Development of a Low-Cost Data Acquisition System for Analyzing the Health of a Photovoltaic System

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Abstract **– In recent years, fault diagnosis has become a major concern for ensuring the sustainability of photovoltaic systems. This article aims to develop a low-cost data acquisition device based on the Arduino card to collect data using sensors on two photovoltaic modules. Four defects were intentionally created on a photovoltaic panel and analyzed individually based on the evolution of current and voltage parameters over time. The results indicate that in the event of a fault, the current drops suddenly with a slight decrease in voltage. Under normal conditions, the maximum observed current was 3.8 A for an irradiation of 904 W/m2, compared to 2.2 A for 909 W/m2 and 32.78°C in the event of partial shading. This value further decreases to a maximum of 1.8 A for 867 W/m2 in an open circuit. The observation reveals that the partial shading fault with a disconnected bypass diode and open circuit has similar characteristics to the open circuit fault. However, it is important to note that this cannot be generalized as the fault only occurs in a configuration of two PV modules in parallel.**

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1. Introduction

In recent decades, photovoltaic installations have become an increasingly significant aspect of contemporary and prospective energy policies. They represent one of the most efficacious sources of renewable energy in addressing climate change. However, harsh environmental conditions have the potential to precipitate the failure of these installations.

The monitoring and control of photovoltaic (PV) systems is vital for the optimal and dependable production of energy. To assess the efficacy of a PV system, a comprehensive statistical analysis of data is essential [1]. The manual collection of data using multimeters and thermocouple sensors is a time-consuming process that can be challenging due to the inherent variability of environmental conditions. It is therefore essential to utilize automated data acquisition devices with sensors, given the enhanced precision and real-time responsiveness that they offer. The parameters typically measured by the sensors include temperature, irradiation, current, voltage, and wind speed [2]. Real-time data collection on current, voltage, irradiation, and ambient temperature allows for better monitoring and control of photovoltaic systems [3], [4]. However, commercial data acquisition (DAQ) systems, also known as data loggers, are expensive and require specific software, additional skills, and a continuous power supply connected to a computer or the electrical grid [5]. To illustrate, the acquisition system TED Pro Home Energy Monitor or the Outback Power Flexware costs approximately $300. These constraints restrict access to commercial devices, particularly in developing countries (DCs).

However, in recent decades, there has been a notable increase in the development of new, flexible, and low-cost data acquisition devices [6], [7]. The first on-site monitoring system have been developed for measuring and collecting operational information of the PV system. Since then, several acquisition devices have been developed to monitor both on-grid and off-grid PV systems [8]. For instance, an acquisition system has been developed to collect operational information about the PV system and estimate solar irradiation by measuring the short-circuit current of the photovoltaic panel [9]. A description of a PV system monitoring device based on Arduino-Wifi combination is proposed for processing and storing critical parameters such as, irradiation, humidity, current, voltage and temperature [10]. A structure of a data acquisition system has been presented for measuring the current, voltage, and power data of a PV installation at the University of Valahia in Targoviste, Romania. The system used the LabVIEW interface to store the collected information on a dedicated computer [11]. An electronic data logging system has been developed for use in developing countries using the open-source Arduino platform [12]. Similarly, a cost-effective device using Arduino UNO and Excel has been created to measure and record the current, voltage and power values of a PV system modelled on MATLAB/Simulink [13]. A wireless monitoring system has been designed to achieve maximum power point tracking (MPPT) of a photovoltaic (PV) installation at a low cost. The aim is to obtain optimal power from the PV system, even in the presence of dust accumulation [14]. In addition, we simulated a real-time acquisition device for sun tracking of a solar panel using the Arduino electronic platform and the LabVIEW interface. To capture the maximum radiation, we used two LDR photoresistors, and a servo motor was employed to rotate the solar panel and locate the optimal position of the sun to receive the maximum illumination [15]. A method using the Arduino microcontroller has been developed to measure the solar energy of a photovoltaic (PV) system simulated using Proteus software. The simulated PV system is evaluated using four parameters: current, voltage, irradiation, and temperature. The results demonstrate that the energy production of the PV system is significantly influenced by the orientation of the panel towards the sun and the amount of sunlight received [16]. In addition, a device has been designed to automatically track the position of the sun, which increases the daily production of the photovoltaic system [17]. Fanourakis *et al.* [6], proposed a data acquisition system based on Arduino Nano microcontroller for monitoring the electrical parameters temperature, and battery state of charge of a photovoltaic (PV) system. The system is designed using the Arduino microcontroller, which collects current and voltage data from the charge controller connected to the PV system. Also, an acquisition system is developed to collect and store data from photovoltaic solar panels on a large memory card. For this, they used the Arduino Mega microcontroller to monitor the parameters of the 240 W power PV system [18]. The obtained results demonstrate precision and performance comparable to those of commercial acquisition systems. Additionally, a low-cost data acquisition system based on Arduino UNO is proposed for monitoring the power of two photovoltaic solar panels. The system records data on current, voltage, power, and energy via the SD card or Bluetooth memory of an Android phone [19]. Jiang *et al.*[2] proposed a low-cost data collection system based on the Arduino microcontroller for monitoring an isolated site photovoltaic system. The system measures current, voltage, and humidity, and communication is achieved remotely using a wireless sensor network. In addition, the acquisition devices not only provide accurate data for monitoring and control, but also offer an efficient diagnostic tool to maintain the performance of PV systems [20]. A proposed platform for automatic supervision of PV systems, based on a network of wireless sensors, aims to detect faults at a lower cost. The authors monitor the output of each panel connected to the system using Arduino and transmit the data to the computer via the LabVIEW interface [21]. Furthermore, Andrianajaiana *et al.* [22] used the Page-Hinkley test to detect the shading defect from low-cost monitoring device data. Given this, we propose an inexpensive acquisition system in this work. This choice meets several important objectives. These include accessibility and adaptability for research and industrial applications in both developed and underdeveloped countries. To sum up, the proposed system facilitates the rapid progress of photovoltaic research, which requires extensive monitoring but faces budgetary and technological constraints [7]. However, it is important to note that much of the existing work in this area is limited to simple or single defects. This article proposes a low-cost data acquisition system, based on the Arduino microcontroller, to analyze the health status of a system consisting of two photovoltaic modules. The system collects data in real-time, allowing for the monitoring of the evolution of the characteristic parameters of the panel and the evaluation of the health status of the photovoltaic system. The primary aim is to monitor the evolution of current and voltage values at the output of the PV module under different faults and as a function of time.

The remainder of article is structured as follows: Section 2 provides a detailed description of the entire acquisition system architecture, Section 3 proposes the fault diagnosis methodology, Section 4 presents the results, their interpretation, and discussion, and Section 5 concludes with perspectives.

