



Double sweep tracer for I-V curves characterization and continuous monitoring of photovoltaic facilities

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ABSTRACT

The good performance of solar photovoltaic energy facilities implies the previous evaluation of the electrical behaviour of the solar modules used. Among other ways, this evaluation can be done by means of the static voltage-current characteristic (I-V curve), but also through a real-time electrical parameters monitoring. This paper proposes the design of an I-V curve tracer with electronic load. The main advantages of the prototype are its reduced cost, scalability, wireless control and sampling rate. A PIC18F46K80 microprocessor was used for the design and construction of the prototype. The development of an Android app allows the control of the prototype and the data acquisition from any mobile or tablet device. Additionally, the tracer can be configured for a continuous monitoring of the electrical parameters, temperature and irradiance.

1. Introduction

In order to evaluate the performance of photovoltaic (PV) modules, it is necessary to measure their current-voltage (I-V) output characteristics. The PV module manufacturers provide the I-V curves measured at laboratory conditions (Standard Measuring Conditions, SMC), which may be rather different to the actual conditions (irradiance, temperature, series-parallel solar cells combinations) that the panels may undergo, so affecting the I-V characteristic (Ibrahim and Anani, 2017), and thus the panel production. Moreover, the degradation of PV cells of modules is usually assessed by means of this I-V characteristic, as well as parameters obtained from it, like short-circuit current (I_{SC}), open-circuit voltage (V_{OC}), maximum power (P_{max}) and fill factor ($FF = P_{max}/I_{SC} V_{OC}$) (Leite et al., 2012). For all these reasons, it is crucial to use an I-V curve tracer.

The most used tracers work with variable electronic DC loads, variable charging capacitors or variable resistive loads (Durán et al., 2008; García-Valverde et al., 2016; Leite et al., 2012; Meiqin et al., 2009; Rivai and Rahim, 2014; Willoughby and Osinowo, 2018). Other less extensive kind of tracers use loads based on DC-DC converters (Durán et al., 2009) or four quadrant power supplies. The latter provide a quick answer, but they are usually expensive and bulky.

This work presents a low-cost double sweep electronic load tracer, with control of both voltage and current, which can provide the module I-V characteristic *in situ*, comfortably and quickly. Moreover, it can be

used for monitoring generating panels and for recording ambient parameters as air temperature, panel temperature, and irradiance.

2. Double sweep tracer design

This paper presents a tracer that uses a MOSFET transistor as load, but integrated in a circuit designed to improve the homogeneous data acquisition all along the curve. Figs. 1 and 2 show the tracer block layout. It is based on an 8-bit PIC18F46K80 microprocessor along with the necessary instrumentation elements for the measurement of radiation and the temperature of three different points, such as ambient, PV module back, and irradiance meter temperatures.

The microprocessor has a 12-bit ADC with a typical conversion time of 20 μ s; with this ADC all the necessary analog signals are taken: voltage, current, irradiance, 3 temperatures, and also the battery level of the module itself. The microprocessor does not have a DAC of the proper resolution for operation, for this reason an external ADC with a resolution of 12 bits is used, connected by SPI.

To have a maximum operating margin, the main variables, voltage and current, have two scales, varying the gain in two levels in relation $\times 1$ and $\times 10$. The voltage is measured through a resistor divisor (120–5 V) using a differential amplifier. A 10 m Ω shunt with Kelvin connection and a high-speed instrumentation amplifier are used for the current measurement. Since the feedback may present oscillation problems, the components, such operational amplifiers and compensation

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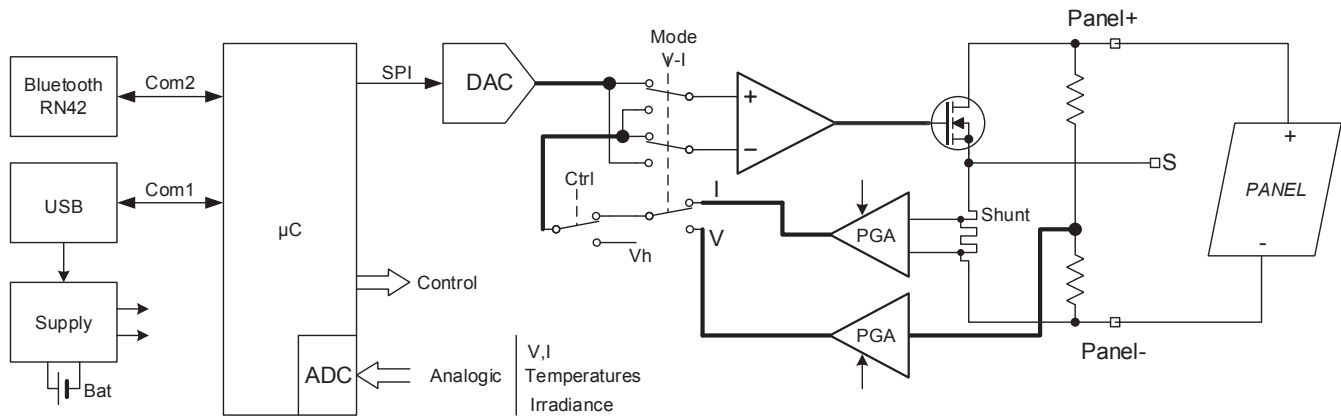


Fig. 1. Complete principle layout of the double sweep tracer. All components are shown working as (i) tracer and (ii) panel monitoring system.

