Raspberry Pi based photovoltaic I-V curve tracer

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**Abstract**

This paper details the design and implementation of a photovoltaic current – voltage (I-V) tracer. The I-V tracer employs a capacitive load controlled by a raspberry pi model 4B. The complete measurement system includes protections, capacitor charging/discharging power electronics and current, voltage, irradiance and temperature sensors. Results, which include maximum power point, open circuit voltage, short circuit current and module efficiency, are displayed on an LCD touch display. Detailed description of the required software and the graphical user interface is also presented. This measurement system is very useful for testing photovoltaic installations, allowing an immediate verification whether the panels fulfill with the specifications and detection of possible failures.

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**Introduction**

In photovoltaic (PV) installations it is very important to know the characteristics of the solar panels used. This information is provided in the PV panels manufacturers datasheets, where some specific working points of the panel are detailed (open circuit, short circuit, and maximum power). This information is valid under standard test conditions (usually constant irradiance = 1000 W/m², temperature = 25 °C and air mass = 1.5) and extrapolations to other working conditions must be...
done with different formulas provided by the manufacturer or found in the technical literature. Besides, other useful information provided in the datasheet is the current versus voltage (I-V) curve and the power versus voltage (P-V) curve of the photovoltaic panel, these curves give a full-picture of the solar panel behaviour and how the working voltage affects the extracted current or power. Fig. 1 illustrates a typical I-V and P-V curve and the key points.

These curves change with the temperature, irradiance, ageing and many other external conditions during the panel’s life. That is the main reason why photovoltaic engineers use curve tracers to validate and test photovoltaic installations. The I-V / P-V curves can be measured periodically, given a detailed analysis of the behaviour when compared with the presented in the datasheets, and being a very useful tool to detect any problem in the PV installation (dirt, breaks, failures, shadows, ...) and to verify if the module meets with the efficiency parameters declared by the manufacturer.

To measure photovoltaic curves different methods have been proposed in the literature, the principle of operation of all of them is the same, they are based on a controlled sweep of the current provided by the panel, from the short circuit point to the open circuit point [1]. In [2] it is presented the development of a low-cost I-V curve tracer acquisition system based on TivaC Series LaunchPad, although the estimated material cost is less than 200 euros, it is not a stand-alone system, it needs a computer and also Labview software, which increments the total costs of the system and compromises its portability. In [3] it is also presented a low-cost PV I-V curve tracer, based on the variable load method, implemented with a MSP430 microcontroller, nevertheless this system also needs a computer to visualize the data and it is only valid for low power measurements. Finally, in [4] it is introduced a I-V curve tracer for PV research and teaching, this tracer is based on the capacitance method [5] and it is controlled by STM32F334R8 microcontroller, the user interface is developed in Visual Basic so an external computer is needed to run it.

The aim of this work it to develop a portable stand-alone PV I-V curve tracer with all functions and the user interfaces included so there is no need of an external computer. The system is based on the capacitive load method. During the capacitor charge process, pairs of voltage and current values are acquired at the output of the solar panel, which will correspond to those of the I-V characteristic curve of the panel. The hardware comprises three main parts:

- Measurement circuit, which will safely connect and disconnect the panel to the capacitor and sense the current and the voltage of the panel during the measurement.
- Control circuit, based on a Raspberry Pi computer, is responsible to control the measurement circuit, acquire the I-V data points, display the results, and interact with the user.
- Power supply, that powers the device from the main grid through AC/DC converter.

**Measurement circuit**

The measurement circuit presented in Fig. 2 is composed by two power relays (K1 and K2), a capacitor (C), a resistance to discharge the capacitor (RL), an IGBT (IGBT1), a voltage sensor (V) and a current sensor (A). An electrolytic capacitor with...
A capacitance of 2200 μF has been selected (Nichicon LNX2G222MSEG), the discharge resistance value is 120 Ω (ARCOL HS50 120R), power relays (G7L-2A-X-L of OMRON) have been used to control the connection and disconnection of the capacitor with the discharge resistance and the solar panel. An IGBT Infineon IHW20N120R5 is used to start the capacitor charging, without the rebounds and delays associated to the relays. Finally for the acquisition of the voltage and current, two transducers have been used. On the one hand, the LEM LV-25P for voltage measurement, and, on the other hand, the LEM LA 100-P for current measurement, both with galvanic isolation between the primary circuit (solar panel output) and the secondary circuit (acquired voltage signal). For the current measurement, four turns of the solar output cable are used to increase the precision and use all the sensor measurement range. As can be seen in Fig. 2, the voltage is measured directly at the solar panel output, and not at the capacitor terminals. Therefore, the measurement carried out by this device is a true reflection of the behaviour of the panel.

