DEVELOPMENT OF A SOLAR SIMULATOR FOR A REAL EVALUATION OF PHOTOVOLTAIC-THERMAL SYSTEM IN TROPICAL ENVIRONMENTS

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Abstract. *Even though the generation of photovoltaic (PV) has grown significantly in last years, two factors have limited its even more exponential growth, which are: the high cost for system acquisition, compared to the cost of connecting to the power grid; and low efficiency in the energy conversion (15% under optimum conditions), which decreases significantly with increasing in panels temperature. The combination of these two factors result in a long term to the return on investment (ROI), and this is preponderant condition for the resistance in the installation of these systems for private purposes in Brazil. In order to increase the efficiency of PV panels, several proposals have been studied to control or reduce its temperature. Photovoltaic panels evaluations are generally performed in outdoor environment, and this makes the results affected by adverse weather conditions, especially the different conditions of irradiation during the day and position of the sun during the year, partial shadows due to clouds, variation of ambient temperature and wind speed. However, for a reliable evaluation of PV panel in outdoor environment, the temperature should not vary more than 2 K and wind speed and irradiation should be practically constant. Therefore, in this work was developed an aparatus for photovoltaic test and evaluation under Brazilian conditions of temperature, irradiation and ventilation, using for this a low-cost Solar Simulator developed by us. The results indicated a good viability in the use of the Solar Simulator for PV panels efficiency evaluations under adverse weather conditions.*

Keywords: *photovoltaic, solar energy, efficiency, solar simulator, temperature*

1. NOMENCLATURE

PV – photovoltaic
ROI – return of investment
NOCT – nominal operatin cell temperature
PWM – pulse width modulation
I – electric current
V – voltage
I_{ph} – photo current
I_o – diode current

q – electron charge
R_{sh} – shunt resistance
R_s – series resistance
n – ideality diode
k – Stefan Boltzmann constant
T - temperautre
T_{cel} – cell temperature

2. INTRODUCTION

Photovoltaic (PV) panels efficiency evaluation follow the international standard IEC 61215 and are performed in climatic chambers at 25 ° C, with air mass of 1.5 and the irradiation of 1,000 Wm^{-2} is provided by a solar simulator, generally using xenon lamps whose spectrum has larger amplitudes in the range of more efficient electrical conversion and lower amplitudes in the infrared band, just to avoid the increase in PV temperature. Thus the nominal efficiency of a PV panel is always an optimum value, whose similar results are hardly achieved in practical (Bloem, 2008).

To decrease the difference between the nominal and practical PV efficiency, a new standard was established named NOCT (nominal operating cell temperature) with radiation tilt 45°, ambient temperature of 20 ° C, wind speed of 1 ms^{-1}) and irradiation of 800 Wm^{-2}. Although this standard allows an approximation of the tests in actual operating conditions in Europe, in Brazil the difference is only made worse, since the ambient temperature and irradiation are set below the values practiced in this country. And these are the main challenges discussed in this paper: the reduction of PV panel efficiency due the its temperature and the difference between nominal and practical efficiency, especially in tropical countries.

Different than the tests performed by manufacturers, many experimental studies aimed at improving the PV panels efficiency are carried out in outdoor, influenced by climatic adversities: variation of radiation during the day and position of the sun during the year, the ambient temperature variation and wind speed and partial shadows due to clouds.

According to (Skoplaki and Palyvos, 2009), such adversities encountered during the PV efficiency evaluation requires special attention. According to (Pó, 2011) and (Peng, et al., 2015), in a controlled environment (indoor) with the possibility of controlling the temperature and irradiation reduces the uncertainties about the results. While PV evaluations in outdoor environment can only be performed reliably when its temperature during the measurements have not vary by more than 2 K and irradiation and wind speed are practically constant. These implications result in the need for a large amount of data acquisition to determine important parameters of the PV panels conducted outdoor experiments, whereas this could be simplified in an indoor environment where there is less uncertainty about the measures.

Therefore, this research, which aims to propose and evaluate new solutions to increase the efficiency of PV panels and reduce the impacts of temperature, was dedicated to design and development of a controlled test environment for experimentation , evaluation and comparison of proposals to the control or reduction of its temperature, named in this paper as Solar Simulator. This environment was developed in the climate chamber of the Thermal Systems Laboratory (LST) of the Pontifical Catholic University of Parana, Brazil (PUCPR) and enables the control of the ambient temperature, ventilation and irradiation.