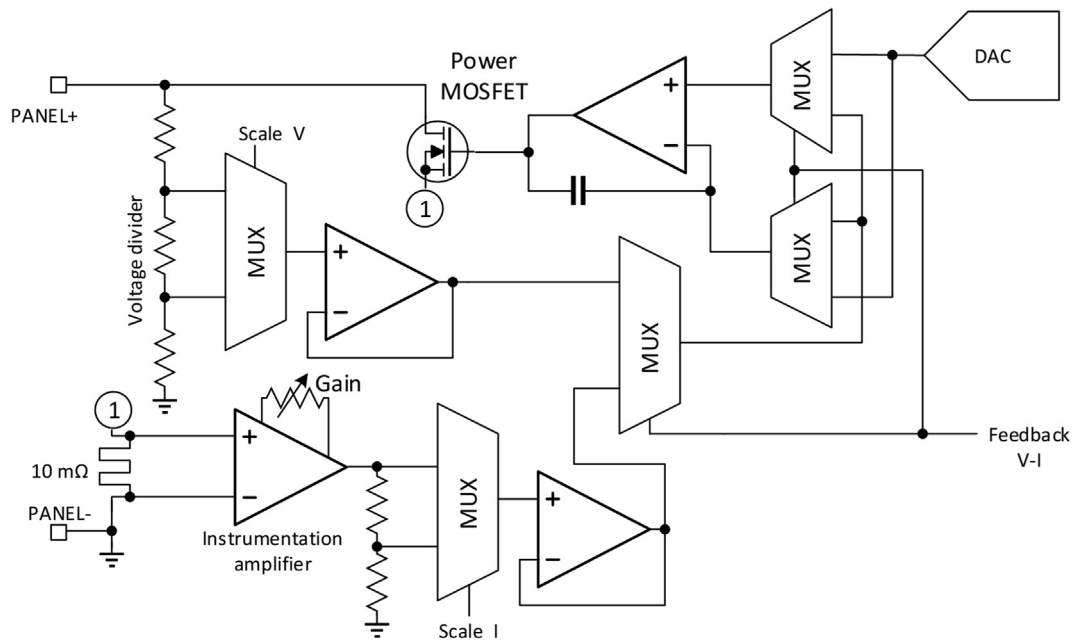


Fig. 2. Analog section of the tracer circuit.

networks, have been selected, simulated and tested so that they do not oscillate.

When the I-V curve of a panel is captured, the voltage and current are sampled 10 times at each measurement point; it takes 200 μ s of conversion time, which is sufficiently fast. This allows reducing the noise and improving the resolution.

The device has two working modes: as I-V curves tracer, and as a system for monitoring magnitudes of a panel while generating power.

The tracer works by means of a double sweep, one at constant voltage and another one at constant current (Fig. 3). More detail in both ends of the curve is achieved with this double sweep in the region where the module provides nearly constant current, applying voltage control (Fig. 3a) and in the zone where voltage can be considered approximately uniform, applying current control (Fig. 3b). Additionally, to get a good curve scan, the sweep has to be as quick as possible, in order to avoid the changes in the photovoltaic module measurement conditions. Besides, a size reduction in the equipment is gained because the dissipation of energy is small even in the case of considerably high instant power.

For the I-V curves plot (Fig. 3), the control microprocessor will establish the interval divisions of the voltage and current scales and the time between measures. In each case, an external computer or smart device can assign these parameters, although they may also be settled

by default.

Unlike other electronic load tracers, this prototype uses a control system for making the (I, V) measurements. For the measurement of a point in the I-V curve, each instant of time the microprocessor will establish a set-point voltage V_{SP} (Fig. 3a) and a set-point current I_{SP} (Fig. 3b). Note that both current and voltage feedback is a negative feedback. In the case of voltage feedback, the polarity of the amplifier that is connected to the MOSFET gate has the polarity changed so that the feedback of the loop is negative, given that what is controlled is the voltage of the panel.

The sweep of the curve begins with the open circuit voltage reading. This will be the full-scale value for the voltage scale, which will be split into programmed intervals. Regulating constant voltages in the panel in decreasing direction, the pairs of values I-V are logged for each interval point, going down until the short circuit end is found. In the measurement of the short circuit current, it is necessary to take into account that a very small impedance is present, due to the MOSFET transistor characteristic and the shunt impedance, typically less than 20 m Ω of equivalent resistance.

Starting with the former short circuit current, constant currents are regulated in decreasing direction down to open circuit. In a similar manner as before, the pairs of I-V values are recorded in each interval, completing both sweeps so.