As can be seen in Fig. 2 there are three different control signals in the measurement circuit: S1, which manages K1 relay; S2, which controls the IGBT and S3, which manages K2 relay. These signals are isolated via opto-couplers from the control circuit for safety reasons. Table 1 shows the controlled sequence to perform a measurement, and Table 2 describes the purpose of each step in the sequence.

Table 1
| States of each control signal at each step. |
|-----------------|-----------------|-----------------|
| S1              | S2              | S3              |
| STEP 1          | OFF             | ON              | ON              |
| STEP 2          | ON              | OFF             | OFF             |
| STEP 3          | ON              | ON              | OFF             |
| STEP 4          | OFF             | ON              | OFF             |
| STEP 5          | OFF             | ON              | ON              |

Table 2
| Description of each step. |
|-----------------|-----------------|
| STEP 1          | Capacitor discharge before measurement |
| STEP 2          | Solar panel connection to the measurement system. |
| STEP 3          | Data acquisition. The IGBT is activated, and the sweep is performed |
| STEP 4          | After the sweep, the panel is disconnected from the circuit. |
| STEP 5          | Capacitor discharges after measurement |

Control circuit

Fig. 3 represents a diagram of the control circuit, and its most significant parts are: the single board computer (Raspberry Pi 4 Model B (8 GB)); the USB oscilloscope (Analog Discovery 2); the AC/DC converter (Adafruit ADS1115); and the touchscreen (Raspberry Pi 7" Touch Display).

A Raspberry Pi 4 Model B has been chosen as a single board computer to make the device completely portable. Moreover, it manages all the control signals via the 40-pin GPIO (General Purpose Input/Output) header.

A Digilent Analog Discovery 2 (AD2) USB oscilloscope has been chosen to acquire the voltage signals generated by the voltage (Oscilloscope channel 1) and current (Oscilloscope channel 2) sensors. This device is powerful enough to carry
out this task, and small enough to be included within the measurement device. Regarding its configuration, it has been pro-
grammed so that it measures with a resolution of 0.32 mV and with a sampling frequency of 320 kHz.

Irradiance and temperature analog sensors are conditioned by the Adafruit ADS1115, a 16-bit analog-to-digital converter with I²C interface. The sensor 7821 from DAVIS has been selected for the irradiance measurement, and the LM35 for temperature measurement.

Power supply

The power circuitry (Fig. 4) begins at the IEC C13 connector, which is connected to an AC / DC converter (TRACO POWER TMP 30452C) that converts 85–264 VAC to isolated 5 VDC and 12 VDC. The 5 VDC output is used by the control circuit
(Raspberry Pi, touch screen and ADS1115 AC / DC converter), and the 12 VDC output is used by two DC / DC converters, which supply the measurement circuit. The converter TEN 5–1223 is responsible for supplying ± 15 V to the current and voltage sensors and the DCP021212U is used to provide isolated control signals.

Design files summary

Bill of materials

Build instructions

A two layers Printed Circuit Board (PCB) has been designed to implement the measurement circuit, the control circuit, and the power supply circuit. Its fabrication is the first step of the assembly, and it may be outsourced to a PCB service provider using the provided Gerber files (iv_tracer_Gerbers.zip) (Table 3). Fig. 5 shows a render of the final PCB designed.

The second step is to populate the fabricated PCB (Fig. 6). Files iv_tracer.sch and iv_tracer.brd (Table 4) indicate the location of each component (Table 5) and the values of the resistors and capacitors. The time required to complete this step is about 6 h, and the necessary tools for soldering PCB are: a soldering iron, tin, flux, and isopropyl alcohol for PCB cleaner.

External connections to PCB is the third step. Table 6 shows the PCB connections with the other components of the device, and a diagram of the complete system assembled can be visualized in Fig. 7.

Next, enclosure machining can be done using the Blueprints.pdf file, which contains the blueprints of all the holes in the box where the different connectors and the screen will be placed. Finally, Fig. 8 shows how the components are positioned inside the box. The time required to complete this final step is about 8 h. Fully assembled device is illustrated in Fig. 9.

