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CONSTRUCTION OF AN I-V CURVE TRACER FOR A PHOTOVOLTAIC RESEARCH AND TEACHING PLATFORM

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Abstract — *I-V curves of photovoltaic modules play an important role in system monitoring, since they cover all possible operating points, from open to short circuit. Also, I-V curves are a great teaching resource, since they allow visual and quantitative evaluation of a PV module output response, due to change in ambient conditions. The modeling of photovoltaic devices allows to obtain I-V curves by means of simulation but measured I-V curves consider every practical aspect, from module real performance to installation issues, as well as partial shading mismatch effects and defective equipment. This study concerns the project and construction of an I-V curve tracer, built specifically to operate along with a research and teaching photovoltaic platform, with remote monitoring capability. The curve tracer conception steps are presented, as well as the validation methodology.*

Keywords *- PV system monitoring, IEC 60891, I-V curve tracer, PV systems, Capacitive load.*

I. INTRODUCTION

This study proposes an I-V curve tracer, built specifically to integrate the PV Research and Teaching Platform installed at Unisinos University. It can be used to verify, in real time, the electrical behavior of photovoltaic modules coupled to two grid-connected microinverters. This behavior check can be performed directly on a computer such as through internet access. The access through the internet allows the researchers and the students to remotely carry out a series of tests and measurements, among them the verification of losses by shading at certain times. PV module I-V curves provide valuable data for troubleshooting, maximum output power measurement and quantification of temperature and shading influence. Also, the behavior of these curves with the change in ambient conditions consists in an important learning resource, especially when considering shading of PV modules equipped with bypass diodes. Module manufacturers provide the curves and other characteristic data in standard test condition, the STC: the cell temperature *Tc* is 25 ºC, and the solar irradiance *G* is 1000 W/m², considering the standard irradiance spectrum. Since these conditions are rarely present in installation sites, it is important that real data can be acquired on the behavior of the PV modules, especially under non-ideal operating condition. This task can be accomplished by an I-V curve tracer. It is a valuable diagnostic tool, since it can provide important data about a PV array: its I-V behavior from open-circuit to short circuit condition [1].

II. BACKGROUND

2.1. PV Research and Teaching Platform at Unisinos

At Unisinos, at the Renewable Energy Laboratory, a PV Research and Teaching Platform is under development, a practical aid for students and researchers. This platform consists of grid-connected microinverters and a stand-alone micro-grid, composed by monocrystalline and multicrystalline modules, connected to charge controllers, which provide power to a battery bank. This bank, in turn, is connected to a DC-AC inverter, which provides power to an AC load system that simulates an isolated community [2]. The PV grid-connected system is composed by two 265 W_p multicrystalline modules connected to microinverters. Both PV systems are provided with remote monitoring. Figure 1 (left) shows the grid-connected equipment panel, containing the microinverters, the curve tracer prototype and the monitoring circuitry. Also, on the right side, the two 265 W_p modules are shown, as well as the calibrated modules that are used as irradiance sensors.