3. DEVELOPMENT

The design and development of the Solar Simulator was divided into the following tasks: conceptual design and development; irradiation system; ventilation system.

3.1 Conceptual design and development

The Solar Simulator was built with the following dimensions: 1250 x 1850 x 2100 mm (width x length x height), so that it could evaluate the most of PV panels commercially available (Fig. 1).
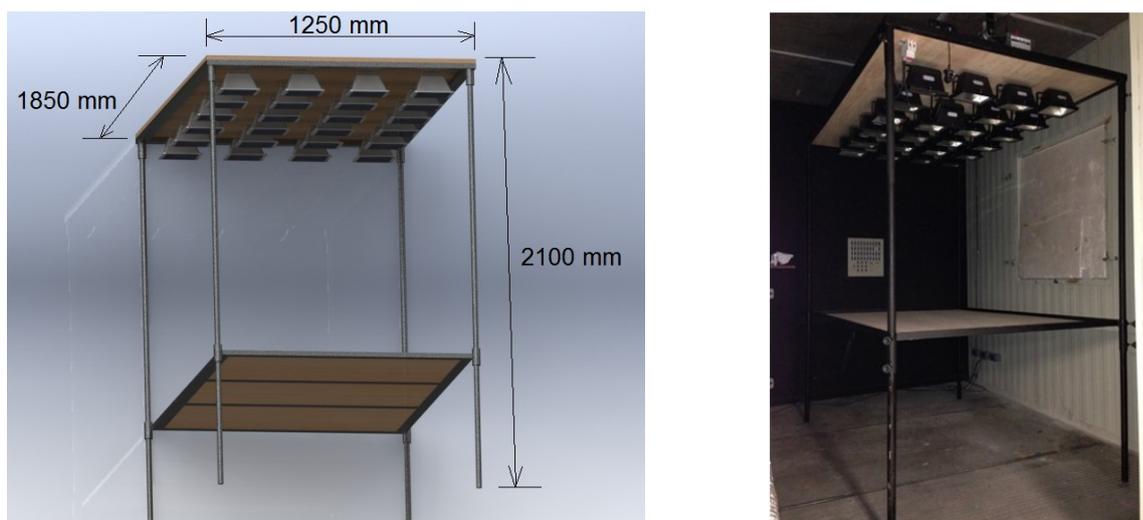

Figure 1. Design and development of the Solar Simulator structure.

The solar simulator was mounted inside the climatic chamber of LST PUCPR, which has the following characteristics:
•   dimensions: 3.000 x 3.000 x 3.000 mm;
•   temperature range: -10°C to 65°C;
•   humidity range: 10 to 95%.

3.2 Irradiation System

The irradiation in the Solar Simulator was generated by a set of lamps arranged as a 4 x 6 array, resulting in a total of 24 lamps. It was decided to this amount of lamps to avoid large gaps between them, which can lead to regions with low irradiation on the panel surface. Halogen lamps were used for having a similar spectrum of the sun, with a band in infrared region, responsible for heating the panel, and the other in the region with higher utilization for photoelectric conversion (wavelength shorter than or equal to 1.15 μm).

The circuit was connected to a 220 V voltage source to prevent significant losses of power by Joule effect in the conductors and reduce spending on oversizing of conductors and protective devices, and it was connected to a power controller (dimmer) using PWM (pulse-width modulation) with a maximum voltage and 220V-12kW for the purpose of controlling the lamp power and therefore the irradiation on the surface of PV panels (Fig. 2).

Figure 2. Dimmer to control the irradiation on PV panels

Several tests of the solar simulator were carried out in order to evaluate:

- ability to control the irradiation intensity on the PV surface;
- spreading of irradiation homogeneously on the PV surface.

Before performing the tests, the surface of the solar simulator was divided in the form of a 10 x 7 array (row x column), resulting in 70 quadrants. The columns were labeled with the letters "A" to "G" and the lines with the numbers "1" to "10".

