

Development of an electronic interface for diagnostics of photovoltaic strings

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Received: 30 June 2023 / Received in final form: 8 September 2023 / Accepted: 6 October 2023

Abstract. Photovoltaic (PV) systems can generate less energy than expected owing to inefficiency of the inverter, deterioration of the PV modules or conditions of partial shading and soiling. The monitoring and diagnosis techniques of PV systems are therefore quite important to recognize the causes of the performances reduction and optimize the PV energy production. For a more in-depth diagnostic capability, it would be necessary to know the short-circuit current (I_{sc}) and the open-circuit voltage (V_{oc}) of the PV system. These quantities are indeed useful to recognize non-uniform operating conditions of the PV modules (partial shadings, malfunctions, generic electro-optical mismatch conditions), estimate the PV module junction temperature and the voltage temperature coefficient. However, so far, these quantities cannot be measured by the inverter in operative conditions. With this contribution we propose and test a new electronic interface for a more advanced diagnostics of the PV system to be easily installed between the PV string and the inverter, able to measure the values of I_{sc} and V_{oc} as well as the inverter voltage, current and power working points, avoiding any downtime of the PV system and minimizing the power losses during the diagnosis activity.

Keywords: Photovoltaic systems / diagnostic functions / inverter / short circuit current / open circuit voltage

1 Introduction

As the demand for the utilization of solar energy continues to rise and photovoltaic (PV) plants age, it is quite useful to establish effective monitoring systems to optimize the PV energy production, helping the maintenance and operational planning (O&M). Monitoring systems that allowed operators to identify issues such as soiling, potential induced PV module degradation (PID), electrical mismatches due to partial shading, inverter failures, would enable timely intervention, maximizing the return on investment for PV systems.

Monitoring and diagnostic techniques for PV systems can be classified as either electrical analyses (e.g., dark/illuminated I-V measurements, transmission line diagnosis, RF measurements) or non-electrical methods (e.g., discoloration, browning, surface soiling, delamination, extraordinary thermal heating) [1]. Non-electrical methods, such as thermal imaging using expensive infrared cameras (sometimes mounted on aerial vehicles), can detect overheating of PV modules [2,3], however, they require specialized personnel and complex software for digitizing the entire PV field. Drone inspections with high-resolution

cameras offer a cost-effective means to detect localized soiling or faults in larger installations, but their accuracy may still be limited.

On the other hand, electrical monitoring methods are usually more cost-effective and commonly used in large-scale PV systems, often exploiting artificial intelligence techniques. These methods involve direct measurements of current, voltage, and power by the inverter, eliminating the need for additional hardware [4–10]. Real-time monitoring systems continuously collect electrical and environmental data (e.g., ambient temperature, solar irradiance, wind speed) to compare PV system performance (energy production) with predicted or historical benchmarks. Advanced data analysis algorithms process the collected data and use machine learning techniques to predict failures or soiling issues based on historical data, enabling proactive maintenance for minimizing the PV system downtime.

However, these methods have some drawbacks related to the quality of the collected solar and electrical data, which can potentially mislead the monitoring algorithms. For example, inaccurate solar irradiance data, resulting from insufficient cleaning of the global solar irradiance sensor (pyranometer or reference cell), can bring to underestimate the PV power output. To enhance the accuracy of solar irradiance data, PV operators often

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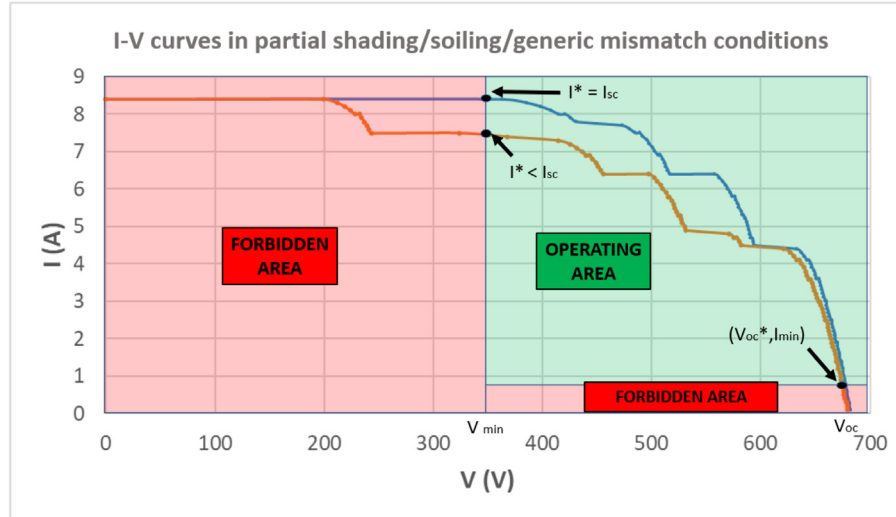


Fig. 1. I-V curves of a PV string under two different partial shading conditions are shown. The red areas (forbidden areas) include the I-V curve points that cannot be reached by a hypothetical inverter due to its voltage and current constraints. The PV string working point can only be set by the inverter in the green area (operating area). In orange, an I-V curve traced when more than 50% of the modules are shaded (or dirty); in blue, an I-V curve traced when the shading (or soiling) involves less than 50% of the modules. It can be pointed out that in the case of the orange curve, the current value I^* , measured in correspondence with the minimum voltage of the inverter, is lower than the correct I_{sc} value. Instead, in the case of the blue curve, the value of I^* coincides with I_{sc} .

integrate satellite data with sensor readings [11]. Electrical data quality issues can arise from an undersized PV inverter size, leading to clipping effects where the power of the PV system is limited by the inverter peak power, resulting in an underestimation of the available PV power. Additionally, maximum power point tracker (MPPT) algorithms implemented in the inverter control can make errors in estimating the maximum power point, especially under partial shading and rapid solar irradiance dynamics conditions, further contributing to the reduction of the measured power compared to the maximum available power from the PV system [12–14].

