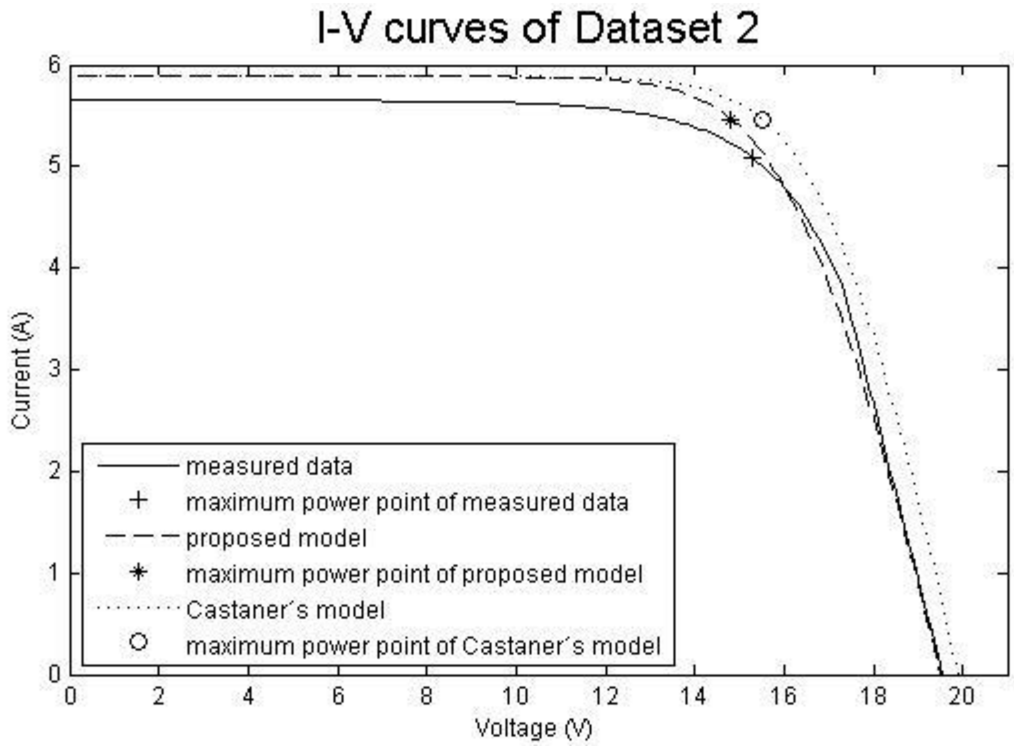

Figure 5 – I-V curves for Dataset 2

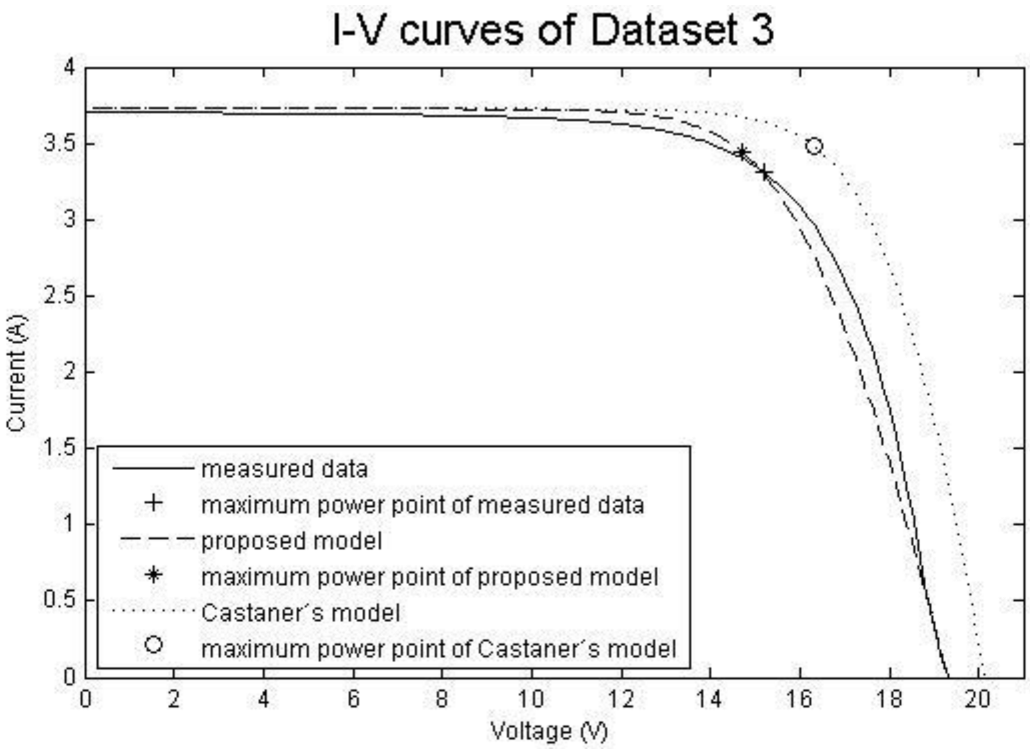

Figure 6 – I-V curves for Dataset 1

Table 1 – Measurement and simulation results of key parameters together with their respective errors and model efficiency coefficients