2. Architecture of a Data Acquisition System

The architecture of a data acquisition system comprises three parts: data acquisition, data preprocessing and recording, and data restitution or display and storage [23].
However, in large-scale PV systems, these three parts are generally applicable when using a wireless communication network to transmit data [24]. This paper proposes a small number of photovoltaic (PV) modules that require only a data logger to record the parameters of electricity production [17]. The acquisition system comprises a PV system, sensors that convert measured signals into electrical signals, a data acquisition unit responsible for organizing and recording the signals, and a digital display with a keyboard for signal restitution. The sensors collect data from current, voltage, irradiation, and temperature variables. Figure 1 illustrates the data acquisition principle of a photovoltaic (PV) system.

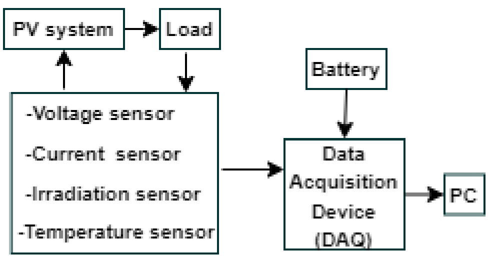


Figure 1. Block diagram of a PV-DAQ system

3. Materials and Methods

In this section, the work is divided into two stages: the presentation of the equipment necessary for the implementation of the acquisition device firstly and secondly the description of the method of collection and analysis of the different defects. To evaluate the condition of the PV system, a number of techniques may be employed, encompassing both traditional methodologies and automated procedures [25].

3.1. Materials

- *PV system*

A PV system is a system that converts light energy from the sun into electrical energy. The system consists of two photovoltaic modules mounted in parallel, a PWM charge controller, and a 12V/9Ah battery. The system operates on 12V, with each PV module having a capacity of 12V/50W.

The charge regulator has a capacity of 12/24V/20A. Figure 2 illustrates the system configuration.

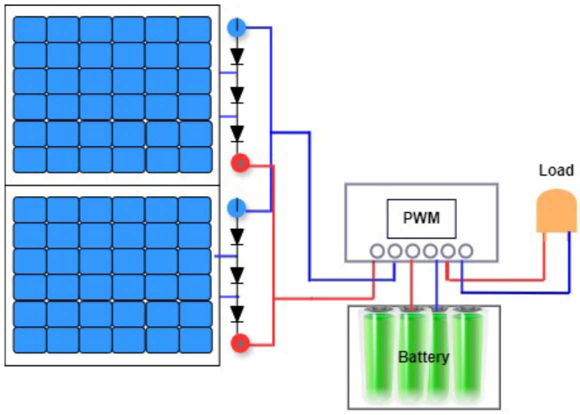


Figure 2. PV system wiring configuration

During the day, photovoltaic (PV) modules convert sunlight into direct current through the photovoltaic effect. This current is then transmitted to the charge controller, which manages the charging and discharging of the battery and powers the load. The battery's function is to store excess energy for later use when sunlight is not available. The PV module used in this work is BLD SOLAR brand monocrystalline silicon whose technical specifications are show in table 1.

Table 1. Technical specifications of the BLD SOLAR solar panel

BLD050-36M	specifications
Power	50W
Open circuit voltage	22.1V
Short circuit current	2.93A
Maximum voltage	18.1 V
Maximum current	2.76 A

- *Acquisition system*

The acquisition system is composed of a set of four sensors that collect information from the PV system. This work proposes a low-cost acquisition device based on Arduino for PV system data collection. Several low-cost acquisition devices are available on the market, including STM8L Discovery, MSP430 launch pad, and Arduino UNO. Waspmote for Libelium is the most expensive, costing just over $144 and is almost inaccessible compared to the others [7]. The justification for using Arduino is its cost-effectiveness compared to other open-source software of a similar nature, as well as its widespread availability on the market. However, in this case, the use of the Arduino microcontroller transforms the analog output D_{g_value} of the sensors into digital values following equation (1) [2].

$D_{g\_value} = (meas_{\_value} \times 1024)/ref\_value$ (1)

Ref_ value of the voltage measured in volts,

$meas_{\_value}$ is the data obtained at the sensor output

- *Voltage sensor*

A voltage sensor is used to measure the voltage generated by the solar panels in volts and send it to the analog input pin of the microcontroller. The analog pins allow a voltage value between 0- 5 V_{dc} to be read. If the measured voltage value is higher than 5 V_{dc}, an additional circuit called a potential divider, composed of two resistors connected in series, is used [26]. Figure 3 illustrates a voltage divider.

Figure 3. B25 Voltage sensor

If the measured voltage value is between 0-5V, the voltage values received by Arduino are presented as a digital to analog converter (ADC) of the Arduino microcontroller. Obtaining the analog voltage from the voltage sensor is given by relation (2)

$$V_o = V_i \left(\frac{R_1}{R_1+R_2}\right) \quad (2)$$

With:

V_i =Maximum input voltage in volts

V_i =ADC voltage (maximum value 5 V)

R_j =Adjustable resistance in ohm

In this work the B25 voltage sensor whose technical specifications are given in Table 2 is used to collect the voltage of the PV system

Tableau 2. Technical specification of voltage sensor

Parameters	specifications
DC Voltage range	0-25V
DC detectable Voltage range	22.1V
Sensor	B25

- *Current sensor*

The sensor provides an output voltage that is directly proportional to the current output from the PV module. The sensor's outputs are connected to the analog input pins of the Arduino for measuring, converting, and calculating the current value produced by the PV modules. The sensor analyzed in this study is the analogue model ACS712-30A, which has an output of 66mV/A and a range from -30 to 30 A. This sensor has the advantage of producing minimal changes in its output around 100mV/A, but it cannot be used with an opto-isolator due to the tightness of its current I/O terminal [12].

The Figure 4 illustrates the picture of current sensor

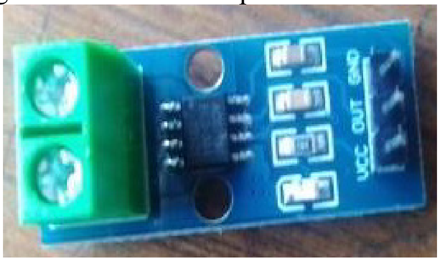


Figure 4. ACS712-30A current sensor

The current value measured by the sensor at the solar panel is given by equation (3)

$$I_{pv} = \frac{\text{Voltage}-\text{Acsofset}}{\text{sensitivity}} \quad (3)$$

With: $\text{Voltage} = \text{Readvalue} \times \text{Analog\_factor}$, $\text{Readvalue} = \text{Analog}_{\text{value}}(\text{A1})$, $\text{Analog}_{\text{factor}} = \left(\frac{5}{1023}\right)$, $\text{Acsofset} = 2.5\text{A}$ et $\text{sensitivity} = 0.066\text{V/A}$

- *Temperature sensor*

The DS18B20 temperature sensor is used to measure the ambient temperature of the working environment. This type of sensor is capable of measuring temperatures ranging from -55°C to 125°C and is the most popular in recent decades due to its fairly high accuracy [27]. Equipped with an integrated circuit that provides a variable output voltage depending on the ambient temperature, it is inexpensive, flexible and compatible with any microcontroller with analog-digital functions [28].