To obtain more advanced diagnostics it would be necessary to perform a frequent scan of the I-V curve to accurately calculate the most important electrical PV system quantities which are the short-circuit current (I_{sc}), the open-circuit voltage (V_{oc}) and the maximum power (P_{MPP}) [1]. Some latest generation inverters are able to acquire part of the I-V curve, between the minimum voltage of the DC side inverter and the V_{oc} (not being able to reach the open-circuit condition in operating condition but only when the inverter is switched off). This technique has the disadvantage that during the scanning of the I-V curve (it can last about a minute), the inverter works in points which have power values much lower than the maximum obtainable, reaching almost a zero value near the V_{oc} and I_{sc} conditions. Therefore, if the I-V curve sweep was too frequent, it would lead to a significant energy loss of the PV system. Furthermore, accurately measuring the actual values of V_{oc} and I_{sc} is challenging because inverters cannot operate under conditions where these values are achieved. However, the inverters could estimate the I_{sc} by setting the working point to the minimum inverter voltage. The current value obtained at this point is nearly equivalent to the short-circuit current, but only if the

PV string does not experience shunt resistance effects and is not affected by intense partial shading or significant soiling that impacts over 50% of the PV string modules. Unfortunately, when these conditions are present, the true short-circuit current would be significantly underestimated (see Fig. 1). It is worth noting that the short-circuit current is primarily affected by solar irradiance and temperature, with minimal influence from the electrical parameters of the photovoltaic string, such as series resistance, shunt resistance, and electrical mismatch. Additionally, the internal capacitance of PV modules can have a substantial impact on the measurement accuracy of current-voltage characteristic points if the scan time is too short, especially in the case of recent high efficiency PV modules [15].

To achieve advanced diagnostics without modifying the existing inverter technology or causing PV system downtime, we propose the development of a new electronic interface device EIDPS that could be easily installed temporarily or permanently between the PV string and any type of inverter. This interface allows the measurement of V_{oc} and I_{sc} under operating conditions, minimizing the PV plant power losses during their measurement.

The EIDPS offers a cost-effective solution to enhance algorithm-based software (online platforms) to accurately evaluate PV system performance. The integration of EIDPS with software tools would allow to identify the potential causes of the reduction of energy production, such as partial shading, malfunctions and electro-optical misalignments, without compromising the PV energy generation.

The contribution is structured as follows: [Section 2](#) describes the EIDPS interface concept, the hardware and control logic specifically designed for fast $I_{sc} - V_{oc}$ measurements. [Section 3](#) presents the experimental tests carried out under relevant outdoor conditions, along with

Table 1. States of each control signal at each step.

	S1	S2	Description of the step
<i>Step 1</i>	CLOSED	OPEN	Normal operating conditions
<i>Step 2</i>	OPEN	OPEN	Voltage transient and V_{oc} measurement – Open circuit conditions
<i>Step 3</i>	OPEN	CLOSED	Current transient and I_{sc} measurement – Short circuit conditions
<i>Step 4</i>	CLOSED	OPEN	Voltage and current transient – Normal operating conditions

the obtained results. Section 4 outlines the main diagnostic and monitoring functions made possible by the additional information provided by the interface (I_{sc} and V_{oc} values), in conjunction with other parameters and electrical measurements. Finally, in Section 5 we describe the future possible implementation.

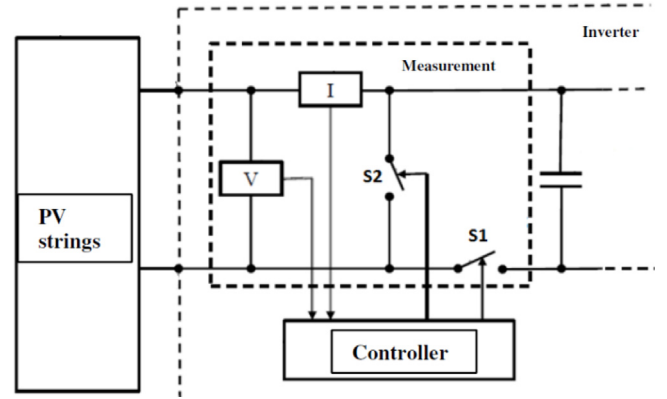
2 The new EIDPS interface concept

The new electronic interface device for photovoltaic systems (EIDPS), shown in Figure 2, uses a patented circuit/logic previously detailed in [14]. Initially, the interface was designed to be integrated into future generation inverters, allowing measurement of V_{oc} and I_{sc} in order to optimize the MPPT (Maximum Power Point Tracking) algorithm. However, to enlarge its applications, here we propose the EIDPS as a stand-alone device that could be used with any type of inverter, including older models. Its main components consist of two solid state relays (S1 connected in series to the PV string and S2 in parallel) controlled by a microcontroller which houses the implemented control logic. Through appropriate control logics, the relays temporarily disconnect the photovoltaic system from the inverter, allowing the measurements of I_{sc} and V_{oc} in a very short time with the aim of avoiding the inverter shutdown. The microcontroller effectively acquires the electrical measurements from two sensors: a current sensor (I) placed in series with the photovoltaic string and a voltage sensor (V) connected in parallel.