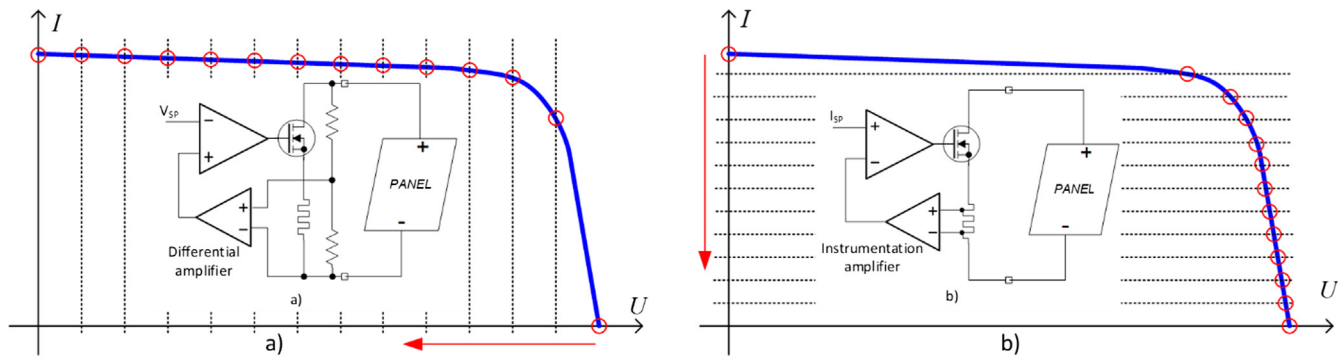


Fig. 3. Principle layout of the device working as a tracer of the characteristic I-V curve. (a) Voltage set-point. (b) Current set-point.

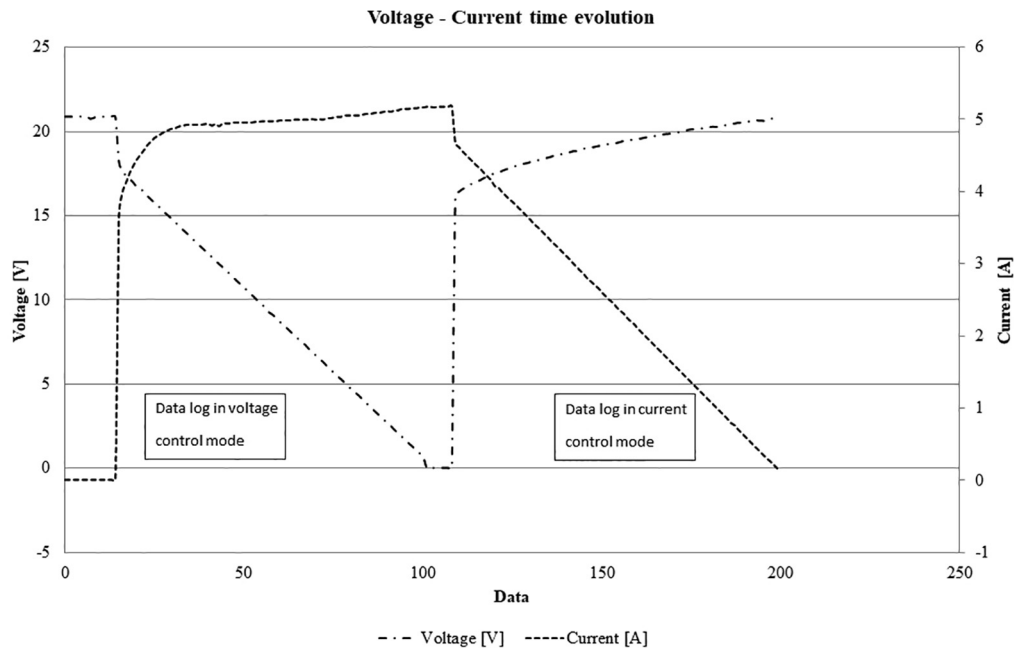


Fig. 4. Time evolution of voltage and current measures.

Fig. 4 shows the evolution of the voltage and current values along the two sweeps.

For the first 100 data, the voltage control is used, while current control is run for the next 100 points.

With the aim of improving the measuring precision in each step or measuring point, ten values are taken and averaged. The ADC converter (12 bits resolution) of the microcontroller is quick enough to carry out the measures in the available time.

The values recorded in each sweep are ready to be transmitted to an external computer or smart device, together with auxiliary values of temperature, irradiance and battery level. An external probe can be used for measuring irradiance, as well as for the measurement of three different temperatures: ambient, panel surface and irradiance probe temperatures.

Scales and calibrations of electrical magnitudes, temperatures and irradiances are stored in the microcontroller EEPROM, enabling the control computer to read these values for correct fittings.

This device can also work as a continuous monitoring system of a panel supplying energy to a load. In this case, the MOSFET is open, but the load current is forced to go through the shunt for its measurement (Fig. 5). The external computer will schedule the measurement of a set of values (voltage, current, temperature and irradiance) at even intervals.

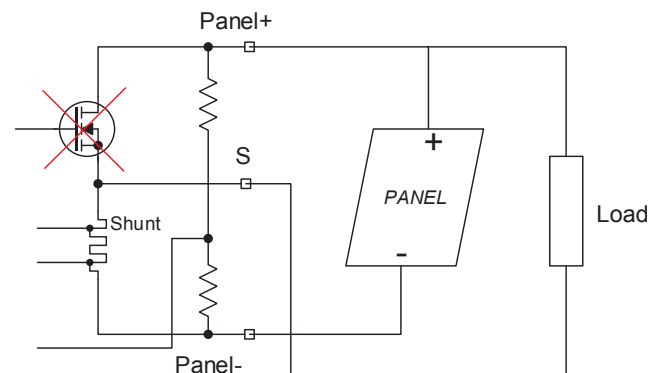


Fig. 5. Principal layout of the device working as monitoring system of a panel connected to a load.

