Wireless internet of things solutions for efficient photovoltaic system monitoring via WiFi networks

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ABSTRACT

The imperative for sustainable energy production has necessitated the significant expansion of renewable energy sources, particularly photovoltaic (PV) systems. The utilization of real-time monitoring and data analysis is imperative to enhance the efficiency and performance of photovoltaic systems. This abstract presents developing and deploying a wireless monitoring system for a photovoltaic system. The system utilizes a Raspberry Pi device connected to a WiFi network and an SD card for data storage to enable remote monitoring and management of PV systems. The proposed monitoring system comprises a Raspberry Pi equipped with sensors to measure various parameters such as voltage, current, temperature, and the ambient conditions of the solar panels; the monitoring system can be remotely accessible through the wireless capabilities of the Raspberry Pi, which are activated by establishing a connection to an existing WiFi network. The proposed configuration facilitates the placement of the monitoring station in any desired location, hence eliminating the requirement for intricate wiring connections. These real-time data enable solar system managers to quickly identify anomalies, anticipate breakdowns, and optimise energy production. The paper presents a wireless monitoring system with a cost-effective and scalable solution for monitoring photovoltaic systems.

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1. INTRODUCTION

Recently, there has been a remarkable surge in the worldwide demand for renewable energy sources, resulting in a significant upsurge in the use of solar energy solutions [1]. Solar panels are crucial in solar energy generation since they capture sunlight and transform it into environmentally friendly electricity [2]. However, the maintenance of optimal performance in solar panels and the maximisation of energy output require continuous monitoring and analysis of data [3]. In response to this crucial necessity, contemporary technical advancements have led to the developing of the solar panel wireless monitoring system, an innovative solution that leverages WiFi technology to facilitate instantaneous monitoring and data analysis [4]-[6]. The wireless monitoring system utilises WiFi as its predominant communication channel, enabling uninterrupted and immediate transmission of data between solar panels and the control centre [7], [8] also has a strong and reliable connection that facilitates prompt analysis of essential electrical characteristics, including voltage, current, temperature, and solar panel power output [9], [10]. This technology streamlines maintenance procedures and effectively minimizes downtime by promptly detecting irregularities or panels that are not working optimally [11].

Numerous prior research investigations have examined alternate approaches to wireless communication inside solar panel monitoring systems. A noteworthy investigation by Wu *et al.* [12], Chao *et al.* [13], and Shariff *et al.* [14] explored the utilization of the Zigbee protocol for conveying data from solar panels, Zigbee technology, which operates based on radio frequency, has exhibited notable efficacy in data transmission speed and coverage range, attaining distances of up to 50 meters. The research highlighted the appropriateness of implementing localized solar panel arrays where devices are nearby, guaranteeing efficient and dependable data transmission. However, radio frequency is extensively utilized for data transmission, its cost increases proportionally with the desired coverage distance. In contrast, the study by Inner *et al.* [7], and Le *et al.* [15] investigated the utilization of Bluetooth low energy (BLE) technology. BLE, a more energy-efficient iteration of Bluetooth technology, has demonstrated its efficacy as a cost-effective option for transmitting data over short to intermediate distances. The study team has effectively integrated (BLE) modules into the monitoring system for solar panels, facilitating uninterrupted communication within a radius of 10 meters; although BLE provided a cost-effective benefit, it had difficulties expanding its range beyond the designated distance, restricting its suitability in bigger solar installations. Sirgar and Soegiarto [16] and Nkoloma *et al.* [17] conducted a study where they explored an alternative technique for transmitting solar panel parameters, utilizing SMS as the primary mode of communication, short message service (SMS) technology, easily accessible and compatible with basic mobile phones, facilitated data transmission over extended distances. Nevertheless, the research emphasized the inherent trade-off between the convenience of long-distance communication and the more sluggish data transmission speed associated with SMS protocols. The delay in data transfer resulted in impaired real-time monitoring and timely response to system problems.