2.1 The EIDPS control logic

Under normal conditions, the switch S1 is closed, while the switch S2 is open and the downstream conversion device, typically an inverter, transfers energy from the photovoltaic system to the grid or to connected loads. The voltmeter (V) and ammeter (I) provide real-time measurements of the voltage (V_{wp}) and current (I_{wp}) values at the working point. It is essential to clarify that the EIDPS logic does not determine the working point on the current-voltage characteristic. Instead, it is the MPPT algorithm, implemented inside the inverter connected downstream of the interface, that establishes the optimal working point for the PV system.

Table 1 shows the control sequence for taking the measurements of I_{sc} and V_{oc} . The I_{sc} and V_{oc} measurement sequence can be activated by pressing a special button located on the interface device or it can be performed in

**Fig. 2.** Block diagram of the electronic interface for advanced diagnostics of photovoltaic system.

timed mode by acting on a control parameter (sequence time – T_{seq}) of the code implemented in the microcontroller.

After each switching command, two transient events occur. The first event concerns the switching time of the solid-state relay, while the second event concerns the charge of the internal capacitances of the PV modules.

To ensure precise electrical measurements close to stationary conditions, the steps related to electrical measurements follow a specific data acquisition routine consisting of three phases.

- **Delay phase:** this phase aims to initiate the measurements close to the steady-state conditions. It involves a predefined time delay ($T_{delay_{V_{oc}}}$ for V_{oc} and $T_{delay_{I_{sc}}}$ for I_{sc}) that must be observed before starting the measurement process.
- **Measurement phase:** this phase involves acquiring a specified number of samples ($N_{sample_V_{oc}}$ or $N_{sample_I_{sc}}$) with a designated sampling time (T_{sample}). The goal is to collect accurate data during this period, ensuring that the measurements are representative of the system's steady-state conditions.
- **Filtering phase:** after the data acquisition, this phase involves the application of a digital filter, specifically an infinite impulse response (IIR) filter, which is implemented inside the microcontroller firmware. The purpose of the filter is to process and enhance the acquired data, thus improving its accuracy and eliminating undesired noises or artifacts (see Sect. 2.2).

A proper firmware (EIDPS firmware) was developed and installed in the microcontroller's flash memory. It implements the control logic sequence described earlier and allows for adjustable parameter settings ($T_{delay_{V_{oc}}}$, $T_{delay_{V_{Isc}}}$, $N_{sample_{V_{oc}}}$, $N_{sample_{I_{sc}}}$, T_{sample} , T_{trig}), hereinafter referred to as *EIDPS parameters*.

The total time (T_{tot}) necessary to perform the entire measurement sequence of the V_{oc} and I_{sc} values is obtained according to the following equation (1):

$$T_{tot} = N_{sample_{V_{oc}}} * T_{sample} + N_{sample_{I_{sc}}} * T_{sample} + 2 * T_{delay_{V_{oc}}}, \quad (1)$$

where $T_{delay_{V_{Isc}}}$ is set equal to $T_{delay_{V_{oc}}}$.

The *EIDPS firmware* enables continuous acquisition and processing via a timed mode trigger (T_{trig}). Taking into account hardware constraints (i.e., microcontroller clock frequency and ADC conversion time), the sampling period T_{sample} can be set as multiples of 42 microseconds, while the delay periods $T_{delay_{V_{oc}}}$ and $T_{delay_{V_{Isc}}}$ can be set as multiples of 5 microseconds. Since the accuracy of measurements improves with a larger dataset (more samples), but this also increases the measurement duration, it is essential to find a balance between the desired accuracy of the measurements and time constraints. This balancing is necessary due to the need to take measurements under steady state conditions while ensuring that the duration of the measurement is short enough to prevent the inverter from shutting down. For this reason, a crucial part of our research has focused on optimizing of the *EIDPS parameters*.

A dedicated software (*EIDPS software*), developed in the LabVIEW environment, facilitates the transmission of parameter settings from a PC to the microcontroller and the retrieval of measured electrical data. *EIDPS software* acts as an interface for continuous communication between the user and the microcontroller, allowing to set the *EIDPS parameters* and the acquisition of accurate electrical measurements.

2.2 IIR digital filter

To reduce the contribution of the rising transient for the measurement of the V_{oc} and the oscillatory component that occurs during the measurement of the I_{sc} , it was decided to digitally filter the signal, this allows reducing the noises effect and getting a more reliable output measurement.

An *IIR* filter equivalent to a first order low-pass analog filter (Resistor filter – RC capacitor) was implemented by in the firmware of the microcontroller.

To allow the *IIR* filter functioning like the corresponding analog filter, the minimum T_{sample} and the time constant τ were set respectively 42 and 420 microseconds in order to obtain a cut-off frequency equal to 380 Hz. Such values were evaluated in order to ensure a time response shorter than the dynamic of the PV string electrical variables during the switching time.

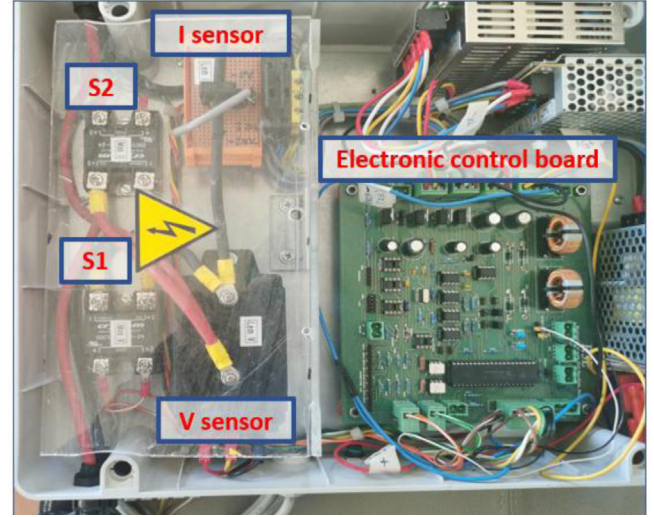


Fig. 3. Hardware implementation of the EIDPS.