Dataset 1					
	Measured	**Proposed model**		**Castaner´s model**	
MADP(%)		2.25		1.77	
E (-)		0.99		0.99	
		value	**error(%)**	**value**	**error(%)**
V_{oc} (V)	19.63	19.67	0.20	19.76	0.62
I_{sc} (A)	7.98	7.98	0.10	7.98	0.10
V_m (V)	14.67	15.00	2.17	14.50	-1.20
I_m (A)	7.25	7.41	2.12	7.63	4.98
Dataset 2					
	Measured	**Proposed model**		**Castaner´s model**	
MADP(%)		4.78		7.07	
E (-)		0.99		0.97	
		value	**error(%)**	**value**	**error(%)**
V_{oc} (V)	19.57	19.50	-0.38	19.88	1.55
I_{sc} (A)	5.65	5.89	4.01	5.89	4.01
V_m (V)	15.40	14.80	-4.04	15.50	0.66
I_m (A)	5.16	5.47	5.61	5.47	5.62
Dataset 3					
	Measured	**Proposed model**		**Castaner´s model**	
MADP(%)		2.64		8.70	
E (-)		0.99		0.89	
		value	**error(%)**	**value**	**error(%)**
V_{oc} (V)	19.26	19.31	0.23	20.13	4.31
I_{sc} (A)	3.71	3.73	0.54	3.73	0.54
V_m (V)	15.10	14.70	-2.76	16.30	7.33
I_m (A)	3.42	3.44	0.58	3.48	1.85

5. CONCLUSION AND RECOMANDATION

It was shown that the newly proposed model can more accuratelymodel a photovoltaic module, i.e. with a relative error of ≈ 5% for the key parameters. The model performs the worst around the knee and thus at the maximum power point of the I-V curve. However, due to its implementation of the temperature dependence through all of its components, especially in the approximation of the series resistance, the model can outperform Castaner´s model in real environmental conditions. The high Nash-Sutcliffe model efficiency coefficients of 0.99 show the overall high accuracy of the model. As mentioned earlier, the proposed model performs yet rather poorly around the knee of the I-V curve, this could be due to the fact that the shunt resistance is assumed to be very high and constantwhich can never be true. In reality the shunt resistance is most likely as well dependent on the temperature and other environmental factors and far smaller than assumed by us. Further experiments and research is needed to determine the influence of environmental factors on the shunt resistance and to develop a model that includes those factors, provided that the main objective is not to undermined, i.e. simulating photovoltaic modules using only electrical parameters.

The herein proposed model will make it easier for researchers and companies to quickly predict the output of their solar modules under varying environmental factors, i.e. ambient temperature and incident irradiance. However, more research is needed to validate the proper operation of the model for photovoltaic modules other than the here used KYOCERA module.

Further investigation into the approximation of the series resistance might as well be necessary, since both the shunt and the series resistance influence the I-V curve, more so around the knee. Thus, improving the modeling of the shunt and series resistances will enhance the overall accuracy of the model.

Acknowledgments

This work has been supported by the Brazilian agency CAPES.

REFERENCES

Barrucho, L. (2013). Brazil drought stokes worries over energy shortages, *BBC Brasil*. Retrieved from http://www.bbc.com/news/world-latin-america-21055803

Castaner, L., & Silvestre, S. (2002). *Modelling photovoltaic systems using PSpice*: John Wiley and Sons.

Frei, C., Whitney, R., Schiffer, H.-W., Rose, K., Rieser, D. A., Al-Qahtani, A., . . . Panos, E. (2013). World Energy Scenarios: Composing energy futures to 2050. London, UK: World Energy Council.

Green Climate Fund. (2014). GCF - Background. Retrieved 19/12/2014, from http://www.gcfund.org/about/the-fund.html

Green, M. A. (1982). Accuracy of analytical expressions for solar cell fill factors. *Solar Cells, 7*(3), 337-340. doi: http://dx.doi.org/10.1016/0379-6787(82)90057-6

Ishaque, K., Salam, Z., & Taheri, H. (2011). Simple, fast and accurate two-diode model for photovoltaic modules. *Solar Energy Materials and Solar Cells, 95*(2), 586-594. doi: http://dx.doi.org/10.1016/j.solmat.2010.09.023

Organisation for Economic Co-operation and Development, & International Energy Agency. (2013). World Energy Outlook 2013.

Sah, C.-T. (1991). *Fundamentals of solid-state electronics*. Singapore: World Scientific.

United Nations Framework Convention on Climate Change. (1998). Kyoto Protocol to the United Nations Framework Convention on Climate Change.

United Nations Framework Convention on Climate Change. (2012). Doha Amendment to the Kyoto Protocol. New York, NY, United States of America.

United Nations Framework Convention on Climate Change. (2014). Lima Call for Climate Action Puts World on Track to Paris 2015 [Press release]. Retrieved from http://newsroom.unfccc.int/lima/lima-call-for-climate-action-puts-world-on-track-to-paris-2015/