This study presents a novel internet of things (IoT) technology implementation to transmit parameter data from solar panels to a designated web server [18]. In the current investigation, we put forth a sophisticated monitoring framework that relies on the adaptable Raspberry Pi platform, the Raspberry Pi can measure many essential factors, such as voltage, current, and temperature of solar panels, by utilizing a diverse range of sensors [9], [10]. Real-time data collection is facilitated by using sensors linked to the GPIO pins of the Raspberry Pi; the collected data is stored on the SD card [19], [20] this processed data can serve as a valuable resource for researchers to ascertain the attributes of the photovoltaic (PV) technology utilized within a PV system. Using interactive graphs, charts, and dashboards facilitates enhanced decision-making capabilities [21], empowering users to optimize the system for optimal efficiency [22].

The results of our study indicate that the monitoring model provided in this research demonstrates a high level of accuracy in estimating the performance of PV systems. Consequently, the real-time wireless monitoring system holds significant value as a predictive tool for forecasting energy output in actual PV systems; in brief, incorporating solar energy alongside innovative wireless monitoring technologies guarantees the effective functioning of solar panels and offers significant insights for ongoing enhancement and optimal efficiency. The solar energy industry is expected to make substantial progress toward achieving a sustainable energy future by adopting cutting-edge solutions such as the real-time wireless monitoring system.

2. METHOD

The research can be classified as applied due to its inherent character, as it seeks to address a specific problem by proposing a solution. In contrast, the study employs an experimental design [23] wherein field-level tests are conducted to manipulate the study variables that exhibit a causal relationship, hence facilitating transformation. The primary objective of this endeavour is to generate novel insights and enhance the subject of inquiry.

To enhance comprehension of the proposal's functioning, a schematic representation was created to illustrate the operational dynamics of the prototype, as depicted in Figure 1. The PV system consists of two main elements: the sensors and the monitoring system. The hardware circuits, which consist of the sensors connected to an amplifier circuit for precise measurements, are all linked to a Raspberry Pi server. In contrast, the monitoring component consists of a recently developed web page application designed to monitor and report the system's condition consistently, to enhance the distance between the server and the monitoring centre, a WiFi router is employed. The following sections provide a thorough overview of the implementation process for the intelligent photovoltaic system utilized in wireless monitoring.

2.1. Hardware development of the system

This part provides a comprehensive examination of the hardware development design of the system, along with many experimental deployments. The various electrical components of the sensors have been organized into distinct modules. An overall schematic of the electronics employed in our project is depicted in Figure 2. One of the issues faced in this project pertains to the absence of inherent functionality for reading analogue inputs in the Raspberry Pi. Nevertheless, many sensors yield analogue data, including current, photoresistors, temperature, and radiation sensors. To address this constraint, the decision was made to employ the MCP3008 analog-to-digital converter (ADC).