2.3 The EIDPS hardware

Figure 3 shows the EIDPS realized on the basis of the conceptual scheme of Figure 2. The S1 – S2 switching time is less than 10 ms in order to supply the downstream loads without significant variations in the DC input of the inverter (DC link capacitor discharging), avoiding any inverter shutdown. The choice of the EIDPS electronic components was made considering the following typical specifications of many commercial inverters: nominal power (P_{nom}) equal to 7 kW, maximum voltage (V_{max}) equal to 780 V and maximum current (I_{max}) equal to 10 A.

The PV string voltage is measured by the LEM DVL 750 sensor, which has the following advantages: very short response times (slew rate); high measurement accuracy (even for values well below the nominal voltage); limited losses (maximum voltage drop of 1.5 V). The maximum voltage allowed by the sensor is ± 1125 V.

The PV string current is measured by the LEM HO 6-P sensor, which has the following advantages: very short response times (slew rate); minimum size; high immunity to external interference; possibility of exploiting the Hall effect, avoiding the wiring of the DC cable to the sensor (this feature eliminates the series resistance of the electrical contacts and consequently increases the life of the system). The maximum current allowed by the sensor is ± 20 A.

The EIDPS consists of Crydom solid state relays for the switching actions, offering advantages such as short switching times (approximately 150 μ s) and high voltage capability (up to 1200 V).

The electronic control board incorporates a Microchip microcontroller and firmware which follow the steps described in Table 1. The solid-state relays are based on Power Mosfet that are controlled by the microcontroller through optocouplers, which improve the galvanic isolation between the power system and the electronic board in order to avoid any overvoltage which could damage the microcontroller.

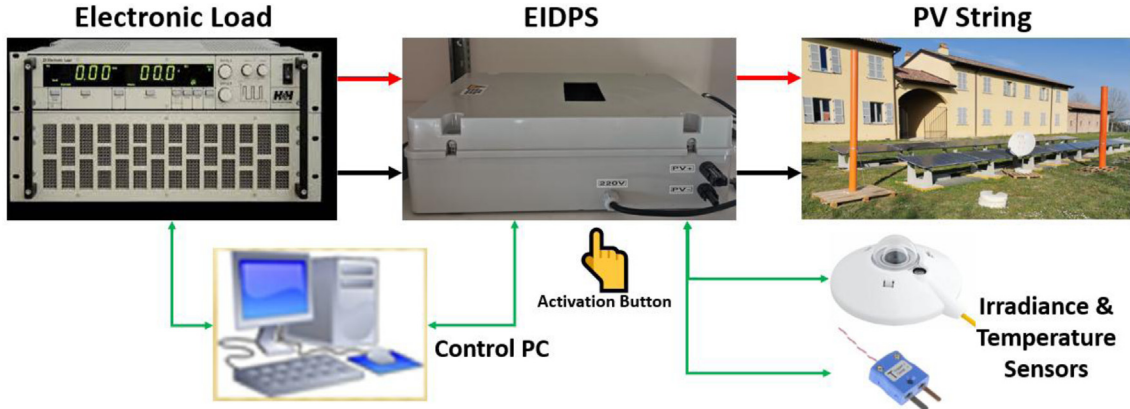


Fig. 4. Block diagram of the outdoor tests performed on the EIDPS.

Additional measurements can be acquired, including solar irradiance, using a solarimeter or reference cell, and ambient temperature for energy yield monitoring. The electronic board is also able to measure its own temperature for operational monitoring.

To adapt the signals, coming both from the current and voltage transducers and from the solar irradiance and temperature sensors to the analog input ranges of the microcontroller, suitable signal preconditioning circuits, based on operational amplifiers, were also integrated in the electronic board. To ensure accurate current and voltage measurements, the EIDPS preconditioning signal circuits were pre-calibrated under steady-state conditions by using, as reference, calibrated laboratory power supplies.

Data communication is facilitated via a RS485 serial port, enabling PV diagnostic routines, based on I_{sc} and V_{oc} values, which can be performed in external process units (PC, smartphone, etc.) with proper software.

The system also includes analog outputs to transfer the measured data to external devices that are not equipped with an RS485 serial port but have analog inputs. To allow synchronization between the analog outputs and the analog inputs of the external devices, *Sample & Hold* circuits were implemented which, as known, allow the measured values to be held until the next measurement.

3 Experimental test and results

3.1 Experimental setup

Outdoor tests were conducted to validate the functionality of the EIDPS and fine-tune its parameters. The experimental setup, showed in Figure 4, involved placing the EIDPS between an actual photovoltaic (PV) string and an electronic load.

The PV string used in these tests consisted of five bifacial modules connected in series, with each module having an area of 2 m^2 . Under Standard Test conditions (STC), this PV string would yield an open circuit voltage of 250 V and a rated short-circuit current of 10 A.

To simulate shading scenarios where the measured current at the minimum voltage of the inverter could be significantly lower than the actual short-circuit current, various obstacles like poles, satellite dishes, and chimneys

were installed near the PV string. These obstructions, combined with the partial shading caused by nearby trees, created realistic shading conditions for testing purposes.