3. Electronic load thermal model

Fig. 6 shows the power to dissipate in the transistor, evincing a saw tooth trend. This will be the power to dissipate in the transistor heat sink. If the sampling time is 1 ms, the curve sweep will take 200 ms.

The power that the tracer can handle is limited by the thermal behaviour of the transistor. The prototype works with a MOSFET

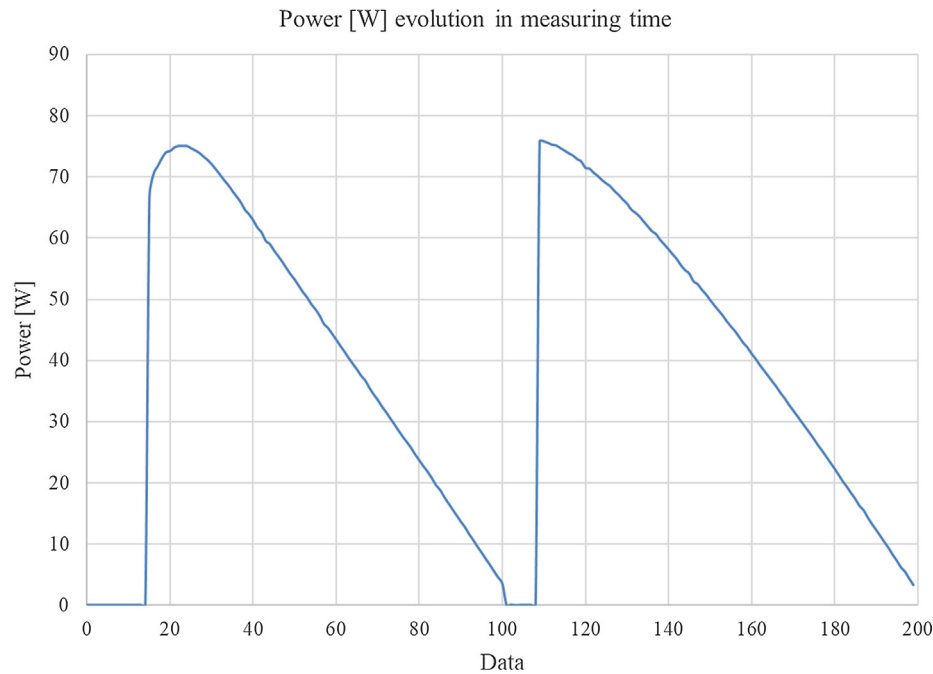


Fig. 6. Power dissipation during measurement.

IRFP4568 transistor (International Rectifier, 2014b) with a maximum dissipation power of 517 W for a capsule temperature of 25 °C, limiting thus to that value the maximum power that the tracer is able to handle.

Fig. 7 shows the thermal model of the transistor-heat sink ensemble. The parameters R_{jc1} , R_{jc2} and C_u define the junction to the case. The parameter R_{cr} models the thermal resistance between case and heat sink, while C_r and R_{ra} model the heat sink. The values of these parameters can be found in Table 1.

The thermal capacity and resistance have been calculated from Fischer Elektronik (2014), as a function of mass and specific heat capacity (C_p) of the dissipaters materials (aluminium). In this case, the specific heat capacity has been $C_p = 897 \frac{J}{K \text{ kg}}$, and the thermal capacity can be calculated as in:

$$C_r = \rho \left[\frac{Kg}{m^3} \right] \cdot Vol [m^3] \cdot c_p \left[\frac{J}{K \text{ kg}} \right]$$

The size used in the simulation has been $y = 50 \text{ mm}$ with $C_r = 363.1 \text{ J/K}$ and $R_{ra} = 1.6 \text{ K/W}$

The thermal power to handle in the transistor may be scaled from the reference power of Fig. 6.

$$\dot{Q}(t) = K \cdot power(t)$$

The evolution of temperature in time was simulated in Pspice to estimate the maximum power that the tracer shall measure, enforcing the condition of not exceeding a transistor junction temperature of an

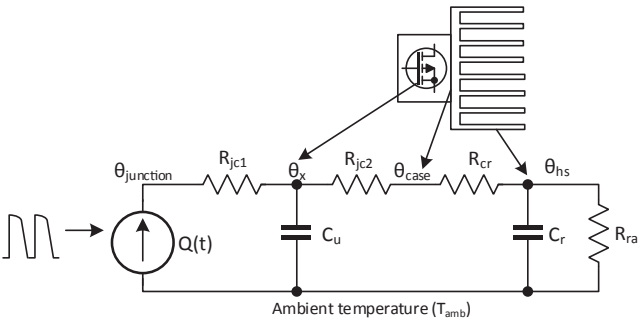


Fig. 7. Transistor thermal model.

Table 1
Thermal model parameters (International Rectifier, 2014b).