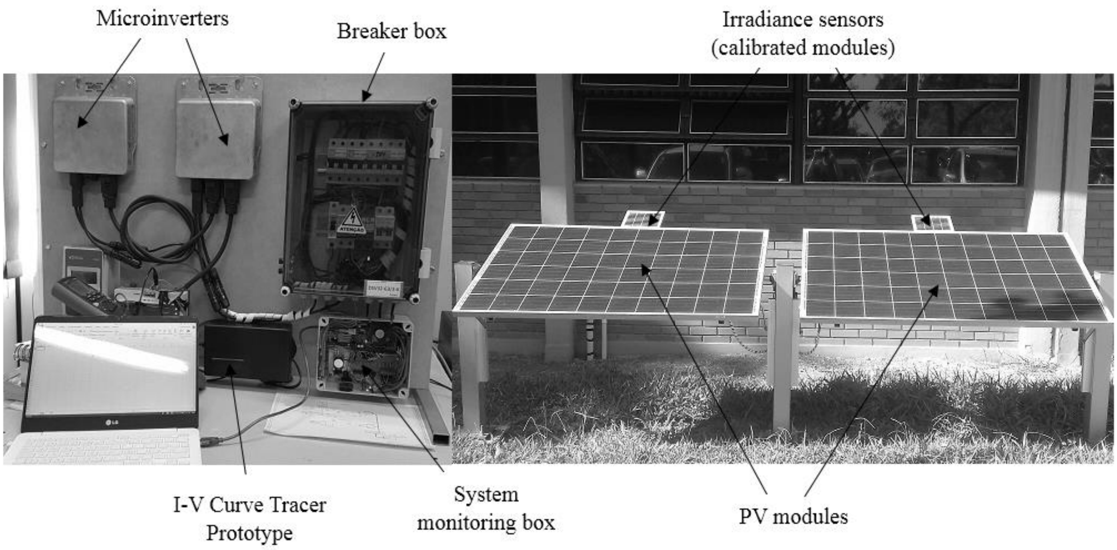

Fig. 1 – The Renewable Energy Laboratory grid-connected PV system, at Unisinos

2.2. Simple Methods to Obtain the I-V Characteristic

The use of a variable resistor (or a set of resistors) to measure the response of a PV module is the simplest way for obtaining data and to plot its I-V curve [3]. This method, however, implies power dissipation issues, which makes it restricted to low power PV modules, since size, weight, heat dissipation problems and cost of resistors increase together with power specification. Another simple method to obtain I-V curves is the capacitive load method. It consists of connecting an initially discharged capacitor to the PV module. During the charging process, the capacitor voltage, which is the same as that of the module, varies from zero to the open-circuit voltage value of the module, V_{oc}. The module current varies from short-circuit *Isc* at the beginning of the charging process, to zero, when the capacitor is fully charged [4]. The basic circuit of this application is presented in Figure 2. The PV module is on the left, and it is connected to the load capacitor by a switch. During the charging process, the capacitor current and voltage values are measured and registered. This is not a power dissipative method, and results in lighter and smaller hardware. Also, it allows the I-V curve measurement to be done in a very short time interval, which is significant, since all the curve points must be recorded under the same ambient conditions. Thus, this is the selected measurement method for this work.

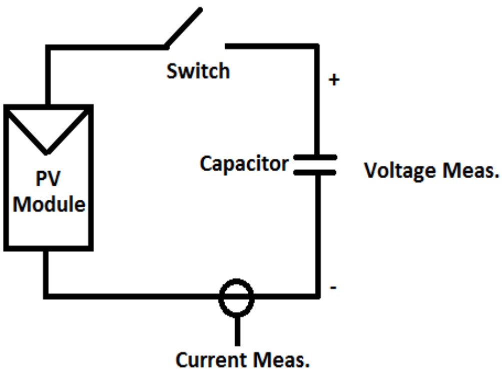

Fig. 2 – Basic diagram to obtain an I-V curve by the capacitive load method

Reference [4] demonstrate the transient capacitive load calculations, which depends on the parameters *Isc* and V_{oc} of the module to be tested, as well as the loading time interval, *ts*. The resulting Equation is (1), where *C* is the capacitance in Farads, *ts* is the voltage settling time in seconds, *Isc* is the module short circuit parameter and V_{oc} is its open circuit voltage.

$$C = \frac{t_s}{2} \frac{I_{sc}}{V_{oc}} \tag{1}$$

2.3. IEC 60891

The IEC 60891 standard [5] presents procedures for transposition of the voltage and current parameters of photovoltaic devices, so that the results can be equivalent to STC. Since Procedure 1 does not consider the irradiance G influence on the voltage, IEC 60891 Procedure 2 was chosen for application in this work. It presents Equations (2) and (3).

$$I_2 = I_1\left(1 + \alpha_{rel}\left(T_2 - T_1\right)\right)\left(\frac{G_2}{G_1}\right) \tag{2}$$

$$V_2 = V_1 + V_{oc1}\left(\beta_{rel}\left(T_2 - T_1\right) + a ln\left(\frac{G_2}{G_1}\right)\right) - R_S\left(I_2 - I_1\right) - kI_2\left(T_2 - T_1\right) \tag{3}$$

In (2) and (3), V_1 and I_1 are the pair of measured values, V_2 and I_2 are the values transposed to STC, G_1 is the measured irradiance, G_2 is the reference irradiance for STC, T_1 is the module temperature, T_2 is the reference temperature for STC and V_{OC1} is the open-circuit voltage measured under the condition of G_1 and T_1. In addition, αrel and βrel are the normalized temperature coefficients for current and voltage. R_s is the series resistance of the device under test, a is the irradiance dependence coefficient and k is the thermal correction factor of R_s.