The electronic load served two main purposes. Firstly, it was used for accurate replication of the inverter's DC-side operations during the testing process. It provided the capability to set the voltage of the PV string's operating point (V_{wp}) and facilitated the measurement of the corresponding current (I_{wp}) and power (P_{wp}). Additionally, the electronic load was used to measure the short-circuit current (I_{sc}) and open circuit voltage (V_{oc}) in steady state conditions, serving as a reference for verifying the accuracy of the measurements previously performed by the EIDPS interface. More precisely, once the measurement operations by the EIDPS interface were completed, the *EIDPS software* instructed the electronic load to switch into an open circuit condition and subsequently into a short circuit condition. This enabled the measurement of V_{oc} and I_{sc} , respectively, which can then be compared to the values obtained from the EIDPS interface.

The EIDPS interface autonomously triggered the I_{sc} and V_{oc} measurements every 20 s while the electronic load continuously controlled the operating point. It is crucial to note that, during these measurements, the voltage and current transients were influenced by the working point at the time of triggering (initial working point).

3.2 Optimization of the EIDPS parameters and results

To study the impact of the starting working point on the transient responses of I_{sc} and V_{oc} measurements, the EIDPS was tested under four different starting conditions:

- Case 1: Open circuit condition ($V_{wp} = V_{oc}$ and $I_{wp} = 0$).
- Case 2: Short circuit condition ($V_{wp} = 0$ and $I_{wp} = I_{sc}$).
- Case 3: Voltage equal to 200 V and a current value depending to the irradiance and shading conditions.
- Case 4: Voltage equal to 100 V and a current value depending to the irradiance and shading conditions.

During the measurements of V_{oc} and I_{sc} , the *EIDPS software* captured the voltage and current transients. This allowed for the analysis of the system's transient behavior and the optimization of *EIDPS parameters*. The goal was to find the optimal balance between the number of samples

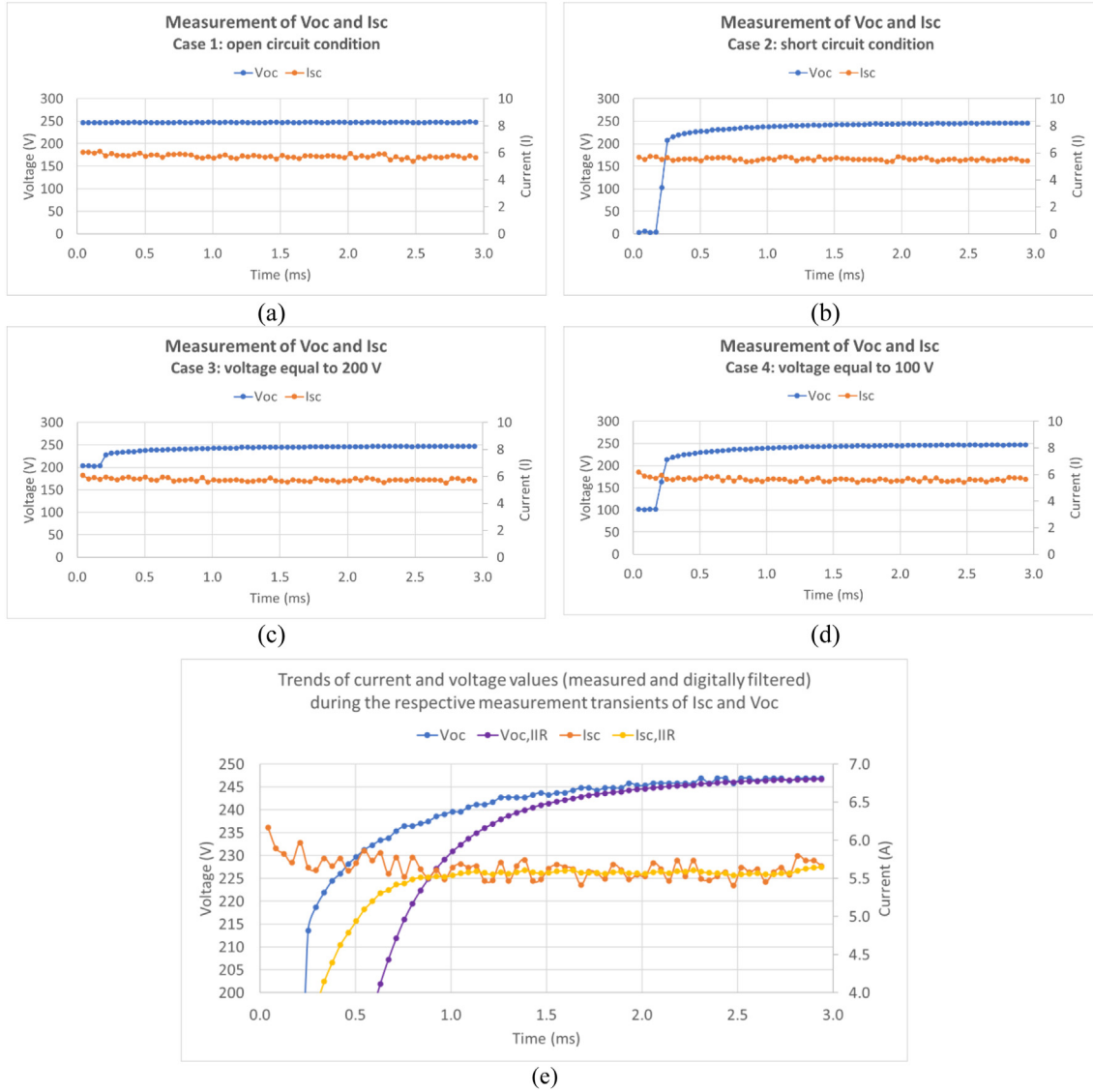


Fig. 5. In the graphs (a-b-c-d) the experimental measurements (not digitally filtered) of V_{oc} and I_{sc} in the four initial cases defined obtained with the optimized EIDPS parameters, are shown. Figure 5e shows, as an example, the current and voltage trends, already shown in graph (d), with the addition of the trends obtained using the digital IIR filter.