The pyranometer was placed in the center of the simulator (D5 quadrant) and the irradiation power was adjusted using the dimmer, until it reaches the irradiation of approximately $1000 \ Wm^{-2}$.

After adjusting the irradiation, it was measured in each quadrant of the Solar Simulator's surface. All irradiation values were collected and stored by data acquisition equipment Agilent 34970A, which was configured to perform the pyranometer readings at 10 seconds.

Some modifications and improvements have been made in the solar simulator based on the results obtained during the tests, which the most important modifications are described below as case A and B (Osaka, Moura and Santos, 2015).

Case A:

In the Case A Figure 3 was generated containing irradiation in each quadrant of the Simulator. In this figure is evident the poor distribution of irradiation generated on the surface of the solar simulator. The irradiation in the central quadrant was close to the desired value ($999,01 \ Wm^{-2}$), but in border regions the irradiation value was much lower than the desired, reaching values of only 33.72% of D5.

	A	B	C	D	E	F	G
1	435,1797	503,8491	561,9952	593,8255	573,3333	529,4629	470,4994
2	554,0726	647,344	714,1991	733,8277	723,9245	662,9705	576,097
3	642,3839	754,1653	813,7156	848,5894	839,7575	783,4704	649,3621
4	682,8402	804,4755	889,6796	911,8069	895,016	823,7578	706,7747
5	733,546	855,4291	941,6247	970,2128	956,6563	887,9084	768,4009
6	745,7466	879,7604	966,8119	999,0143	969,3785	888,0854	767,8114
7	690,8242	807,4145	875,6752	900,2709	876,7975	805,3243	701,1751
8	657,8586	756,665	831,4494	864,4425	849,5253	769,5757	665,6003
9	585,9951	688,9709	748,2478	774,4616	774,4616	700,9581	604,9519
10	470,3128	542,9565	602,2919	611,873	596,6945	563,0187	483,2322

Lamp 300W

A)   B)

Figure 3. a) configuration of the lamps in the solar simulator (Case A); b) irradiation spreading on the surface of the Solar Simulator.

In this Case A we conclude that:

- the Solar Simulator was able to adjust the irradiation on the surface with satisfactory precision, with a variation of only 0.1% below the desired value;
- irradiation in each quadrant of the simulator surface is strongly influenced by the side lamps (neighborhood), and this has influenced in the peripheral areas of the simulator, making its surface with low homogeneity of irradiation.

This problem of non-homogeneity in the simulator can generate the same effect occurred in panels with partial shading. That is, some cells generate electrical currents more intense than others and can negatively polarize cells that generate less current, significantly affecting the performance of the entire panel (DOLARA, LAZAROIU, *et al.*, 2013), (LOPES, 2013) (ISHAQUE, 2011).

Case B

In case B, using an specific irradiation software, it was possible to simulating various conditions in order to obtain the best results in terms of uniformity of irradiation. After the simulations, the best result was obtained with only four halogen lamps distributed at the corners of the Simulator (Fig. 4), where the problem of low irradiation was stronger.
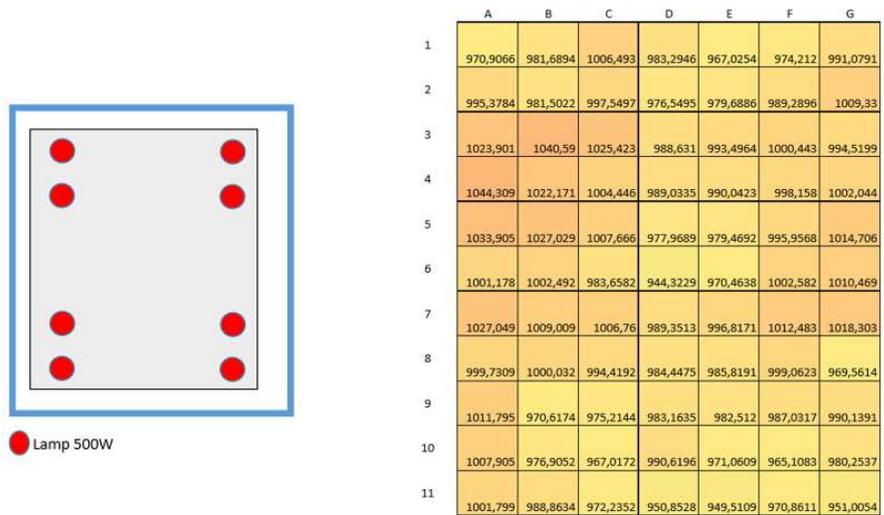

Figure 4. Configuration of the lamps in the Solar Simulator (letf) and irradiation spreading on its surface (right).