- *Photoresistor*

Photoresistor is used in this work to control the incident radiation on PV modules. The LDR (Light Dependent Resistor) is a radiation sensor whose resistance offered is inversely proportional to the light intensity received [28]. The variation in resistance is easily measured by converting the resistance into voltage, its digital equivalent at the analog input of the Arduino microcontroller [29]. In this work, the input of the LDR connected in series with a resistance of 10 kΩ is connected to the 5V pin of the microcontroller. The midpoint between the LDR and the resistor is connected to the analog A0 input pin of the Arduino board. The photoresistor circuit is show in Figure 5.

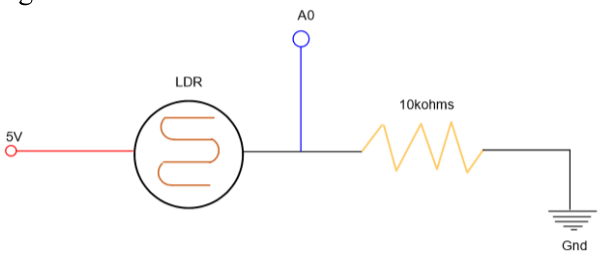


Figure 5. Circuit of a solar radiation sensor

- *Processing and recording system*

- *Microcontroller*

A microcontroller is an active electronic device responsible for digitally processing information on board. The microcontroller used in this work is composed of two parts:

- The hardware part in the form of an open-source input/output (I/O) card
- The software part also open source with IDE software to write programs and drivers for the connection with the computer.

The microcontroller is used as an interface between the solar panels and the various sensors necessary for data acquisition [7], [28], [30]. The information received is processed by the microcontroller then recorded and stored in an SD card. However, for economic and availability reasons we have chosen to use open-source software and hardware. Among these open-source microcontrollers available in the market, Arduino UNO Rev3 open-source microcontroller based on ATmega 328 board is chosen in this work. This choice denotes its low cost, flexibility, and availability on almost all the most used operating systems [30].

It also consists of a set of analog and digital input/output pins that can be interfaced with various expansion cards and other circuits. Among these pins, 14 input/output pins are digital, of which 6 pins are used for PWM output, 6 analog input/output pins programmable with the Arduino IDE environment via a USB type B cable. microcontroller has a serial interface device (SPI) and an internal integrated circuit (I2C).

- *Programming algorithm*

This section outlines the process of converting analog outputs from various sensors into digital equivalents using the analog-digital converter of the Arduino microcontroller. The Arduino Uno microcontroller used open-source software in an Integrated Development Environment (IDE) and is connected to a computer via a USB (Universal Serial Bus) cable. The program converts the analog input voltage into a binary value ranging from 0 to 1023 bits. Figure 6 shows the algorithm for converting analog values from various sensors into digital values

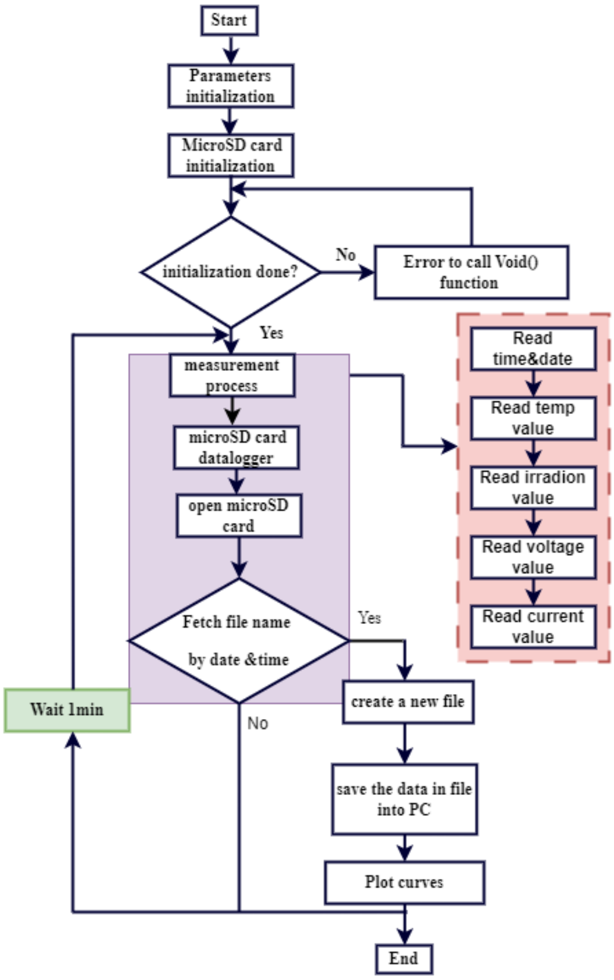


Figure 6. Flowchart Arduino ADC conversion of PV system data acquisition

3.2. Defect Experimentation and Data Collection

In this part, four types of faults are created on one of the two PV modules mounted in parallel. Data collection took place over a period of 05 days corresponding successively to the case of the system without faults and four cases with faults. All data is collected every 1 min and over 5 days. These data obtained minute by minute were transformed per hour in order to optimize the scale of the graphs.

- *Partial shading defects*

To create the partial shading defect on our system, we obscured a panel for a time interval of 3 hours, then a cell of this panel and ½ of the PV panel. Figure 7 shows the different occultation processes of the module and the cell.

Figure 7. Experimental tests with shading defects

This defect is observed all day from October 20, 2023 from 8:30 a.m. to 5:30 p.m. and the data collected is stored in the SD card.

- *Bypass diode fault with partial shading*

To induce this fault, one of the two bypass diodes, F_1 was disconnected from the shaded module and left disconnected from October 22, 2023, 8:52 a.m. to 4:50 p.m. All sensor data was automatically recorded and stored on the SD storage medium. Figure 8 illustrates the partial shading fault with the disconnected bypass diode.

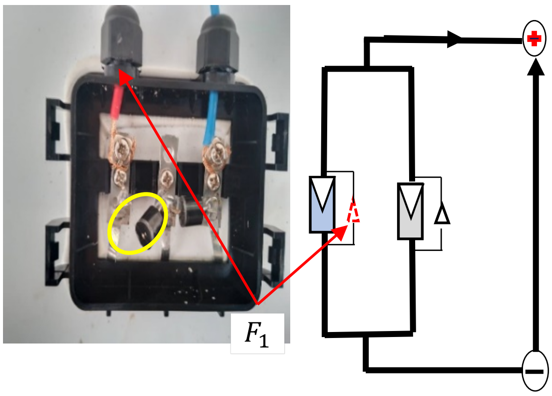


Figure 8. Partial shading experimental test with bypass diode disconnected.

- *Open circuit fault*

Since our system is composed of two PV modules connected in parallel, we disconnected the wire connecting the positive terminal of module 1 to the positive terminal of module 2 to create the open circuit fault. This process took place on October 21, 2023 from 8:06 a.m. to 4:34 p.m. and the data from the various sensors were automatically recorded and stored on the SD card. Figure 9 is an illustration of the open circuit fault (F_2) on a PV system module.