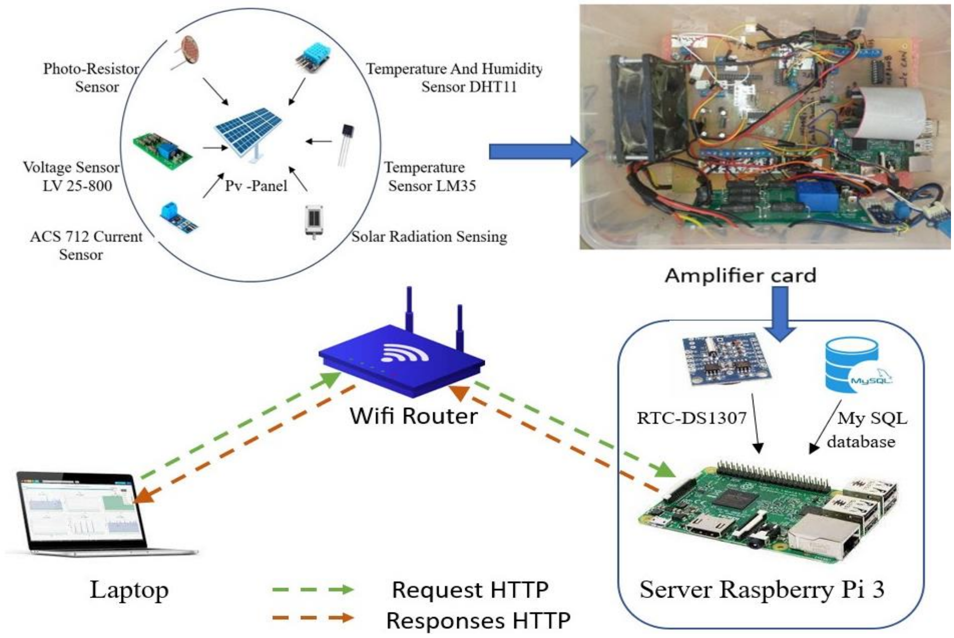

Figure 1. General system design

2.2. The integrated circuit MCP3008

The MCP3008 helps digitize analogue sensor readings; it can process numerous data streams in parallel thanks to its eight analogue inputs; the MCP3008 was powered by connecting its VDD and Vref pins to a 5V supply and its AGND and DGND pins to the ground. Using 4 GPIO pins, we connected the MCP3008 to the Raspberry Pi and read up to 8 analogue input channels [24]. After hooking up the analogue sensors, the MCP3008 converts the analogue input voltage between 0 and 5 volts into a digital value between 0 and 1023 [25], this digital output facilitates efficient sensor data processing and analysis on the Raspberry Pi. In conclusion, we overcame the Raspberry Pi's native lack of capability for reading analogue inputs by means of the MCP3008 ADC. This allows us to gather precise digital data from various analogue sensors, which can then be analyzed and processed.

2.3. The specification of Raspberry Pi 3

The Raspberry Pi 3 is a little single-board computer specifically engineered to instruct fundamental computer science concepts within educational environments; the single-board computer is designed to consolidate all the necessary components for computer operation onto a single card [26]. The particular model employed in this research incorporates a Broadcom BCM2837 64-bit microprocessor, including a quad-core 64-bit central processing unit (CPU) operating at a frequency of 1.2 GHz. It has 1 gigabyte of LPDDR2 SDRAM memory, 4 USB ports, 40 GPIO pins, an HDMI port, a BCM43438 wireless module, and integrated BLE support. Additionally, it offers a microSD card port for loading the operating system and storing data. The device possesses several notable characteristics, including a 4-pole stereo output, a composite video port, and a display socket that facilitates the connection of a Raspberry Pi touchscreen display.

2.4. Temperature sensor LM35

The LM35 temperature sensor was employed to determine the solar panel's temperature. The LM35 temperature sensor is widely utilized for measuring temperatures from 0 °C to 100 °C. However, the specific LM35 sensor in this study has an extended temperature range from -55 °C to +150 °C [27], [28]. To obtain accurate measurements, we inserted a TL084 operational amplifier (AOP) with continuous voltage capability between the LM35 sensor and the ADC MCP3008. The TL084 operational amplifier can provide a gain of up to 3.2, resulting in a change in the voltage applied to the input channel CH0 of the ADC MCP3008. This results in a voltage applied to the CH0 port of the MCP3008 that is 32 mV per °C rather than the 10 mV per °C provided by default by the LM35 sensor. The connection circuit between the LM35 and the AOP (TL084) is illustrated in Figure 2, and the voltage applied can be calculated using (1).

$$V_s = \left(1 + \frac{R_4}{R_2}\right).V_e = 3{,}2.V_e \quad (1)$$

2.5. Humidity and temperature sensor

The DHT11 sensor is a digital signal output device primarily calibrating environmental temperature and humidity to provide accurate readings. It features three connection pins labelled Vdd (for power), D0 (for data to the Raspberry Pi), and GND (for ground). The pin layout of the DHT11 sensor is depicted in Figure 2. This sensor's resistive humidity measurement component demonstrates an accuracy of 5% within the relative humidity range of 20% to 90% [29]. Additionally, it incorporates a temperature-measuring component with a negative temperature coefficient (NTC), enabling it to achieve an accuracy of 2% within the temperature range of 0 to 50 degrees Celsius [30]. The DHT11 sensor is compatible with a wide range of platforms due to its ability to operate within voltage levels ranging from 3.3V to 5V; when activated, it transmits a signal comprising 40 data bits [31], encompassing both the present temperature and humidity readings. To facilitate data exchange and communication with the CPU of the Raspberry Pi, this sensor will be connected to the GPIO 17 pin.