III. MATERIALS AND METHODS

Simulations were done to validate the capacitor sizing and to test the influence of the power switch on the voltage and current measurements. Then, the measuring circuit was built. The complete tracer prototype also incorporates software, running on a microcontroller, which manages the measuring board, performs the analog to digital conversion, and sends the data to a computer, which presents the curves and key measured values.

3.1. Capacitor Sizing

The module [6] which composes the Research and Teaching Platform and is a 60 cells and 265 W_p, model P265NPB, with I_{sc} = 9.24 A and V_{oc} = 37.81 V. In addition, the module current and voltage at the maximum power point are, respectively, I_{mp} = 8.63 A and V_{mp} = 30.71 V. The module maximum power P_{mp} is the I_{mp} x V_{mp}. This module contains three bypass diodes, connected in parallel with groups of 20 cells each. By the application of Equation (1), the value is 10 mF for the capacitance, considering a charging time of 80 ms. This value of ts meets the capacitance selection presented in [4], which recommends 20 ms < ts < 100 ms as the ideal test duration range. Considering the module V_{oc} value, the capacitor voltage is rated for 50 V maximum.

3.2. Simulations

Using the PSIM ® simulator, a study of voltage and current transient was carried out, while applying the specifications of the P265NPB module and a capacitance value of 10 mF. Figure 3 shows the simulated circuit. MOSFET transistors were selected as switching devices since there is no current flow through the control terminal, which would introduce measuring errors concerning the capacitor current.

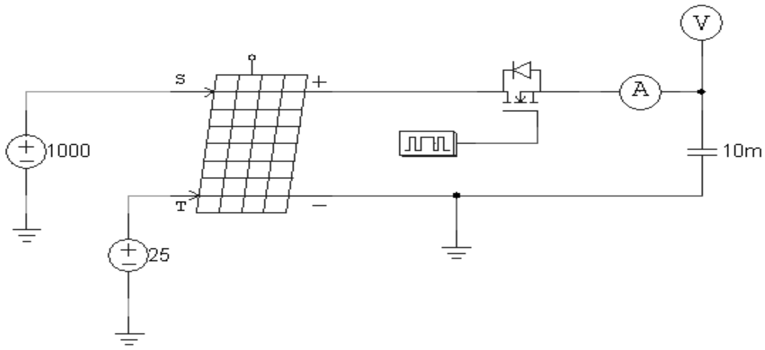

Fig. 3: Circuit simulated in PSIM®

The effects of different drain-source resistance (RDS) values on the I-V curves of the same photovoltaic module were analyzed. RDS values and selected MOSFET transistor models are shown in Table 1, where VDS (max) stands for maximum voltage between the power terminals of the device, and ID (max) is the maximum operation current.

Table 1: Specifications of different MOSFETs

	R_{DS} (Ω) (typical)	V_{DS} (V) (max.)	I_D (A) (max.)
IRF3205	0.008	55	116
IRF460	0.27	500	20
IRF840	0.85	500	8

The I-V curves considering the devices presented in Table 1 are shown in Figure 4. The curve with *RDS* = 0 Ω (ideal situation) and the curve marked with 8 mΩ, (IRF3205 MOSFET) are practically overlapped.