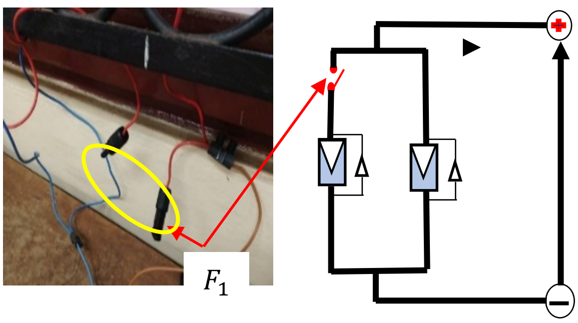


Figure 9. Experimental test of open circuit fault on one PV module

- *Partial shading with bypass diode disconnected and open circuit*

After disconnecting the bypass diode on the partially shaded module, we added the open circuit fault. The data is collected automatically during the half-day of October 23, 2023 from 8:18 a.m. to 12:00 p.m. In Figure 10, this fault is represented by F_3.

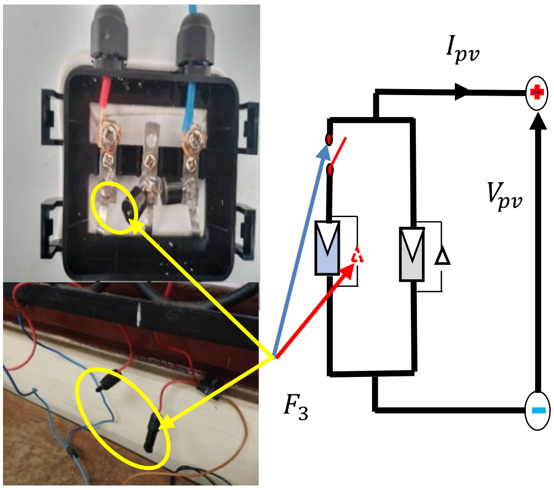
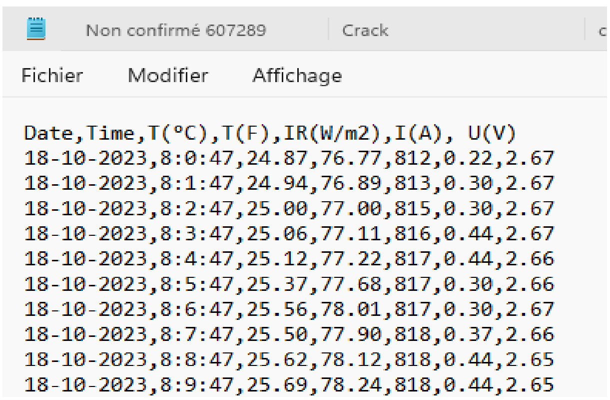


Figure 10. Experimental testing of partial shading with bypass diode disconnected and open circuit fault

3.3. Curve Processing and Drawing

The data collected was processed in an Excel file. During the cleaning process, outlying data was eliminated. A total of 2,543 data samples were collected (figure 11), but due to sensor errors and the absence of anti-return diodes at the output of each module, only 1,429 data samples were used, including 343 samples for healthy operation and 1,086 samples for faulty operation. The reduction in the number of data samples from 2,543 to 1,429 is justified by the removal of current outliers and the standardization of the collection time from 8 a.m. to 4:30 p.m., which is a difference of 0.3 to 0.7 hours following the conversion of the software used.



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Date,Time,T(°C),T(F),IR(W/m2),I(A), U(V)
18-10-2023,8:0:47,24.87,76.77,812,0.22,2.67
18-10-2023,8:1:47,24.94,76.89,813,0.30,2.67
18-10-2023,8:2:47,25.00,77.00,815,0.30,2.67
18-10-2023,8:3:47,25.06,77.11,816,0.44,2.67
18-10-2023,8:4:47,25.12,77.22,817,0.44,2.66
18-10-2023,8:5:47,25.37,77.68,817,0.30,2.66
18-10-2023,8:6:47,25.56,78.01,817,0.30,2.67
18-10-2023,8:7:47,25.50,77.90,818,0.37,2.66
18-10-2023,8:8:47,25.62,78.12,818,0.44,2.65
18-10-2023,8:9:47,25.69,78.24,818,0.44,2.65
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Figure 11. Partial view of file data collection

After processing, the clean file is imported into the software to plot the different curves for each variable as a function of time.

4. Results and Discussion

A total of 2,543 samples were collected over five days, covering a wide range of sunshine and temperature variations. Negative current values were recorded at certain times of the day for each type of fault due to the assembly type and the absence of anti-return diodes. The highest number of negative values was obtained on the fifth day with overcast skies and in the presence of the twin fault (partial shading with bypass diode disconnected and open circuit). Figure 12 provides an overview of the proposed acquisition system assembly.

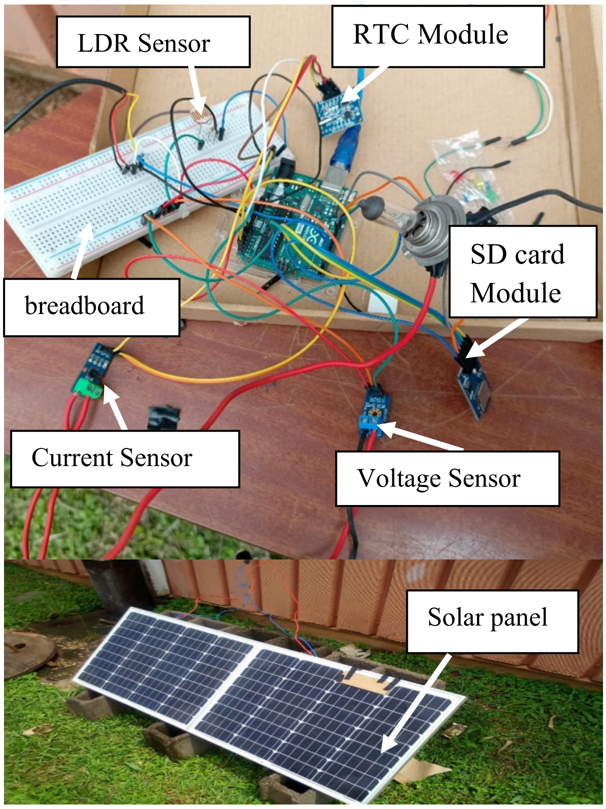


Figure 12. Experimental setup

The data logger used in this paper consists of an Arduino UNO Rv3 digital board with an ATmega328 microcontroller, a microSD card reader, communications, user interface and sensors at a cost of $59.28. Table 3 shows a comparative study of the implementation of a low-cost data logger.