Table 2. EIDPS parameter values for V_{oc} and I_{sc} measurement.

N_{sample_Voc} $= N_{sample_Isc}$	$T_{sample} (\mu s)$	$T_{delay_Voc} =$ $T_{delay_Isc} (\mu s)$
70	42	350

(N_{sample}), sampling time (T_{sample}), and delay time (T_{delay}) to ensure accurate measurements in the shortest time. For the optimization process the tests were carried over several days with varying environmental conditions, including ambient temperature, solar irradiance, intermittent cloud cover, and different levels of partial shading caused by artificial obstacles and nearby vegetation.

Figure 5 shows the experimental voltage and current samples (not digitally filtered) for the four cases, using the optimized EIDPS parameters (see Tab. 2). From the graphs, it is evident that the optimized delay value ($T_{delay_{Isc}}$) minimizes the number of the I_{sc} samples captured in transient condition, allowing a rapid stabilization at steady state regardless of the cases considered. However, there is considerable noise in the I_{sc} measurement, mainly due to the quality of the Hall effect current sensor. During the engineering phase of the device, the choice of more accurate current sensors, such as those based on shunts, will certainly be evaluated.

Analyzing the V_{oc} measurement, it is evident that when the initial working point voltage is different from V_{oc} , there is a greater number of samples captured in a transient condition than the number of samples for the I_{sc}

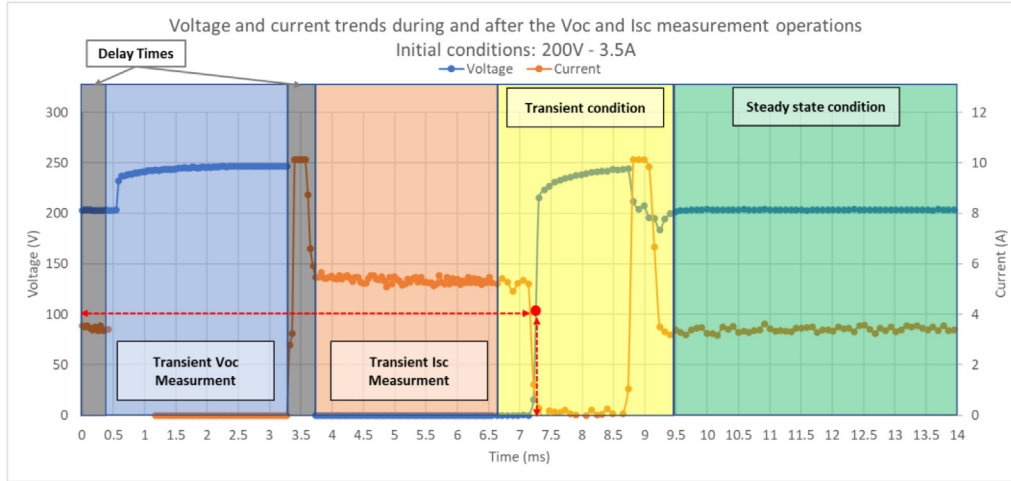


Fig. 6. The graph shows the voltage and current trend both during the V_{oc} and I_{sc} measurement phase (blue and red areas) and immediately after reconnection to the electronic load (yellow and green areas). It can be observed that, after about 7.25 ms from the activation of the measurements, in correspondence with the transient return to operating conditions (yellow area), the voltage rises to a value close to 100 V (which could be representative of the minimum voltage of a small commercial inverter). After about 9.5 ms from the start of EIDPS operation, the steady state conditions are restored.

measurement. However, when the initial voltage is equal to V_{oc} , the response is stable and the measurement quickly reaches a steady state without significant transients.

The voltage sensor measurements, unlike the current sensor, are less affected by noise, allowing for a more accurate and reliable acquisition of the V_{oc} value than the I_{sc} value. Figure 5. e shows the noise reduction obtained by filtering the experimental values with the IIR filter.

Using the optimized EIDPS parameters, V_{oc} and I_{sc} were measured in steady state conditions in a total time T_{tot} equal to 6.58 ms. By comparing the EIDPS measurements with those performed by the electronic load, an accuracy of 1% was estimated.

Figure 6 shows voltage and current trends during the measurement phases, including transient return to steady state. In particular, it is observed that the voltage rises to a value close to 100 V (which could be representative of the minimum voltage of a small commercial inverter) just under a millisecond after the opening of switch S2 and the closing of switch S1. Therefore, the partial voltage dip due to the measurement of V_{oc} and I_{sc} , under the conditions described up to now, is overall equal to 7.25 ms in terms of time. After a transient that lasts about 2 ms, and therefore after about 9.5 ms from the start of the trigger, it is certain that the initial steady state conditions are restored.

In Figure 6, two distinct current peaks are visible: one during the second delay phase (in grey) and another during the return to steady-state conditions (in yellow). It is important to note that these extra currents are limited to 10 A, corresponding to the full-scale capacity of the current sensor as configured during the tests.

Some simulations, conducted using electronic software tools, suggest that these current peaks are likely a result of discharging internal module capacitances, which include the junction and diffusion capacitances. Although these extra currents can be substantial, reaching tens of amperes,

their impulsive nature, lasting only 2–3 tenths of a millisecond, should not cause problems for the components. More extensive tests will be conducted in the upcoming research phases to further analyze these extra currents.

The EIDPS operation was verified with a specific PV string characterized by a certain internal electrical capacity. For larger capacity PV strings, longer measurement times may be required. However, in this case predictive algorithms can be used to process transients and obtain accurate estimation of the $I_{sc} - V_{oc}$ values within the required time that avoids shutdown of the inverter.