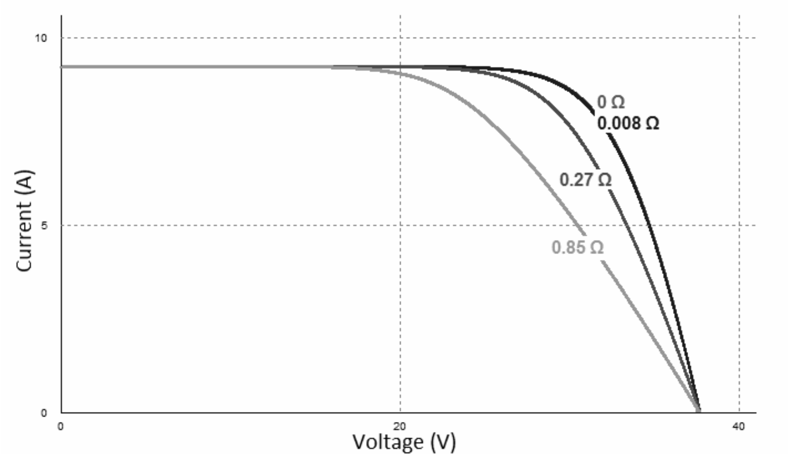

Fig. 4: I-V curves for different *RDS*

By graphical inspection, the adoption of IRF3205 would not cause significant I-V curve distortions. Table 2 presents the quantitative analysis of the errors introduced by adopting the IRF3205 transistor. Parameters P_{mp}, I_{sc}, V_{oc}, I_{mp}, and V_{mp} measured via simulation presented a maximum error of -2.47 %, in relation to the values reported on the PV module datasheet. Therefore, IRF3205 introduces errors that are tolerable for this work, and it is the device of choice.

Table 2 –Module parameters: datasheet, simulation and errors

	V_{oc} (V)	I_{sc} (A)	P_{mp} (W)	V_{mp} (V)	I_{mp} (A)
Datasheet	37.81	9.24	265.00	30.71	8.63
Simulation	37.73	9.24	258.70	29.95	8.64
Error (%)	-0.21	0	-2.37	-2.47	0.11

3.3. Tracer Prototype

The complete electronic circuit that was designed is shown in Figure 5. In addition to the capacitor charging circuit, a discharge control stage was added, as well as optocouplers to interface with the microcontroller outputs. To perform voltage and current measurements during the capacitor loading process, an instrumentation section must be included.

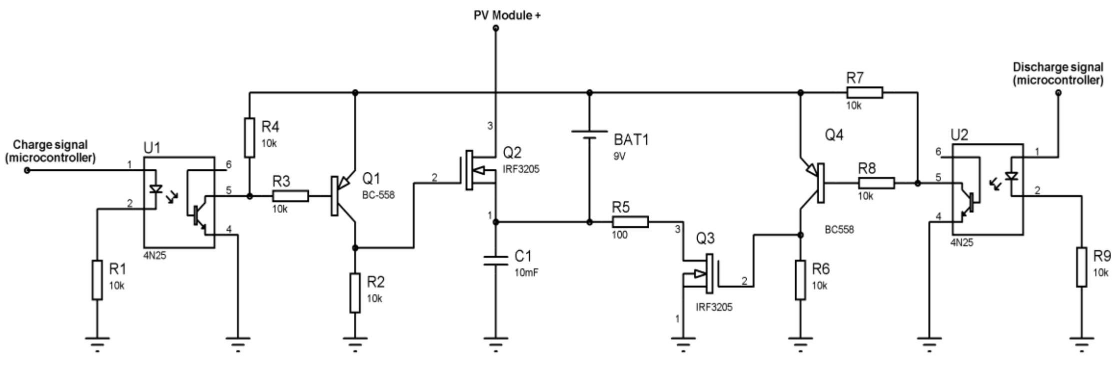

Fig. 5: Complete electronic circuit

The voltage measurement must be planned in such a way that it does not interfere with the capacitor voltage and current: its equivalent impedance must be high. Similarly, the current measurement circuit must not cause interference in the capacitor loading process: its impedance must be low, so that it does not introduce series resistance in the loop containing the capacitor. Therefore, the use of series resistors for indirect current measurement will be avoided. The solution adopted was based on current measurement by hall effect. The sensor model is the ACS-712, which has voltage output proportional to the current, with 100 mV/A ratio. The electronic circuit board containing the capacitive load and charge control circuit, as well as voltage and current measuring elements, is presented in Figure 6. In addition, the microcontroller board and the back of an LCD display are also shown.