Table 3

Design Files Summary.

| Design file name       | File type          | Open source license            | Location of the file          |
|------------------------|--------------------|--------------------------------|-------------------------------|
| iv_tracer_EG_program.py| Software           | GNU Lesser General Public License (LGPL) 3.0 | https://osf.io/zrs5f/          |
| iv_tracer_library.py   | Software           | GNU Lesser General Public License (LGPL) 3.0 | https://osf.io/htkbv/          |
| iv_tracer_Gerbers.zip  | CAM files – PCB   | GNU Lesser General Public License (LGPL) 3.0 | https://osf.io/qm7se/          |
| iv_tracer.brd          | CAD file - PCB    | GNU Lesser General Public License (LGPL) 3.0 | https://osf.io/vpwre/          |
| iv_tracer.sch          | CAD file - Schematic | GNU Lesser General Public License (LGPL) 3.0 | https://osf.io/hujwn/          |
| Blueprints.pdf         | PDF                | GNU Lesser General Public License (LGPL) 3.0 | https://osf.io/yqukd/          |

Fig. 5. 2 layers PCB render.
Table 4
Design Files Description.

| Design file name         | Description                                                                 |
|--------------------------|----------------------------------------------------------------------------|
| iv_tracer EG_program.py  | Python script for the Graphic User Interfaces.                             |
| iv_tracer_library.py     | Python script. Requires installation of Python 3 or higher.                |
| iv_tracer Gerbers.zip    | Collated Gerber and drill files for PCB manufacture. An external manufacturer will likely require these files, packaged within the .zip archive. |
| iv_tracer.brd            | BRD (Autodesk Eagle) format design files for the printed circuit board.     |
| iv_tracer.sch            | SCH (Autodesk Eagle) format design files for the design of the circuit board. |
| Blueprints.pdf           | PDF with the blueprints of all the holes in the box.                       |

Table 5
Bill of Materials.

| Designator               | Component                        | Number | Cost per unit -EUR | Total cost -EUR | Source of materials | Material type |
|--------------------------|----------------------------------|--------|--------------------|-----------------|---------------------|---------------|
| Raspberry pi 4 8 GB      | RASPBERRY PI 4 MODEL B 8G        | 1      | 62.82 €            | 62.82 €         | Digikey             | Other         |
| Heatsink RPi case        |                                  | 1      | 20.90 €            | 20.90 €         | Digikey             | Other         |
| Raspberry Pi 7” Touch Display | 8997,466                  | 1      | 50.26 €            | 50.26 €         | Digikey             | Other         |
| Analog Discovery 2       | 410–321                         | 1      | 334.20 €           | 334.20 €        | Digikey             | Other         |
| Voltage Transducer       | LV 25-P                         | 1      | 22.81 €            | 22.81 €         | Digikey             | Other         |
| Current Transducer       | LA 100-P                        | 1      | 51.31 €            | 51.31 €         | Digikey             | Other         |
| Optoisolator             | HCPL-2231-500E                  | 4      | 5.77 €             | 23.08 €         | Digikey             | Other         |
| DC DC Converter 12 V     | DCP021212U                      | 1      | 8.04 €             | 8.04 €          | Digikey             | Other         |
| AC/DC Converter 5 V 12 V | TMP 30252C                      | 1      | 65.67 €            | 65.67 €         | Digikey             | Other         |
| DC/DC Converter +/-15 V  | TEN 5–1223                      | 1      | 21.70 €            | 21.70 €         | Digikey             | Other         |
| Relay 20A 12 V           | G7L-2A-X-L DC12                 | 2      | 72.94 €            | 145.88 €        | Digikey             | Other         |
| BJT Transistor NPN 350 V | BST39TA                         | 2      | 0.33 €             | 0.66 €          | Digikey             | Semiconductor |
| MOSFET N 240 V           | BSS87H6327FTSA1                 | 4      | 0.38 €             | 1.51 €          | Digikey             | Semiconductor |
| IGBT Transistor 1200 V   | IHW20N120R5XKSA1                | 1      | 2.78 €             | 2.78 €          | Digikey             | Semiconductor |
| Fuseholder               | 4527                            | 1      | 0.57 €             | 0.57 €          | Digikey             | Other         |
| Fuseholder cover         | 4527C                           | 1      | 0.27 €             | 0.27 €          | Digikey             | Other         |
| Fuse                     | 5SF 1-R                         | 1      | 0.20 €             | 0.20 €          | Digikey             | Other         |
Table 5 (continued)