3.3 Measurements in operating conditions

The EIDPS is not only able to measure V_{oc} and I_{sc} values but also captures real-time voltage and current values of the imposed working point by the inverter (electronic load). Figure 7 shows the trends of V_{oc} , V_{wp} , I_{sc} , I_{wp} , and P_{wp} (calculated by multiplying V_{wp} and I_{wp}) during a day of testing. These measurements were conducted with the electronic load setting a working point voltage of 195 V, while the EIDPS measured V_{oc} and I_{sc} at timed intervals (approximately every 20 s). The PV string used in the tests was affected by continuous partial shading, which varied over time due to nearby obstacles, affecting the ratio between I_{wp} and I_{sc} . By analyzing this ratio and with suitable algorithms it could be possible to identify the presence of partial shading and evaluate the power loss.

It is important to clarify that the measurement frequency of V_{oc} and I_{sc} (set at every 20 s during the tests) was chosen primarily to demonstrate the EIDPS potential. In practice, this frequency can be adjusted as needed through software (depending on the diagnostic algorithm needs the frequency could be reduced too).

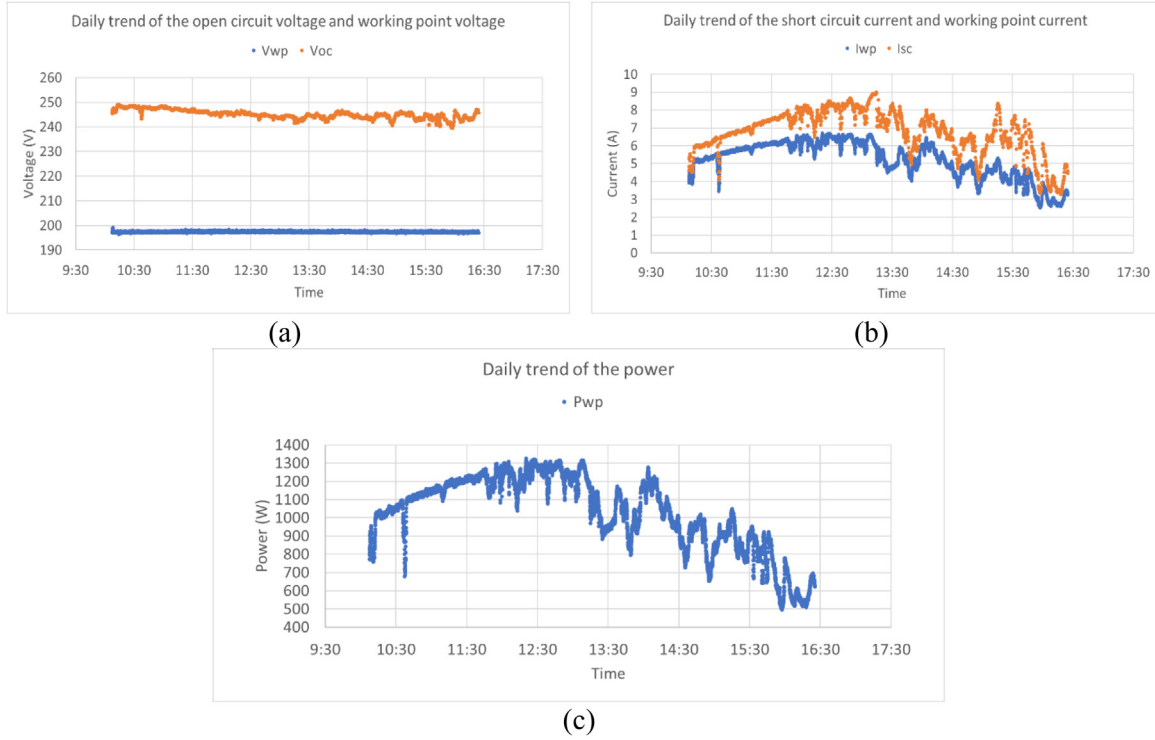


Fig. 7. The graphs (a-b-c) show the trend of the electrical quantities, measured by the EIDPS interface, during a test day. The acquisition of these electrical variables was performed by setting the electronic load in voltage control mode (voltage equal to 195 V). Such data could be exploited by software based on monitoring algorithms to perform diagnostic functions of the photovoltaic string in real time, avoiding any power losses.

4 Additional diagnostic functions with EIDPS data

This chapter highlights the benefits of using EIDPS data (I_{sc} , V_{oc} , V_{wp} and I_{wp}) to improve existing algorithms for accurate estimation of PV system degradation. In particular, a range of example methods using EIDPS data are presented, focusing on the estimation of key parameters such as average PV module junction temperature, voltage temperature coefficient, soiling ratio (SR), and current mismatch loss.

4.1 Estimation of the PV module junction temperature

The equation (2), defined in the technical standard IEC 60904-5, allows to estimate the average of the PV module junction temperature T_{PV} , by using the I_{sc} and V_{oc} values measured by the EIDPS interface.

$$T_{PV} = 25^{\circ}\text{C} + \frac{1}{N\beta_c} \left((V_{oc} - V_{ocR}) + N \frac{KT_{25}}{q} n_{eq} \ln \left(\frac{I_{sc}}{I_{scR}} \right) \right), \quad (2)$$

where:

- N is the number of series connected PV cells;
- T_{25} is the junction temperature at 25 °C, but translated in Kelvin degrees;

- β_c is voltage temperature coefficient of the cell;
- V_{ocR} is the V_{oc} value at 25 °C and solar global normal irradiance of 1000 W/m²;
- I_{scR} is the I_{sc} value at 25 °C and solar global normal irradiance of 1000 W/m²;
- I_{sc} is provided by the EIDPS interface;
- V_{oc} is provided by the EIDPS interface.