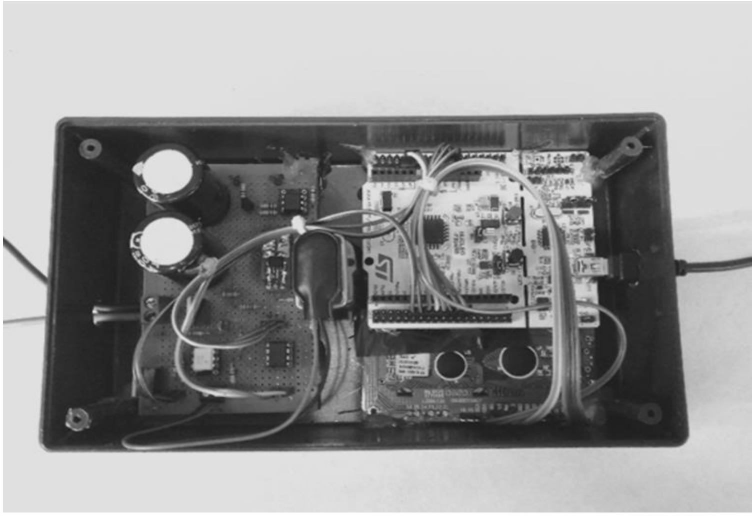

Fig. 6: Tracer prototype physical construction

The microcontroller board is model STM32F334R8, with an analog-digital (A/D) converter with 12-bit resolution. Figure 7 is a picture of the user interface developed in Visual Basic. The I-V and P-V curves are displayed, and I_{sc}, V_{oc}, I_{mp}, V_{mp}, P_{mp} and FF (fill factor) parameters are shown. In addition, system status messages are also available.

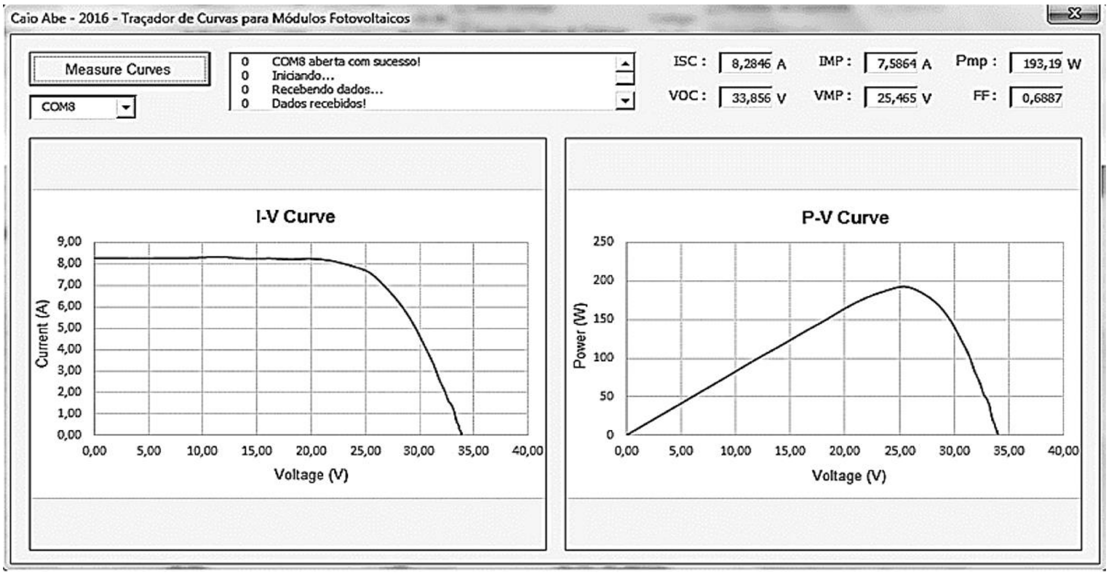

Fig. 7: Software user interface

IV. RESULTS AND DISCUSSION

To evaluate the I-V tracer response, a verification in steps was developed. As a first accuracy check of the prototype, I-V curves were measured under different conditions of irradiance and temperature. The parameters I_{sc}, V_{oc} and P_{mp} of the measured curves were compared with reference values: given by Equation (4) and by a calibrated digital multimeter. Second, the parameters in IEC 60891 equations were adjusted and checked according to the PV module datasheet information. The PV module manufacturer documentation provides data related to tests under STC and NOCT – normal operating cell temperature (G = 800 W/m² and Tc = 48 ºC, standard spectrum). Once equations 2 and 3 had their parameters defined, they were used to transpose the NOCT test data to STC equivalents. These transposed values were very similar to the original STC data provided by the module datasheet. Then, to check all the curve points measured by the tracer, data from the three tests under different conditions were transposed to STC via the already adjusted IEC 60891 equations. This resulted in three curves transposed to STC, which could then be directly compared to the original STC curve informed by the module datasheet.