Parameter		
Junction	R_{jc1}	0.17424 K/W
	R_{jc2}	0.11484 K/W
	C_u	0.4668 J/K
	T_{max}	175 °C
Case	R_{cr}	0.24 K/W
Heat sink	$C_r = 363.1 \text{ J/K}$	
	$R_{ra} = 1.6 \text{ K/W}$	

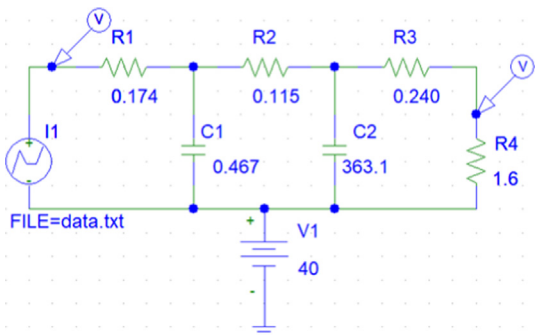


Fig. 8. Pspice thermal model.

80% of its maximum nominal value (Fig. 8).

The restriction of the junction temperature to 140 °C, limits the maximum power to handle to 322.5 W (Fig. 9).

4. Prototype and interface

The communication with the computer or smart device (smart phone, tablet) can be implemented by means of a serial port through a RN-42 Bluetooth® module working in SSP class, or through a USB (Fig. 1). Both types of communication are available simultaneously, and the microcontroller will reply to the commands of the active interface demanding data. The communication always starts with a request of the computer or smart device and the tracer will always attend the demand.

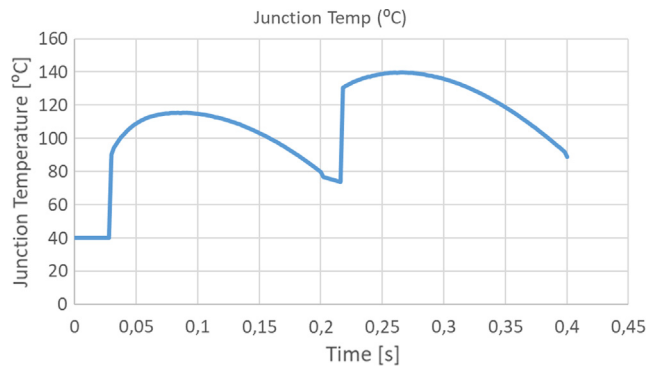


Fig. 9. Simulation of junction temperature time evolution for 322.5 W [K = 4.285] dissipation.

The communication uses a data frame running an “ad-hoc” protocol with a minimum overhead and data check (check sum). The USB connection allows also the charge of the battery.

Fig. 10 shows the appearance of the prototype, as well as of the app interface developed for *Android* systems. Table 2 summarizes the main features of the I-V tracer.

The tracer has no built-in interfaces and so it can only be handled by means of an external controller, *Windows* PC or *Android* device. A specific program has been developed for each system. The PC software is more complete because, among other reasons, it has more storing capacity and comfortability, with a bigger screen and keyboard. For this reason, calibration is always done on the PC.

The *Windows* PC application was programed in C# Net with Microsoft® Visual Studio. It is the most complete application because it allows the device calibration and disk recording. It enables the recording of the captured data, both from the curve tracing and auxiliary data and from the continuous monitoring process, if it is the case. Data are logged in a file with CSV format for its later processing.

Figs. 11 and 12 show a look of the initial and configuration screens of the *Windows* PC application.

The communication with the tracer is established through a virtual serial port, allowing the alternative use of USB or Bluetooth® connections, just selecting the available corresponding port.

An alternative application for *Android* devices (mobile phones and tablets) was programed in *Java* with *Android Studio* (Google®). This app allows the tracer control through the Bluetooth® communication (see Fig. 13).

Like the PC *Windows* app, the *Android* app allows the recording of tracer data. In this case, only the I-V and P-V curves can be recorded and recovered, as CSV files. The app can show in the screen instantaneous values of electrical variables, temperature and irradiance, but they cannot be recorded (Fig. 14). It uses calibration values stored in the tracer for each variable, but it is not possible to modify them

Table 2
Double sweep tracer features.

Characteristic parameter	Value
Maximum voltage	120 V
Maximum current	20 A
Maximum power	322.5 W
time between readings	1–100 ms
Maximum points data	512
Temperature channels	3
Measuring temperature range	20–150 °C
Irradiance measure	External cell, using a temperature channel; a transconductance amplifier is used for the measure (virtual short circuit)
Bluetooth® communication	38,400 baud Alternative: WiFi module (WiFi-Direct) SSP Class
USB communication	38,400 baud PC configuration as <i>Virtual Comm</i> Battery charge
Size (LWH)	12 cm × 8 cm × 5,5 cm

(Fig. 15).

5. Tracer validation and testing

After the design and construction of a tracer, it is necessary to compare it with other reference tracers for its validation. The validation was possible thanks to the collaboration of the National Research Centre CIEMAT, that prepared an “ad-hoc” I-V tracer for the inter comparison with the double sweep tracer. A set of tests were performed over two kind of modules: APOLO SOLAR ENERGY with 180 Wp (monocrystalline silicon) and KANEKA GEA211 with 60 Wp (thin layer), that have very different I-U characteristics, open voltages and short circuit currents. In the case of the Kaneka module, open voltage reaches 91.8 V, while the Apolo open voltage lies on 44.93 V. With such differences, it was possible to observe the behaviour of the tracer at different voltages, and how the automatic scale change works.

The comparison between the results of both tracers also enables to calibrate the studied tracer, by reference to the CIEMAT tracer. Fig. 14 shows the obtained I-V curves for both modules with both tracers, with the correction in voltage and current applied to the double sweep tracer for its calibration.