A similar formula can be applied to estimate the average junction temperature of concentrating PV modules, according to the IEC 62670-3 standard. For this technology this calculation is very important because it is very difficult to measure it directly using thermal sensors.

4.2 Estimation of the voltage temperature coefficient

The possibility of creating a dataset of V_{oc} values acquired during the year, makes it possible to perform a correct filtering when the global solar irradiance is 1000 W/m². The voltage temperature coefficient β_c can therefore be calculated as the angular coefficient of the linear regression of the V_{oc} as a function of the rear module temperature.

As potential electrical mismatches could impact the accuracy of β_c estimation, it is crucial for the algorithms to have the capability to filter out data affected by electrical mismatches. This filtering process can be implemented following the procedure outlined in Section 4.4. The interesting approach of using EIDPS data is that the β_c

value can be updated during the life cycle of the plant. Otherwise, only the voltage temperature coefficient value defined in the module datasheet could be used.

4.3 Estimation of the soiling ratio SR

The soiling ratio SR_{ST} , as defined in the IEC 61724-1 standard, quantifies the impact soiling accumulation on the performance of a PV system. It represents the ratio between the actual power output of the PV system under outdoor conditions and the expected power output if the system were clean. In clean conditions, the soiling ratio is 100%, indicating optimum performance. However, relying solely on the SR ratio may not provide sufficient accuracy, as other factors such as clipping effects, module parameter variations, and MPPT errors can also affect the power output of a PV system.

To address the limitations of relying solely on the soiling ratio (SR) for assessing PV system performance, the SR_{EIDPS} ratio can be considered. It is calculated by dividing the actual short-circuit current (I_{sc}) measured from the EIDPS interface by the expected I_{sc} in clean conditions, which can be estimated using solar irradiance measurements or satellite data.

The SR_{EIDPS} ratio offers improved accuracy compared to the SR ratio because I_{sc} is independent of MPPT errors, clipping effects, and is less influenced by variations in module parameters such as series or shunt resistance. However, it is important to note that this method may not be suitable for scenarios with non-uniform soiling, as I_{sc} is only related to the substring with the least amount of dirt. To achieve a more comprehensive analysis and mitigation strategy, a hybrid approach that combines both the SR_{ST} and SR_{EIDPS} ratios can be adopted. This allows for a more robust assessment of PV system performance by considering multiple factors and mitigating the limitations of individual indices.

4.4 Estimation of the electrical current mismatches

The measurement of electrical current mismatches turns out to be a fundamental operation in identifying shade or non-uniform dirt conditions, as well as performance losses in specific PV strings. This evaluation could be performed by calculating the ratio MR_{EIDPS} between the working point current (I_{wp}) and the short-circuit current (I_{sc}) obtained from the EIDPS interface.

Ideally, in an optimal scenario without PV system discrepancies or solar cell degradation, this ratio should closely align with the values calculated by using the data provided by the module datasheet. However, if the MR_{EIDPS} falls below a certain threshold, it indicates potential degradation caused by shading, soiling, or malfunction/breakage of some cells.

These measurements could be leveraged by advanced machine learning algorithms to effectively analyze the causes of degradation, allowing for targeted corrective actions to be taken. This approach enables accurate

assessment and diagnosis of PV system performance issues, facilitating appropriate interventions for optimal system functioning.

5 Conclusions and outlook

A cost-effective and versatile electronic interface for advanced diagnostics of photovoltaic systems (EIDPS) was developed and tested, supporting a maximum open circuit voltage of 1000 V. The interface, measuring the short circuit current I_{sc} , the open circuit voltage V_{oc} and the working point voltage and current V_{wp} , and I_{wp} , allows enhancing the algorithms which identify the more common causes of power losses in real-time, without compromising the PV system energy production. The diagnostic techniques described in this article, using EIDPS data (I_{sc} , V_{oc} , V_{wp} , and I_{wp}), are just a few examples of the potential algorithms that can be developed or optimized.

Preliminary outdoor tests were conducted by connecting the EIDPS between a real PV string and an electronic load. These tests demonstrated that the I_{sc} and V_{oc} values can be reliably measured with an accuracy of 1% in a total time of 6.6 ms that should be enough short to avoid the inverter shutdown. The next step will be to test the EIDPS interface connected between a real PV string and some commercial inverters to verify its compatibility and non-interference with the normal operation of the converter system. The final version of the EIDPS will be designed for installation on any photovoltaic system, whether new or existing, and will include features for data storage on a web server accessible through specialized software or a smartphone application.

It is important to note that PV systems with V_{oc} above 1000 V will require specific development to meet safety requirements.

The development of the EIDPS interface presents a promising solution for enhancing PV system monitoring and diagnostics, enabling efficient maintenance and maximizing energy production while minimizing losses.

This work has been financed by the Research Fund for the Italian Electrical System under the Contract Agreement between RSE S.p.A. and the Ministry of Economic Development – General Directorate for the Electricity Market, Renewable Energy and Energy Efficiency, Nuclear Energy in compliance with the Decree of April 16th, 2018.

Author contribution statement

E.C took the lead in writing the manuscript and All authors reviewed the results and approved the final version of the manuscript. A.M conceived the idea of the device. E.C and A.M developed and tested the EIDPS. The data processing was carried out by E.C and A.M with the help and supervision of G.T.

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Cite this article as: Edoardo Celi, Alessandro Minuto, Gianluca Timò, Development of an electronic interface for diagnostics of photovoltaic strings, *EPJ Photovoltaics* 14, 36 (2023)