4.1. Testing Conditions

For the curve tracer accuracy checking, three tests were performed outdoors, under very clear sky, considering different conditions of irradiance and temperature along a day. The irradiance G was measured by means of a previously calibrated PV module, in short circuit condition. Thus, the measured I_{sc} could be linearly related to G. The calibrated module was positioned very close and with identical inclination as that of the 265 W_p module under test. The 265 W_p module temperature was measured in its back face, with thermocouples following a diagonal line. Five symmetrically spaced points were taken, and the mean temperature was then calculated.

4.2. Initial Analysis

The first reliability analysis of the data acquired by the tracer was performed based on Equation (4), which considers the output power calculation, considering the module power, the irradiance and the temperature in STC, the thermal coefficient of power (γ), the irradiance and temperature values during a test. Therefore, since the irradiance G and cell temperature Tc are known, it is possible to estimate the module maximum power in such conditions.

$$P_{mp} = P_{STC}\ \frac{G}{G_{STC}}\left[1-\gamma\left(T_C - T_{C(STC)}\right)\right] \qquad (4)$$

Comparative results for V_{oc} and I_{sc}, whose reference was a calibrated digital multimeter, and P_{mp}, whose reference was Equation (4) are shown in Figure 8. V_{oc} and I_{sc} were measured during a clear sky day and were stable during this test. First, these parameters were measured with the digital multimeter. Then, the I-V curve was immediately traced. Parameters V_{oc} and I_{sc} presented maximum error on Test 3, with -2.17 % and -0.73 % respectively. Also, the maximum error for P_{mp} in this section was observed in Test 1, with -3.98 %.

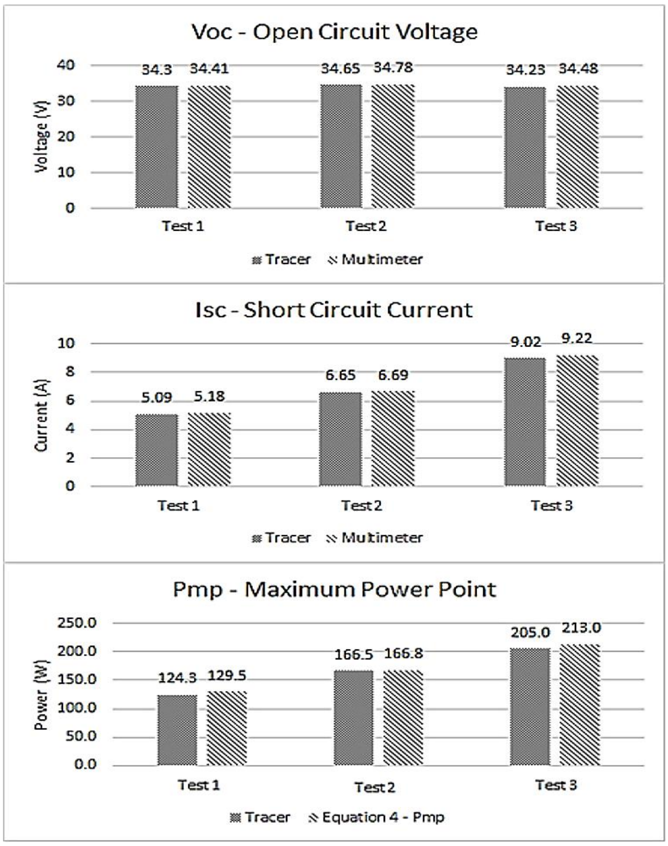

Fig. 8 – Accuracy tests data: initial analysis

4.3. IEC 60891: Parameters Adjustment

Equation (3), from Procedure 2 of IEC 60891 standard, contains parameters that are not normally provided on PV modules datasheets. They are *a*, *Rs* and *k*. These parameters, already described in section II (Background), were determined according to IEC 60891 [5], based on the STC and NOCT characteristic I-V curves provided by the 265 W_p module manufacturer. The STC and NOCT tests data contained on the module datasheet are presented in Table 3. In turn, the parameters concerning the adjustment of IEC 60891 Equations (2) and (3) are shown in Table 4.