Table 3. Comparative cost of datalogger

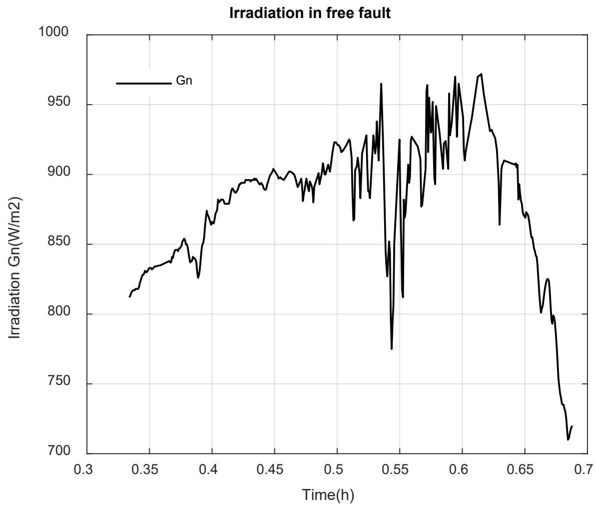
Authors	Type of card	Total cost
Fuentes et al. [7]	Arduino UNO	63 $
Fanoukaris et al. [6]	Arduino Nano	60.3 $
Proposed system	Arduino UNO Rev3	59.28$

Looking at Table 3, it is clear that the data acquisition device developed in this study has a lower cost compare to similar device proposed by others authors [6], [7]. In particular, the cost of the system developed in this work represent only 5% of the cost of commercial acquisition device [24]. It is important to note that the equipment used including the sensor and PV system, for this test bench cost approximately $146.9.

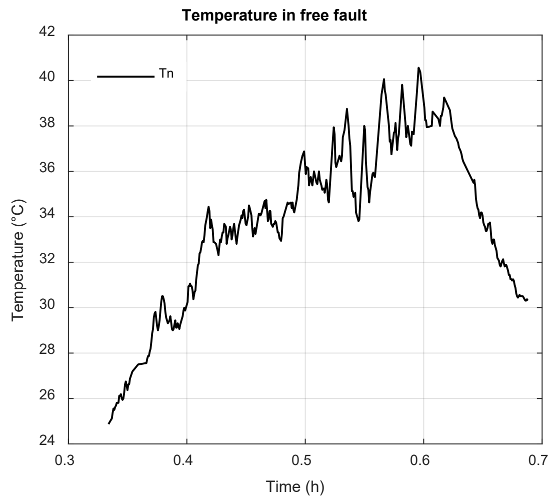
Case 0: absence of fault (N)

The performance of the PV system is affected by ambient temperature and irradiation. Therefore, the current, voltage and power of the PV system are closely related to the variation of these parameters over time. Figure 14 show the evolution profile of the measured parameters during free fault of the system

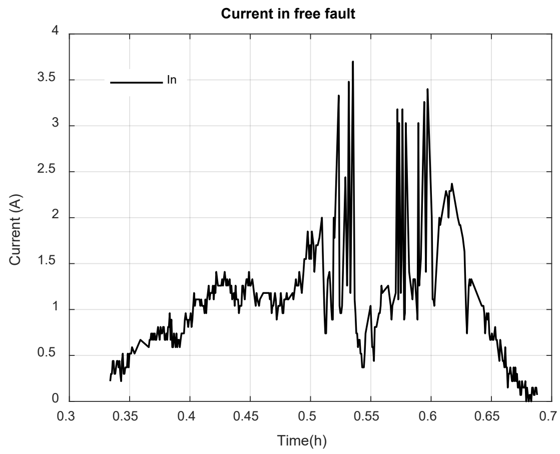
The performance of the PV system is affected by ambient temperature and irradiation. Therefore, the current, voltage, and power of the system are closely related to the variation of these parameters over time. Figure 13 displays the evolution profile of the measured parameters during normal operation of the PV system.



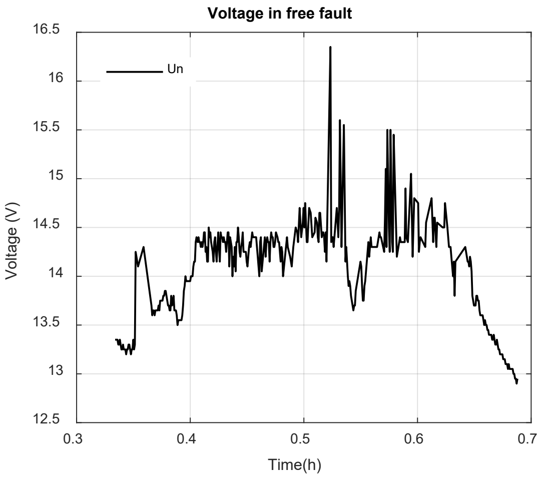
(a)



(b)



(c)



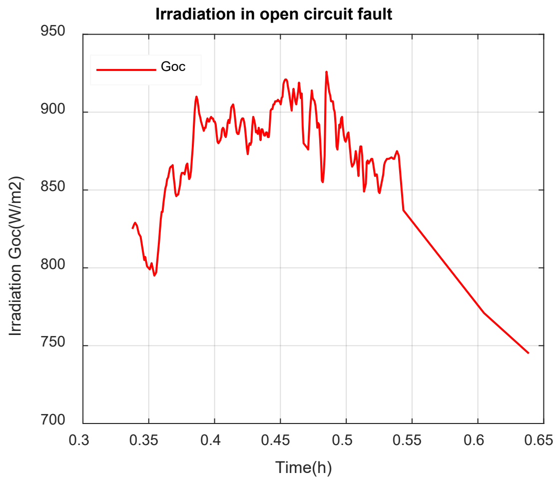
(d)

Figure 13. Daily profile (a) Irradiation, (b) Temperature, (c) Current, (d) Voltage of October 18, 2023

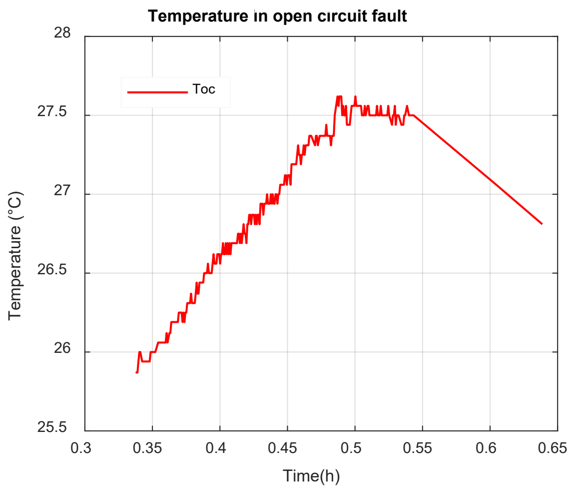
Figures 135a and 13b clearly shows that irradiation and temperature values are influenced by environmental conditions and thus have a free fault daily structure.

Case 1: Open circuit fault (OC)

As previously demonstrated, the diagnostic procedure for detecting an open circuit involved disconnecting a cable from the system. This resulted in a slight voltage drop (Figure 14d), which in turn affected the load's power supply due to the sudden decrease in current (Figure 14c). Figure 16 illustrates the variation of these parameters, independent of irradiation (Figure 14a) and temperature (Figure 14b). The maximum output voltage in this case is around 16 V with a maximum current of 1.25 A, given an irradiation of approximately 925 W/m2 and a temperature of 27.5°C. In comparison, for the normal case, the maximum output voltage is 16.4 V with a maximum current of 3.7 A.