3.2 Ventilation System

To control ventilation in the Solar Simulator was developed a ventilation and exhaust system, consisting of 24 coolers controlled by a PWM system (Fig. 5).

Figure 5. Ventilation systems controled by a PWM circuit.

After some trials, the ventilation system is able of controlling the ventilation satisfactorily with relatively constant flow in the central region of the Simulator (Fig. 6).
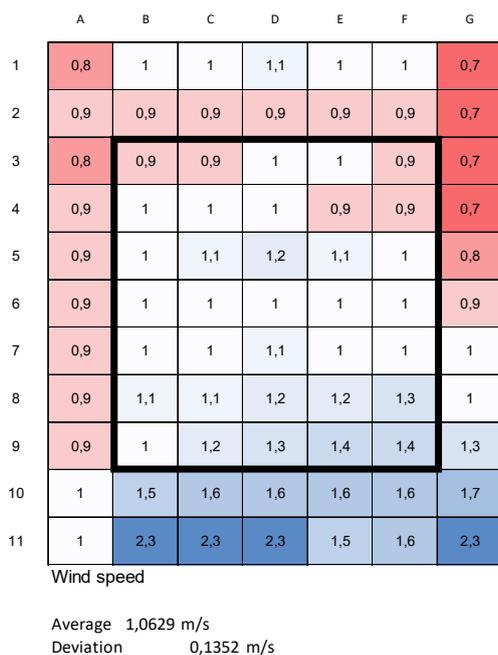
	A	B	C	D	E	F	G
1	0,8	1	1	1,1	1	1	0,7
2	0,9	0,9	0,9	0,9	0,9	0,9	0,7
3	0,8	0,9	0,9	1	1	0,9	0,7
4	0,9	1	1	1	0,9	0,9	0,7
5	0,9	1	1,1	1,2	1,1	1	0,8
6	0,9	1	1	1	1	1	0,9
7	0,9	1	1	1,1	1	1	1
8	0,9	1,1	1,1	1,2	1,2	1,3	1
9	0,9	1	1,2	1,3	1,4	1,4	1,3
10	1	1,5	1,6	1,6	1,6	1,6	1,7
11	1	2,3	2,3	2,3	1,5	1,6	2,3

Wind speed

Average   1,0629 m/s
Deviation   0,1352 m/s

Figure 6. Ventilation map on the surface of the Solar Simulator

4. RESULTS

In order to validate the Solar Simulator was performed an evaluation of PV electrical efficiency (Fig. 7). For the validation was necessary: rheostat; piranometer; 2 thermocouples for measuring the panel operating temperature and room temperature; thermal camera for analyzing the temperature distribution on the panel; and equipment for data acquisition.

The rheostat was connected to the PV panel to scan voltage x current shape. The current and voltage values have been recorded by the data acquisition equipment, duly connected in series and parallel with the load according to Fig. 7. Two thermocouples were used to record the PV temperature and the climatic chamber temperature. The Solar Simulator was adjusted for a constant irradiation of $1000 \ Wm^{-2}$ and the chamber was set to a constant temperature of 25°C.
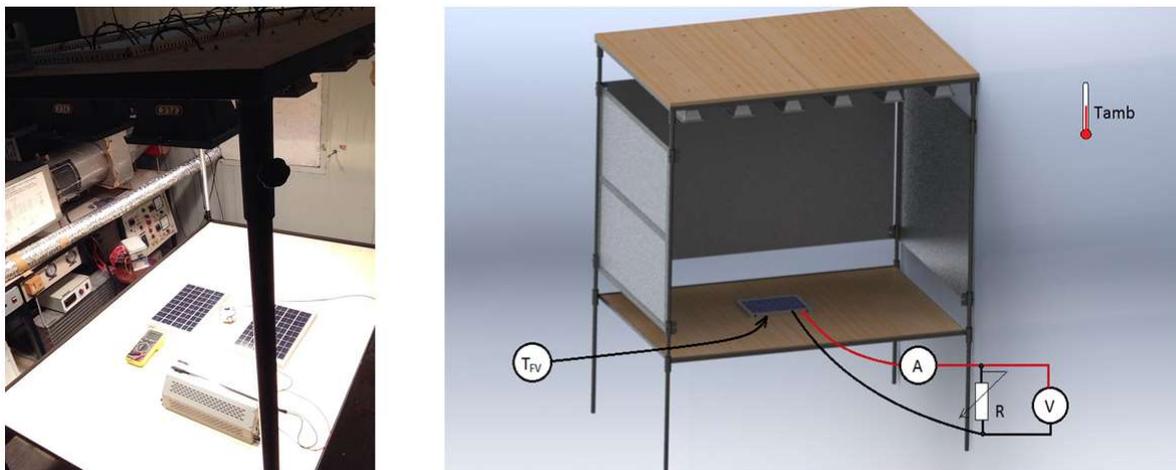