Table 3: Summary of tests: STC and NOCT data (from manufacturer)

	STC	NOCT
G (W/m^2)	1000	800
T (°C)	25	48
P_{mp} (W)	265.03	197.13
I_{mp} (A)	8.63	6.9
V_{mp} (V)	30.71	28.57
I_{SC} (A)	9.24	7.45
V_{OC} (V)	37.81	35.46

Table 4: Adjusted parameters – IEC60891 (equations 2 and 3)

α *rel* (A/°C)	**5.41E-05**
β *rel* (V/°C)	-8.20E-05
Rs (Ω)	0.403
K	0.01086
a	0.084

With the data from Tables 3 and 4, along with the IEC 60891 equations, the transposition of the NOCT test to STC equivalent results in the values and associated errors shown in Table 5. It can be observed that by following IEC 60891 procedure, the NOCT test data transposed to STC resulted in values that are very close to the original STC values. This indicates that such equations are adjusted for this module, therefore they can be used in further analysis.

Table 5: Transposition of NOCT test results to STC equivalents and associated errors

	NOCT test (transposed to STC)	STC data (datasheet)	Error (%)
G (W/m^2)	Transposed to 1000 (original 800 W/m²)	1000	-
T_c (°C)	Transposed to 25 (original 47 °C)	25	-
I_{mp} (A)	8.61	8.63	-0.18
V_{mp} (V)	30.76	30.71	0.17
P_{mp} (W)	266.31	265	-0.01

4.4. Accuracy: transposition via IEC 60891 and module datasheet as reference

For the tracer prototype validation, the data provided by the module manufacturer were compared with the values obtained from the practical tests. These practical results had their values transposed to STC equivalents, via the already adjusted IEC 60891 equations, so that the values could be directly compared with the PV module datasheet. The ambient conditions and the values measured by the tracer in each test are presented in Table 6.

Table 6: Accuracy tests data: tracer measurements

	T_c (ºC)	G (W/m²)	P_{mp} (W)	V_{oc} (V)	I_{sc} (A)	V_{mp} (V)	I_{mp} (A)
Test 1	52.62	542	124.34	34.30	5.09	25.85	4.81
Test 2	55.23	720	166.50	34.65	6.65	26.64	6.25
Test 3	67.81	976	205.01	34.23	9.02	24.09	8.51

From I-V and P-V curves provided by the tracer during the three tests, points transposed to STC were generated by the application of Procedure 2 of IEC 60891. The three transposed I-V curve points are shown grouped in Figure 9, which also includes the reference curve line provided by the module manufacturer, in STC.

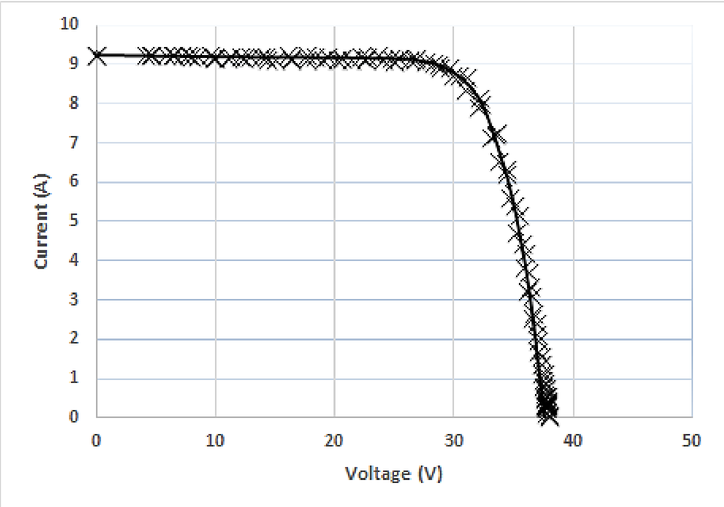

Fig. 9 – I-V transposed points and reference curve (STC)

The P-V curves points, from the transposed tracer measurements, are shown in Figure 10. It also shows the P-V curve informed by the PV module manufacturer.