The graphs show that the results and evolution of both characteristics coincide, if the corrector factors are applied to the entire curve track of the double sweep tracer. First, the scale factors of voltage at the open circuit point and current at the short circuit point need to be determined:

$$f_v = \frac{V_{oc}^{tracer\ ref}}{V_{oc}^{tracer}}; \quad f_i = \frac{I_{sc}^{tracer\ ref}}{I_{sc}^{tracer}}$$

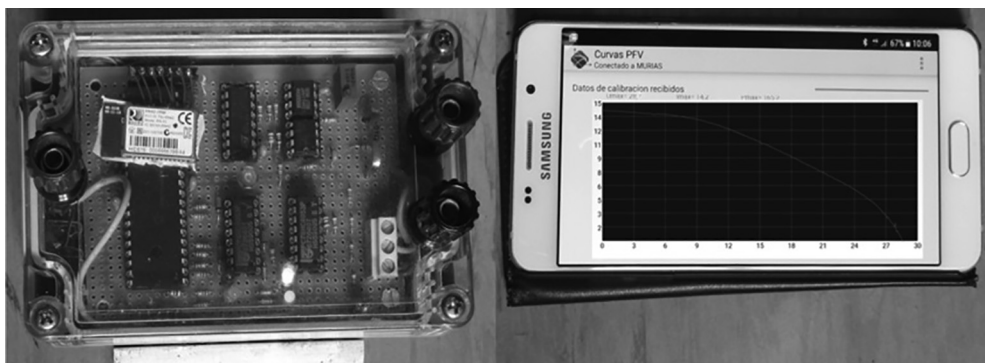


Fig. 10. Prototype of the double sweep tracer in communication with an *Android* mobile phone.

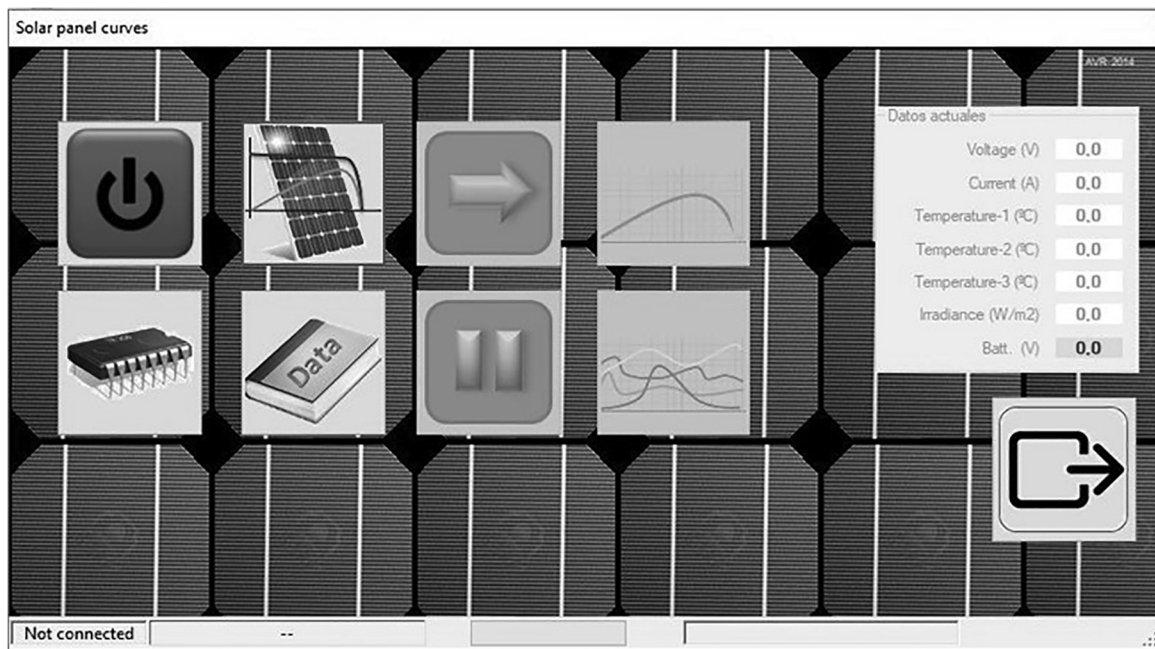


Fig. 11. Initial screen of the Windows PC application developed for the double sweep tracer control.

And after that, the factors are applied to the entire curve results, such that:

$$V_i^{tracer\ corr} = f_v V_i^{tracer}; \quad I_i^{tracer\ corr} = f_i I_i^{tracer}$$

The former results lead to the conclusion that the double sweep tracer has an identical behaviour as the reference one and, furthermore, it shows a good response testing modules of different technologies. The biggest problem related to the measurements was the fragility of the prototype, due to its artisanal manufacture.

With the aim of exploring the possibilities of the tracer, different measurements were carried out on modules under different shadowed conditions, and so in conditions that imply very different I-V characteristics from the standard curves. Figs. 15 and 16 show the results of the I-V and P-V curves.

The cost of prototype components and assembly is estimated around 250 EUR, while similar tracers (PVA-600 TRI-KA i DS-100; see Table 3), have a cost around 3400 EUR, reason why it could be competitive in comparison with other commercial tracers. The prototype characteristics, Table 3, are compared with other commercial tracers. This prototype has been handmade with the minimum cost as possible. For this reason, the maximum power available is limited, but adding transistors in parallel (International Rectifier, 2014a) it is possible to measure larger photovoltaics plants.