| Designator | Component | Number | Cost per unit -EUR | Total cost -EUR | Source of materials | Material type |
|------------|-----------|--------|--------------------|-----------------|---------------------|--------------|
| C          | LNX2G222MSEG | 1      | 43.56 €           | 43.56 €         | Digikey             | Other        |
| C, C4      | EEE-FK1E220R | 2      | 0.35 €            | 0.70 €          | Digikey             | Other        |
| C7         | EEE-TK1J101AQ | 1      | 1.59 €            | 1.59 €          | Digikey             | Other        |
| C8         | EEE-HD1H180R | 1      | 0.30 €            | 0.30 €          | Digikey             | Other        |
| C6         | CL21B473KCFNNNE | 1      | 0.08 €            | 0.08 €          | Digikey             | Other        |
| C1, C2, C5, C9, C10, C11, C12 | CL21B104KCFNNNE | 6      | 0.08 €            | 0.48 €          | Digikey             | Other        |
| R31        | RMCF2512J10K0 | 1      | 0.25 €            | 0.25 €          | Digikey             | Other        |
| R32, R35, R42, R43 | RMCF2512J10K0 | 4      | 0.25 €            | 1.00 €          | Digikey             | Other        |
| LED1, LED2, LED3, LED4 | EAST2012WA1 | 4      | 0.21 €            | 0.85 €          | Digikey             | Semiconductor |
| LED_R, LED_R2 | SML-D12U1WT86 | 2      | 0.10 €            | 0.19 €          | Digikey             | Semiconductor |
| LED_G1, LED_G2, LED_G3, LED_G4 | SML-D12M1WT86 | 4      | 0.10 €            | 0.38 €          | Digikey             | Semiconductor |
| Connector Header | S103308–8 | 1      | 2.27 €            | 2.27 €          | Digikey             | Other        |
| RPi Connector | 1988     | 1      | 2.47 €            | 2.47 €          | Digikey             | Other        |
| USB 3.0 Cable | BC-HH003F | 1      | 5.85 €            | 5.85 €          | Digikey             | Other        |
| RJ45 Cable | A-USBD00AM-30AM-050 | 2      | 4.63 €            | 9.26 €          | Digikey             | Other        |
| Aluminium box 250x250 | 1550WNBK | 1      | 41.92 €           | 41.92 €         | Digikey             | Other        |
| RJ45 Connector | EHRJ45P5ES | 1      | 10.20 €           | 10.20 €         | Digikey             | Other        |
| USB 3.0 Connector | AC-USBD3-AAB | 2      | 12.25 €           | 24.50 €         | Digikey             | Other        |
| HDMI Connector | AC-HDMI-RBB | 1      | 10.26 €           | 10.26 €         | Digikey             | Other        |
| IEC320-C14 Connector | 1–1609112-3 | 1      | 9.62 €            | 9.62 €          | Digikey             | Other        |
| Temperature sensor | LM3352/NOPB | 2      | 1.43 €            | 2.86 €          | Digikey             | Other        |
| Davis irradiance sensor | 6450    | 1      | 168.29 €          | 168.29 €        | Davis instruments   | Other        |
| TOTAL      |           |        | 1151.85 €         |                 |                     |              |

Table 6

PCB connections.

| Connector | Connected to |
|-----------|--------------|
| X1-1      | Discharge resistor |
| X1-2      | Discharge resistor |
| X1-3      | Negative terminal capacitor |
| X1-4      | Positive terminal capacitor |
| X2-1      | +Vout1 TMP 30252C |
| X2-2      | -Vout1 TMP 30252C |
| X2-3      | +Vout1 TP 30252C |
| X2-4      | -Vout1 TP 30252C |
| X3-1      | 5 V to sensors |
| X3-2      | GND to sensors |
| X3-3      | Irradiance sensor data |
| X3-4      | Temperature sensor 1 data |
| X3-5      | Temperature sensor 2 data |
| X4-1      | Solar panel positive connector |
| X4-2      | Solar panel negative connector |
| X6-1      | IGBT 1 Collector |
| X6-2      | IGBT 1 Gate |
| X6-3      | IGBT 1 Emitter |
Fig. 7. Diagram of the PCB connections.

Fig. 8. Inside view of the device. In this image are not the USB, HDMI, and Ethernet cables that connect the Raspberry Pi to the connectors on the case. The USB cable that connects the Raspberry Pi with the Analog Discovery 2 is also not connected. The TMP 30252C converter is under the PCB.
Operation instructions

First, the I-V tracer should be powered through the IEC C13 switch. Second, open a terminal window and execute the Python script "iv_tracer_EG_program.py". Then, the graphical user interface is shown on the screen. In Figs. 10 – 13 are explained all the buttons and their purpose to perform a measurement. As can be seen in Figs. 14 – 15, there is a section devoted to display the results, where a preview of the last measure can be consulted. Also, the parameters and I-V and P-V curves of a specific measurement can be checked.

Fig. 9. View of the rear face (I), where there are the positive and negative connectors for the solar panels, and the connector for the electrical network; the front face (II), where are the USB, HDMI, and Ethernet Raspberry Pi connectors of the; and the upper cover (III), which only contains the touch screen.