Figure 7. Validation of the Solar Simulator through a PV efficiency test.

The evaluation of the Solar Simulator was performed irradiating the PV panel with the halogen lamps. After irradiating the PV panel, its temperature increased from 25°C to 65°C. At each increment of 5°C on the panel temperature was recorded the voltage x current value, whose results are shown in Fig. 8.
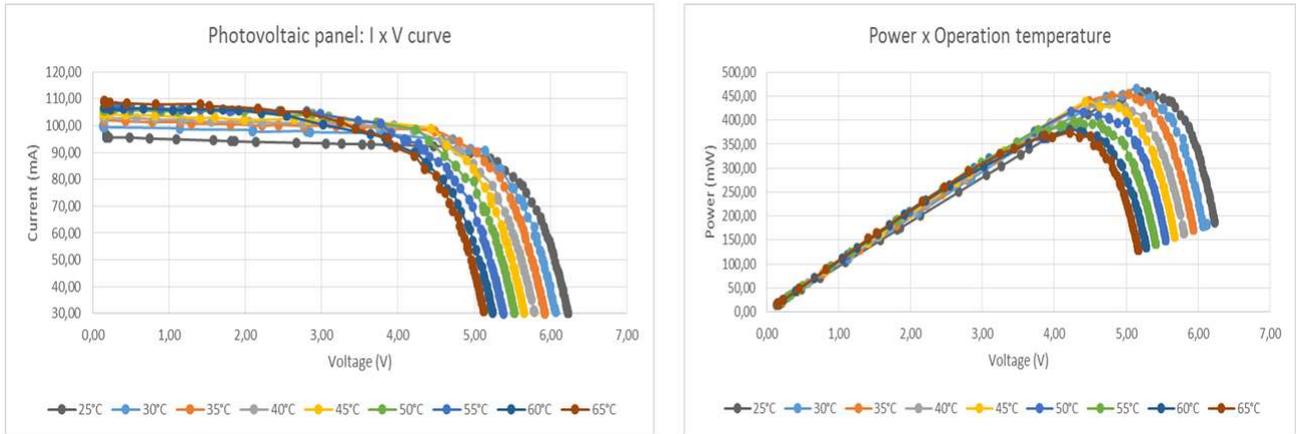
Figure 8. Photovoltaic I x V curve (left); power x operation temperature (right).

In the Figure 10 we can observe the decreased power, the drop in open circuit voltage (voltage temperature coefficient) and the slight increase in short circuit current (current temperature coefficient) caused by the increase in the PV panel operating temperature.

From the results, it was proposed a mathematical model for predicting the electrical efficiency of the panel by increasing their operating temperature. Using Newton-Raphson method (Eq. 1) and the 1 diode mathematical model for photovoltaic panel (Eq. 2) and (Eq. 3), the results of the model were compared with the experimental results indicated a significant level of correlation (Fig. 9).