(a)



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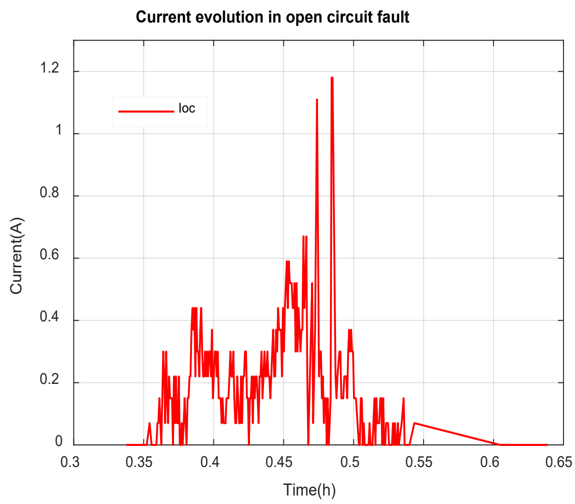
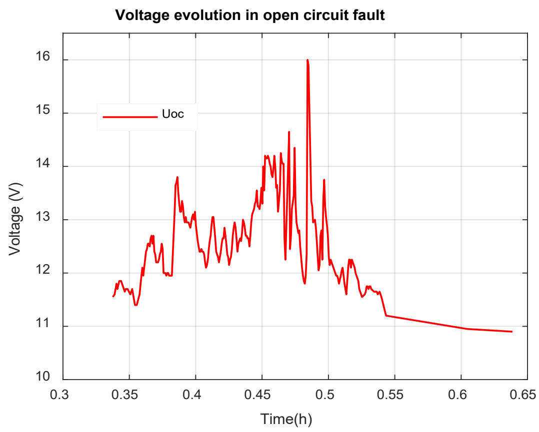


(c)

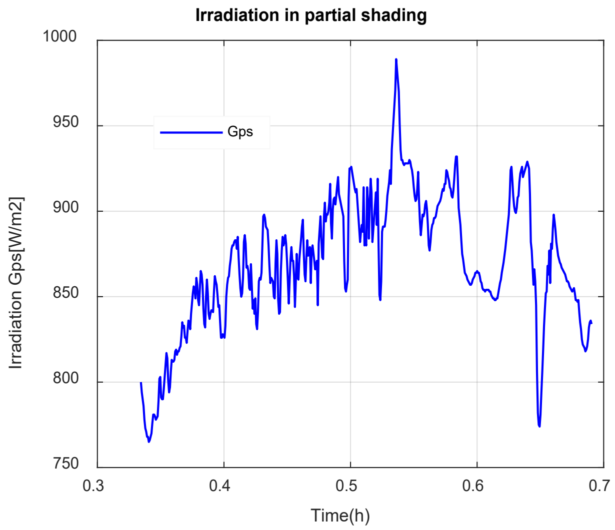


(d)

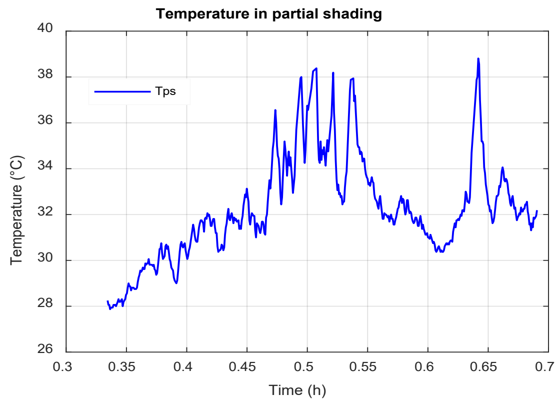
Figure 14. Daily profile: (a) Irradiation, (b): Temperature, (c): Current and (d) Voltage of October 20,2023

Case 2: partial shading (PS)

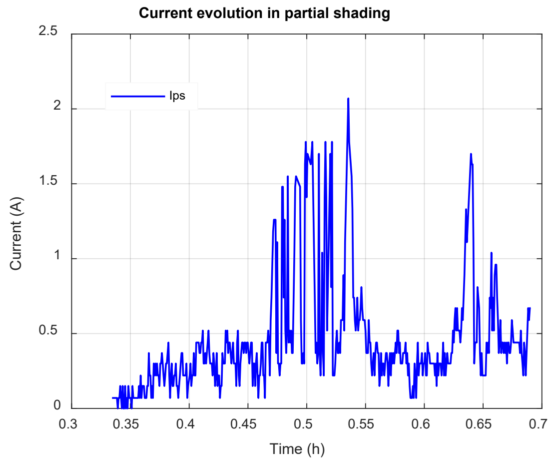
In this case, this defect leads to an increase in the ambient temperature characterized by a non-uniform distribution of irradiation (Figures 15a and 15b). A change is noticeable in significant parameters such as current and voltage as shown in Figures 15c and Figure 15d respectively between 0.35h or 9:30 a.m. and 0.6h or 4:30 p.m. There is also a drop in voltage with increasing temperature. On the other hand, the output current drops quickly. Partial shading has a significant impact on the output current compared to the voltage output compared to the absence of shading.



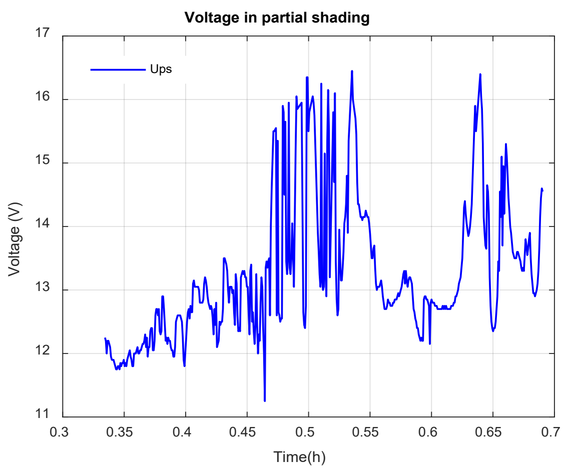
(a)



(b)



(c)



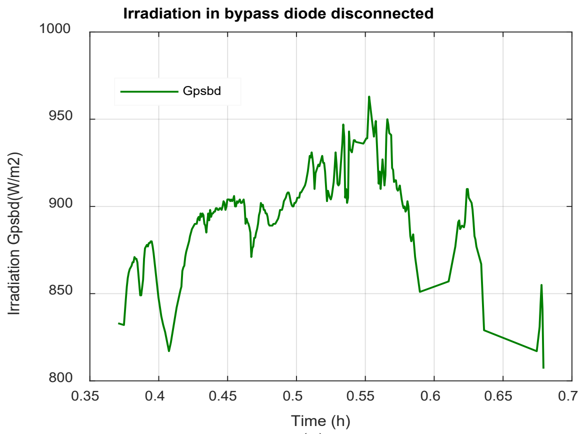
(d)

Figure 15. Daily profile: (a) Irradiation, (b) Temperature, (c) Current and (d) Voltage of October 21, 2023

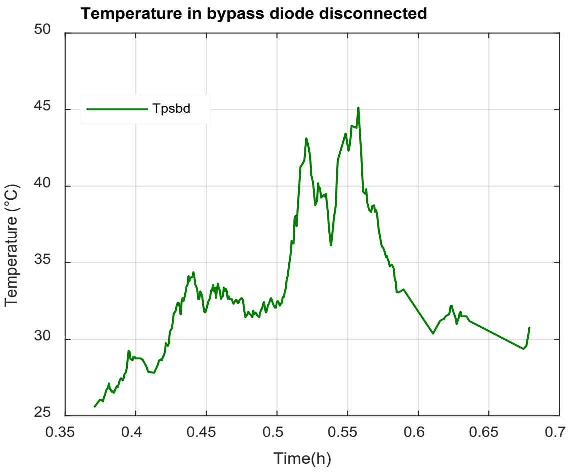
Case 3: Partial shading with bypass diode disconnected (PSBD)

In this case, a more significant reduction in current is observed (Figure 16c), which tends to cancel out at low irradiation levels (Figure 16a).