Fig. 10. Starting screen. At the bottom there is a button for each section: Home (Section for starting new measures); Results (Section to consult previous measures); Settings (Section to configure measurement parameters); Exit (Button to close the program).
**Fig. 11.** Home screen. At the top there is a text field to write the name of the folder where the measurements will be saved. On the left is the current irradiance and temperature data. On the right is the current program settings. In the centre is the button to start the measurement.

**Fig. 12.** Measurement screen. It is generated by pressing the start button. To stop press the red button. In the centre there is a progress bar of the measurements. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
**Fig. 13.** Device settings screen. The capacitor discharge time is 1.32 s by default. If the capacitor is changed, it will have to be modified. In addition, the number of measurements in a series, the time between measurements, and the number of points in each measurement (it is limited to 16000) can be modified.

**Fig. 14.** Results screen. First, a preview of the last measurement appears on the screen. To see a specific measure, select the folder and the measure that you want to consult. Then select parameters, I-V / P-V curves, or export (Measurements can be exported to a USB stick).
Validation and characterization

To test the device's operation, tests have been carried out with the SR-P660255 panels of Sunrise. Table 7 shows its characteristics under Standard Test Conditions (STC) according to its manufacturer:

Table 7
Manufacturer information with STC (Standard Test Conditions): 1000 W/m², AM = 1.5, 25 °C.

| Parameter                        | Value          |
|----------------------------------|----------------|
| Maximum power (Pmax)             | 255 W          |
| Voltage at MPP (Vmpp)            | 30.24 V        |
| Current at MPP (Impp)            | 8.44 A         |
| Short circuit current (Isc)      | 9.11 A         |
| Open circuit voltage (Voc)       | 37.49 V        |

Fig. 15. Parameters screen.

Fig. 16. I-V and P-V curves of the measurement.
On the one hand, a measurement has been made without shadows. Fig. 16 shows the $I-V$ and $P-V$ curves of the measurement, and Table 8 shows the measurement parameters where FF is the Fill Factor, $G$ the irradiance and $T_1$ and $T_2$ the ambient temperature.

On the other hand, another measurement has been made with shadows on the panel. Fig. 17 shows the $I-V$ and $P-V$ curves of the measurement, and Table 9 shows the measurement parameters.

As shown in Figs. 16 and 17, the $I-V$ curve tracer measures in different conditions and provides the relevant information to discern between nominal and abnormal (shadowing) conditions. This information reveals very useful to photovoltaic installations.

Table 8
Measurement parameters.

| $V_{OC}$ [V] | $I_{SC}$ [A] | $P_{MAX}$ [W] | $V_{MPP}$ [V] | $I_{MPP}$ [A] | FF | $G$ [W/m²] | $T_1$ [°C] | $T_2$ [°C] |
|--------------|--------------|----------------|---------------|--------------|----|------------|------------|------------|
| 34.49        | 8.95         | 198.30         | 24.98         | 7.94         | 0.64| 945        | 28.1       | 28         |

![I-V Curve](image1.png)

![P-V Curve](image2.png)

Fig. 17. $I-V$ and $P-V$ curves of the measurement.

Table 9
Measurement parameters.

| $V_{OC}$ [V] | $I_{SC}$ [A] | $P_{MAX}$ [W] | $V_{MPP}$ [V] | $I_{MPP}$ [A] | FF | $G$ [W/m²] | $T_1$ [°C] | $T_2$ [°C] |
|--------------|--------------|----------------|---------------|--------------|----|------------|------------|------------|
| 34.42        | 8.91         | 120.60         | 15.39         | 7.84         | 0.39| 950        | 28         | 28.2       |

Conclusions

Previous tests show that the design implemented in this article verifies the immediacy and precision that can be obtained with the capacitive charge method. All the tests can be performed in real time and the data is processed instantly. In addition, the graphical interface allows the user to control the device without the knowledge of Python for its operation. Some of the possible applications where this curve tracer would be useful would be:

- Detect shadow losses.
- Check the correct operation of a photovoltaic installation.
- Characterize photovoltaic panels.

However, the device presented in this document has some limitations, such as:

- No battery for use in areas without electrical network.
- Low rated voltage (200 V) compared to commercial devices (more than 1000 V).
Various alternatives to the proposed curve tracer are available on the market, two examples are SOLAR I-Ve from HT Instruments, and IV TRACER FTV200 from Chauvin Arnoux. Table 10 benchmarks the proposed device against these commercial devices. As can be seen from this data, commercial systems have higher rated voltage (more than 1000 V) compared to PV IV curve tracer (200 V). Nevertheless, they are quite more expensive.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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