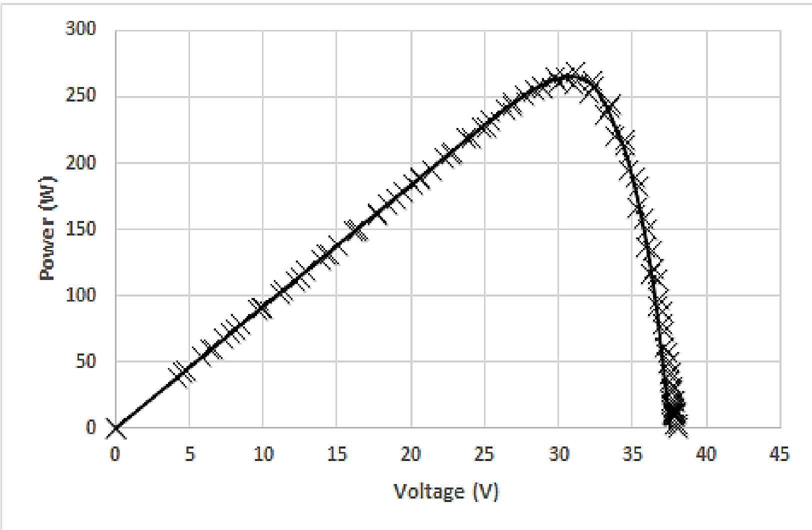

Fig. 10 – P-V transposed points and reference curve (STC)

The parameters I_{mp}, V_{mp} and P_{mp} transposed to STC, as well as P265NPB module nominal ratings, are presented in Table 7.

Table 7: Accuracy tests data: values transposed to STC

	T_c (ºC)	G (W/m²)	P_{mp} (W)	V_{mp} (V)	I_{mp} (A)
Test 1	Transposed to 25 ºC	Transposed to 1000 W/m²	261.04	29.97	8.71
Test 2	Transposed to 25 ºC	Transposed to 1000 W/m²	269.41	31.11	8.66
Test 3	Transposed to 25 ºC	Transposed to 1000 W/m²	265.26	30.49	8.70
Module Datasheet	25 ºC	1000 W/m²	265.00	30.81	8.63

In turn, the transposition errors, taking the PV module datasheet information as reference, are shown in Table 8. The largest error observed at the transposed P_{mp} was 1.66 %, referring to Test 2. Also, for the same test, I_{mp} and V_{mp} presented errors of 0.36 % and 1.30 %, respectively. The largest errors for V_{mp} and I_{mp} were found in Test 1: -2.73 % and 0.93 %, respectively.

Table 8 - Associated errors – transposition to STC

	P_{mp} (W)	V_{mp} (V)	I_{mp} (A)
Test 1 % error	-1.49 %	**-2.73 %**	**0.93 %**
Test 2 % error	**1.66 %**	-2.27 %	0.35 %
Test 3 % error	0.01 %	1.04 %	0.81 %

V. CONCLUSIONS

The purpose of this work was the construction and performance evaluation of an I-V curve tracer integrated to a research and teaching platform in solar photovoltaic energy. The prototype is connected to the section of the system that contains the microinverters. Tests can be performed in real time and can be accessed remotely through the internet. The prototype, although simple in design and low-cost, is suitable for the application. Initial accuracy analysis considered the parameters V_{oc}, I_{sc} and P_{mp}, which presented maximum error below 4 %. The application of IEC 60891 Procedure 2 equations allowed to transpose the curves measured during the tests to STC equivalents. Then, the data could be easily compared to the PV module datasheet curves. Concerning the parameters I_{mp}, V_{mp} and therefore P_{mp} transposed to STC, the maximum error was below 3 %. The authors expect that the inclusion of this I-V curve tracer to the Research and Teaching Platform on Photovoltaics at Unisinos will contribute to its usefulness, by providing real graphical resources regarding the PV modules under test. This information can be reached remotely by students and researchers without any cost.

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