$$x_{n+1} = x_n - \frac{f(x_n)}{f^f(x_n)} \tag{1}$$

$$f(I) = -I + I_{ph} - I_o \cdot \left(\exp\left(\frac{q \cdot (V + I \cdot R_s)}{n \cdot k \cdot T_{cel}} - 1\right) - \frac{V + I \cdot R_s}{R_{sh}}\right) \tag{2}$$

$$f'(I) = -1 - I_o \cdot \left(\exp\left(\frac{q \cdot (V + I \cdot R_s)}{n \cdot k \cdot T_{cel}}\right) \cdot \frac{q \cdot R_s}{n \cdot k \cdot T_{cel}} - \frac{R_s}{R_{sh}}\right) \tag{3}$$
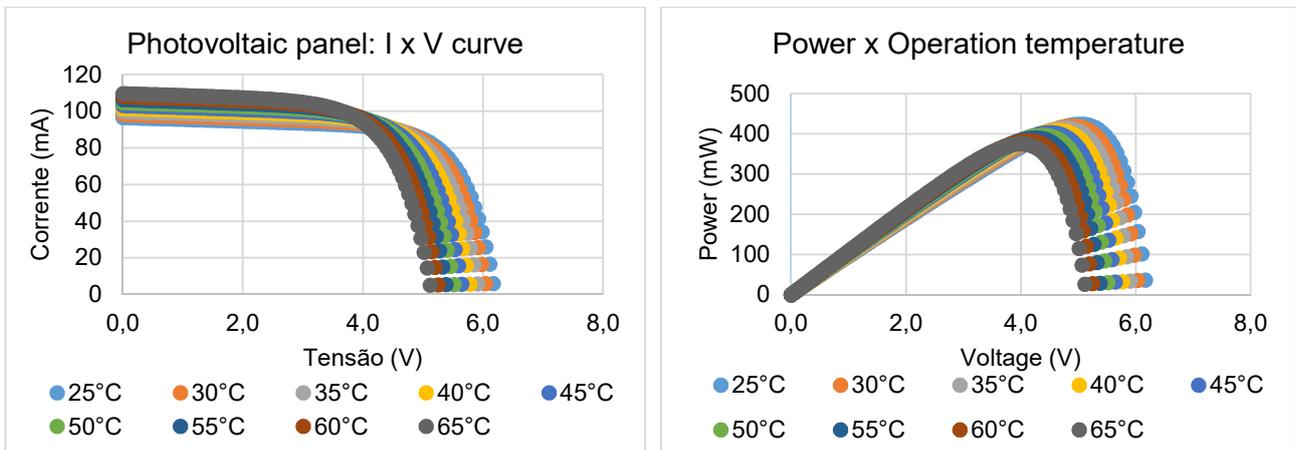

Figure 9. Simulation of photovoltaic I x V curve (left); power x operation temperature (right).

4. CONCLUSION

Even though IEC 60904-9 standard defines that the variation in the irradiation of the panel surface should be less than ± 2% in tests performed by the manufacturer, which applies only a flash of artificial light for a short period of time, it is important to emphasize that this project has a different proposal, which requires the panel heating and simulating various operating conditions to thus evaluate new technological solutions aimed at increasing the efficiency of PV panels by decreasing or controlling its temperature. In this proposal of simulating real conditions of power generation and heating, (Atkin and Farid, 2015) developed a Solar Simulator using two halogen lamps of 500 W each, to assess the efficiency of a PV-MMF system and obtained a variation of irradiation of approximately 10% in an area of 0.22 x 0.235 m. Considering this, the result obtained in the Solar Simulator was considered satisfactory for this proposal, with a maximum variation

of irradiation of 5.6% in an area of 1.25 x 1.85 m. The Solar Simulator manufactured by Apollo all real, used in the article (Peng, et al., 2015), offers a uniformity of 15% to an area of 2.1 x 1.5 m.

Furthermore, the simulator provides the necessary conditions to evaluate the electrical efficiency of a PV panel for different conditions of irradiation, temperature and ventilation in accordance to a typical climatic conditions in tropical countries. During the evaluations, it was found to influence the PV panel operating temperature of, mainly, the open circuit voltage. The results were consistent with the mathematical models presents in scientific articles.

In the face of what was presented, it is concluded that the design and development of Solar Simulator is an low cost alternative for PV test and evaluation, able to perform adverse conditions of temperature and irradiation, bringing the development of new solutions aimed at improving the electrical efficiency of these technologies, taking into account mainly the thermal aspects and radiative.

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