6. Conclusions

As a conclusion, it has been proved that the double sweep tracer obtains valid results for the determination of the I-V characteristic of

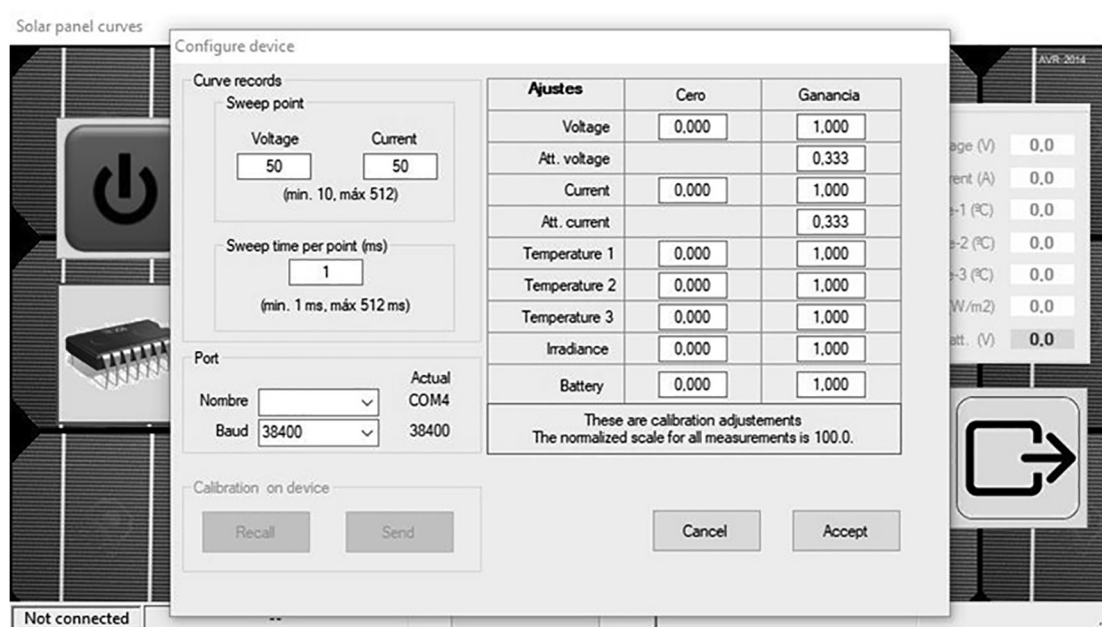


Fig. 12. Configuration screen of the Windows PC application developed for the double sweep tracer control.

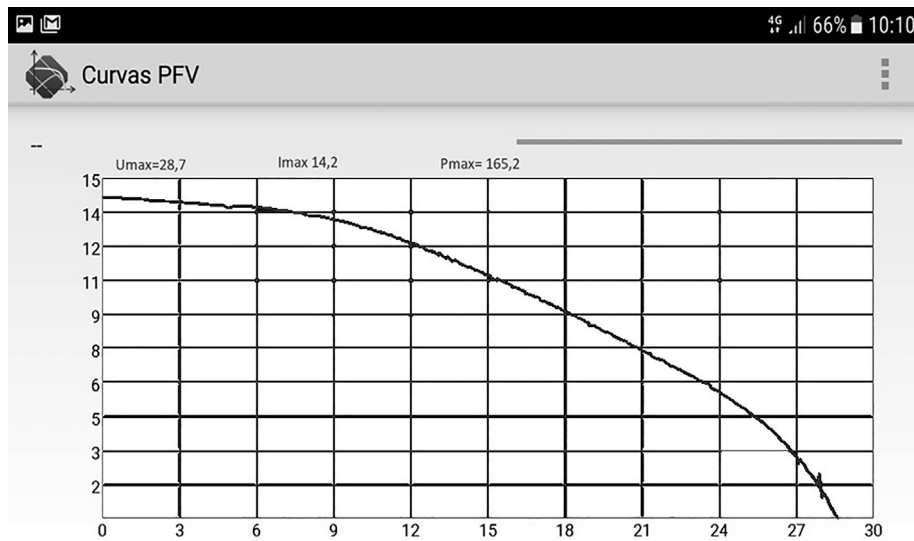


Fig. 13. Main window of the application developed for Android devices showing the I-U or P-U characteristic at user choice, by long press on screen or through the menu.

solar panels. Its main advantages compared to other tracers of extended use are a low size and weight, easiness of connections and the possibility to use a portable smart device (such as a tablet or mobile phone) for the tracer control and measurements recording.

The double sweep tracer prototype controls the data acquisition, both in voltage and current, what allows obtaining a homogenously distributed cloud of points along the entire I-V characteristic.

The transistor used as load limits the power to be tested. With the improvement in the design of the tracer with transistors in parallel (International Rectifier, 2014a), or simply using another transistor, for example the IGBT IXYK120N120C3, tests up to 1.5 kW (at 25 °C) could have been carried out. The prototype would enlarge the power measurement reach.

In addition to the tracer function, the possibility to work as a data acquisition system makes it very attractive for the monitoring and testing of a photovoltaic facility.