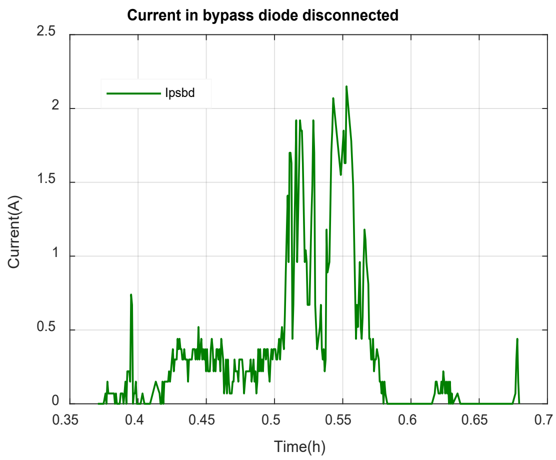
The voltage also decreases, but only slightly compared to the current and is practically proportional to the change in temperature, as shown in Figures 16d and 16b. Analysis of the photovoltaic generator/module parameters shows that when shading is present and a bypass diode is installed, the module's output current is higher compared to a shaded module without a bypass diode.



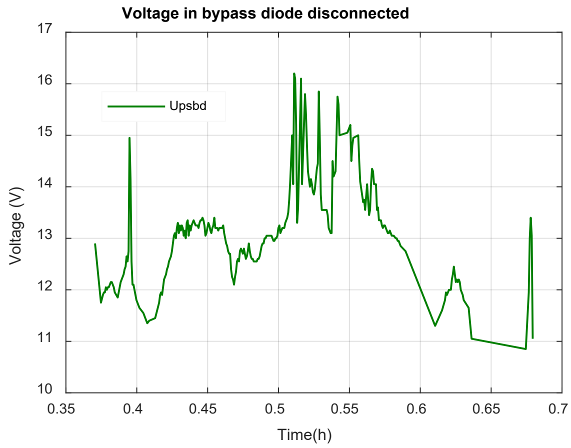
(a)



(b)



(c)

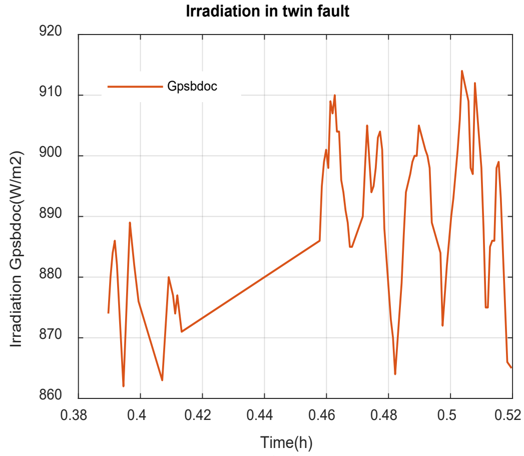


(d)

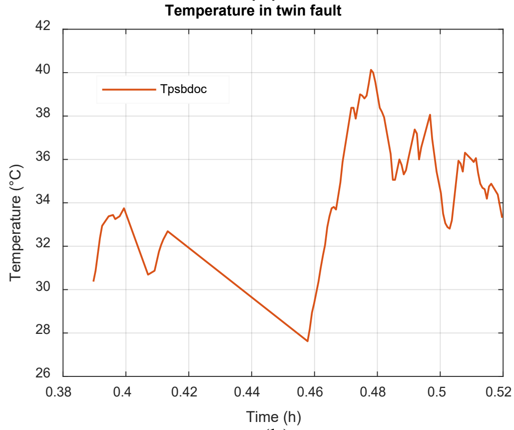
Figure 16. Daily profile: (a) Irradiation, (b) Temperature, (c) Current and (d) Voltage of October 22,2023

Case 4: partial shading with bypass diode disconnected and open circuit (twin faults)

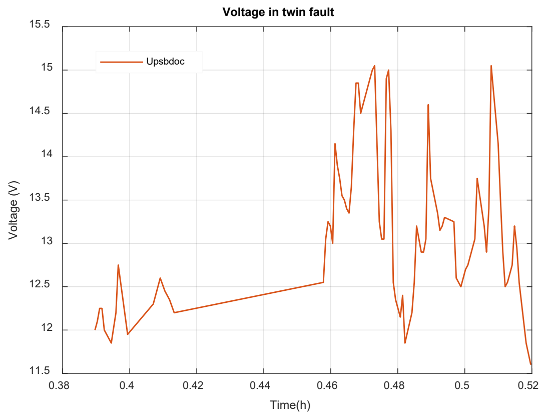
It is observed that the maximum current value is less than 1.5 A in this case, whereas it is 2.76 A for partial shading with bypass diode disconnected and 3.82 A for the normal case, regardless of the irradiation. Additionally, when the irradiation is below 870 W/m2 (as shown in Figure 17a), the current tends to cancel out. In contrast, as demonstrated in Figures 19d, the voltage marginally rises as the temperature decreases. For instance, at 32.25°C, the voltage is 12.25 V, whereas at 27.32°C, the voltage increases to 12.48 V. This twin fault scenario yields low current values and a relatively constant voltage, resembling an open circuit fault. For instance, at 32.25°C, the voltage is 12.25 V, whereas at 27.32°C, the voltage increases to 12.48 V. This twin fault scenario yields low current values and a relatively constant voltage, resembling an open circuit fault. For instance, at 32.25°C, the voltage is 12.25 V, whereas at 27.32°C, the voltage increases to 12.48 V. This twin fault scenario yields low current values and a relatively constant voltage, resembling an open circuit fault. Therefore, diagnosing this type of fault requires close attention to the current's evolution, which tends to cancel out. Figure 17 illustrates a summary of these different fault cases.



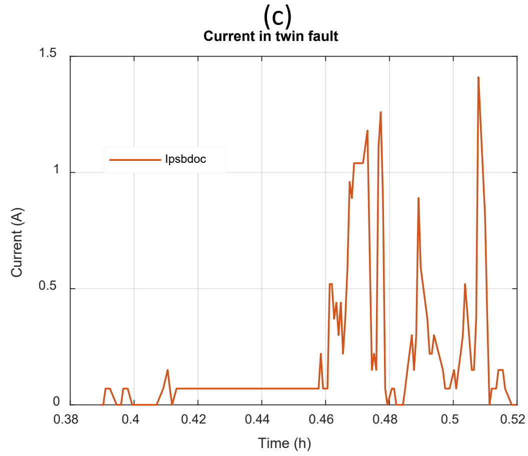
(a)



(b)



(c)

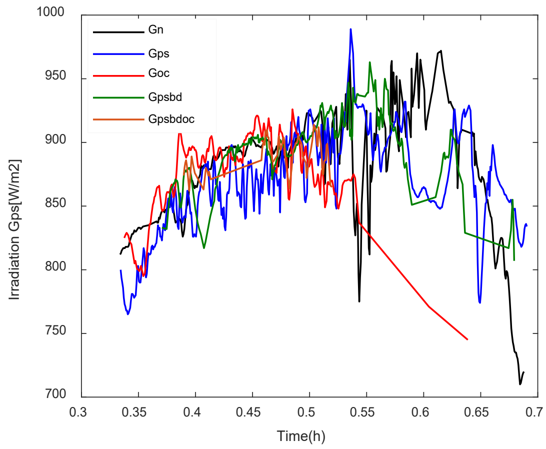


(d)

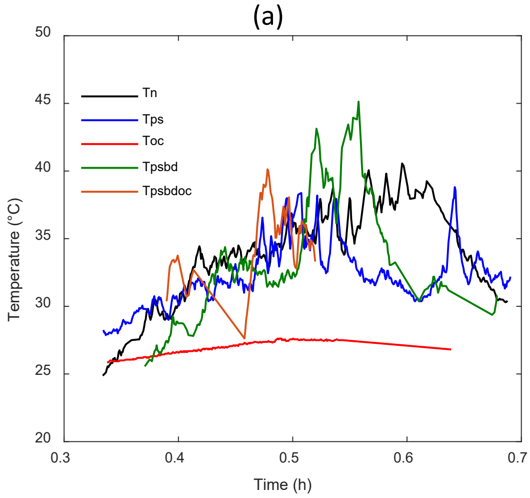
Figure 17. Daily profile: (a) Irradiation, (b) Temperature, (c) Current and (d) Voltage of October 23,2023

Synthesis

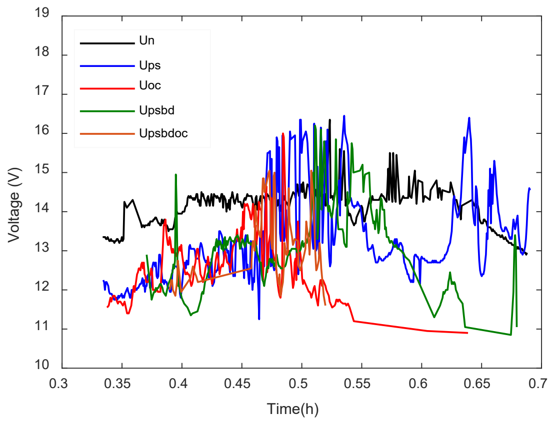
Looking at Figure 18c, we can see that the current value drops suddenly in the presence of faults. For instance, without any faults, the maximum value is 3.8 A for an irradiation of 904 W/m2 and a temperature of 38.8°C. However, when partial shading is present, the maximum value observed is approximately 2.2 A at an irradiation of 909 W/m2 and a temperature of 32.78°C. This value decreases further in the event of an open circuit, with a maximum value of 1.8 A observed at an irradiation of 867 W/m2 and a temperature of 27.51°C. The current in the event of an open circuit fault is approximately the same as in the case of a twin fault with a value of around 1.45 A. However, the voltage fluctuates significantly in the presence of a fault, unlike in the absence of a fault, as shown in Figure 18d. Finally, the observations of these various faults indicate that the paired partial shading fault, combined with a disconnected bypass diode and an open circuit, has the same effect on the current and voltage as the open circuit fault. A slight difference is noticeable when the irradiation is relatively stable, with a slight drop in the output voltage occurring with the twin fault. This fault can be discriminated using machine learning method [31].



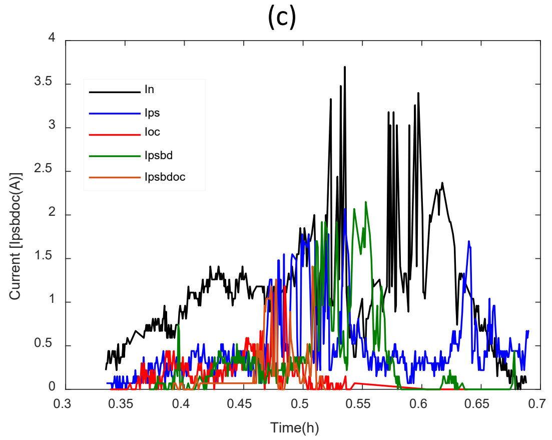
(a)



(b)



(c)



(d)

Figure 18. synthesis Daily profile: (a) Irradiation, (b) Temperature, (c) Current and (d) Voltage of October 22,2023

Table 4 provides an overview of the changes in current and voltage values following the fault event.

Table 4. Comparative study of the influence of the fault on the current and voltage values

Fault description	Current	Voltage
Normal case (N)	o	o
Open circuit (OC)	+++	o
Partial shading (PS)	++	+
Partial shading with bypass diode disconnected (PSBD)	++	+
Partial shading with disconnected bypass diode plus open circuit (PSBDOC)	+++	+
o Steady +++: Very pronounced reduction ++ Accentuated reduction +: Slight decrease		

5. Conclusion

This study introduces a low-cost data acquisition system based on the Arduino UNO Rev3 microcontroller. The system, which remains unaltered, is designed to collect data on current, voltage, irradiation, and temperature using dedicated sensors on a system of two PV modules connected in parallel. The main goal was to induce faults in a module and examine their impact on the current and output voltage of the PV system. The total cost of the device used was $59.28, which was less than the budget. Four distinct fault types were created: partial shading fault (PS), open circuit (OC), partial shading with bypass diode disconnected (PSBD), and twin fault partial shading with bypass diode disconnected plus open circuit (PSBDOC). Data collection took place over five days, incorporating the following scenarios: no fault (N), partial shading, open circuit, partial shading with bypass diode disconnected, and partial shading with bypass diode disconnected plus open circuit. Each fault case was individually analyzed, with particular attention given to the evolution of current and voltage parameters over time in different irradiation and temperature conditions. The findings indicate that the impact of the mentioned faults on the output current of this PV system, when mounted in parallel, is greater than that on the output voltage, which remains relatively stable. Notably, both the open-circuit fault and the twin fault have comparable effects on both the current and the voltage. However, it is important to note that this fault only occurs in a very specific configuration of two PV modules in parallel, and not in a PV field with a mixed assembly. In the upcoming work, the plan is to employ a machine learning-based numerical approach to differentiate between the two defects. There is also intention to use a series-parallel configuration of multiple modules to investigate the relationship between the two faults. Additionally, the authors will observe the system over several days and under different configurations to better understand the negative current values that occur when the paired partial shading fault with a disconnected bypass diode and open circuit is present.

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