Thanks to its connectivity, the prototype is notably smaller than other commercial tracers.

Improvements in wiring and a printed circuit board will provide enhanced hardness to the tracer, as well as a size reduction.

The improvements will be completed by a calibrated and corrected in temperature cell implementation, the measurement of ambient and module temperatures, the development of an algorithm for the calculation of the I-V curve in SM conditions and an estimation of an

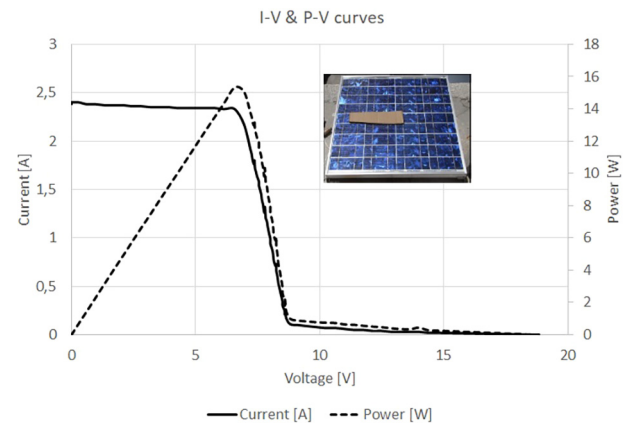


Fig. 15. Curves I-V and P-V obtained with the double sweep tracer for the module KC50.

equivalent model of the module.

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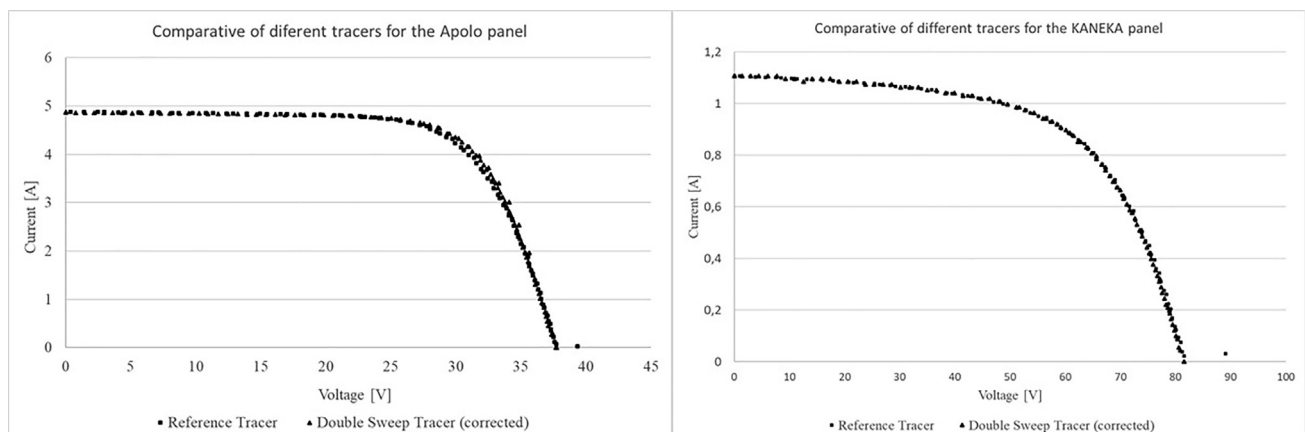


Fig. 14. I-U characteristic curves obtained both with the double sweep tracer (corrected) and reference tracer, for the Kaneka panel and Apolo panel.

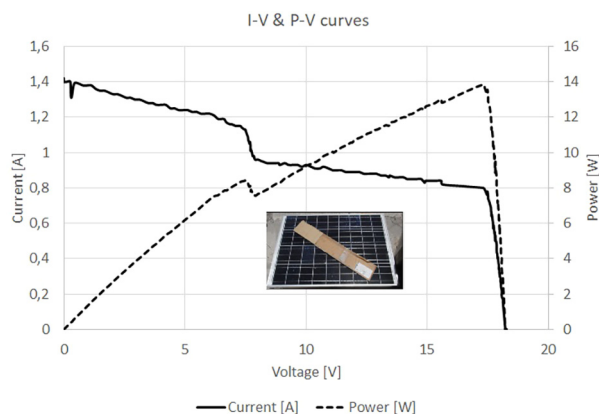


Fig. 16. Curves I-V and P-V obtained with the double sweep tracer for the module KC85GX-2P.

Table 3

IV-Tracers comparison.

Specifications	PVA-600 ^a	TRI-KA ^b	DS-1000 ^c	Prototype
Current Range	0–20 A	0.1–15 A	1–100 A	0–20 A
Voltage Range	20–600 V	1–1000 V	10–1000 V	0–100 V
Max Power			100 kW	322.5 W
Sample Time	–	–	–	1–512 ms
Sweep Time	50–240 ms	15–30 s	–	10–4 min
Weight	4.1 kg	0.5 kg	12 kg	0.5 kg
Trace points	100	–	1000	10–512
Cost	3400 EUR	–	–	250 EUR

^a <http://www.solmetric.com/pva600plus.html>.

^b http://www.tritec-energy.com/images/content/10801001_TRITEC_TRI-KA_web_esp.pdf.

^c <http://daystarpv.com/curvetracer2.html>.

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