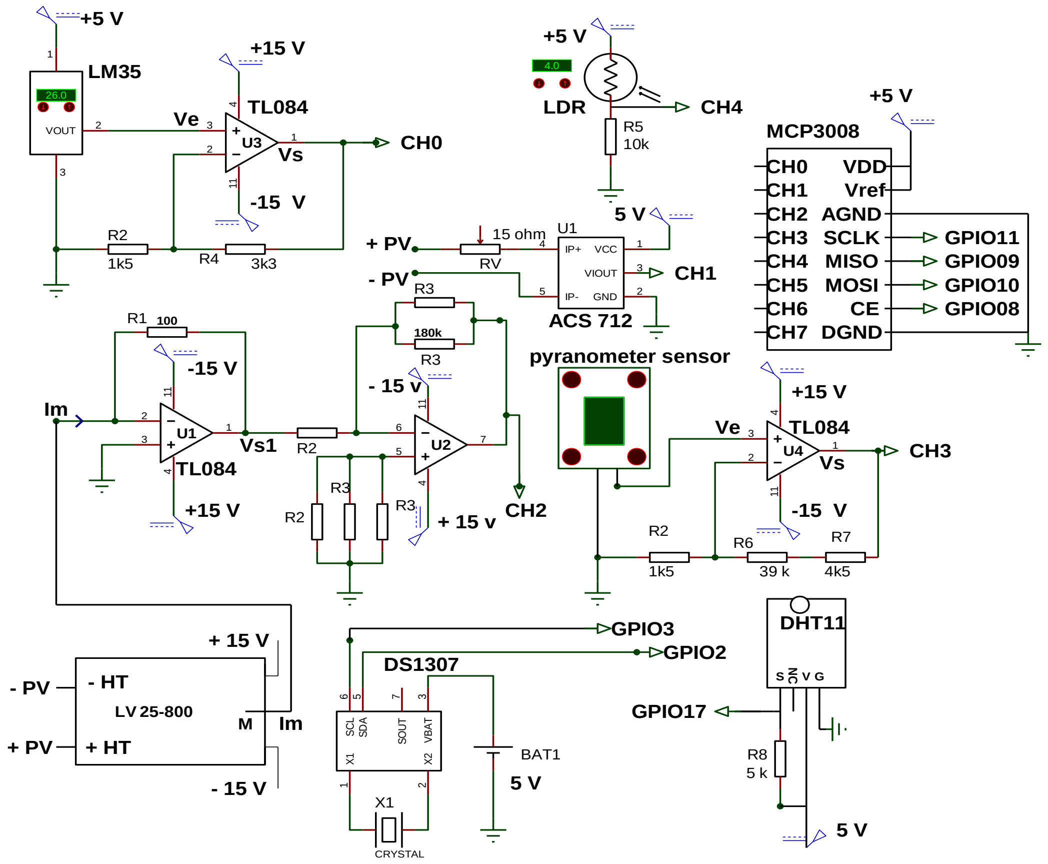

Figure 2. The amplifier card's global scheme

2.6. Voltage sensor LV 25-800

When measuring the voltage at the terminals of a photovoltaic panel, one major challenge is that the voltage can exceed the 5V range supported by the MCP3008 circuit, which is commonly used for voltage conversion. To address this issue, a potential solution is to employ the LV 25-800 voltage sensor, designed specifically for direct current and alternating current (DC/AC) voltage measurement [32]. This sensor offers galvanic isolation between the primary circuit (high voltage side) and the secondary circuit (electronic circuit side), enabling safe and accurate voltage measurements even if they exceed 5V.

The LV 25-800 sensor has a linear relationship between the generated current and the input voltage, where the current increases by 25 mA for every 800 V. Notably, this sensor demonstrates a remarkable +/- 0.8% precision. To achieve accurate voltage measurements within the appropriate range for the MCP3008, it is possible to incorporate a DC voltage inverting amplifier with a gain of 60 between the current-voltage converter and the MCP3008. Consequently, the voltage supplied to the input of the MCP3008 is 150V out of 800V, a value that fits within the permissible range. Subsequently, the output of the TL084 operational amplifier is linked to the CH2 analogue input channel of the MCP3008. The current-voltage inverting amplifier is employed to convert the output current of the LV 25-800 sensor into a corresponding voltage, as outlined in (2). Determining the voltage for a particular channel can be achieved by employing (3), which outlines the conversion and amplification procedure depicted in Figure 2.

$$V_{s1} = -\mathrm{I_m}.R_1 = -\mathrm{I_m}.100 \quad (2)$$

$$V_s = -\left(\frac{\mathrm{R3}}{2.\mathrm{R2}}\right).\mathrm{V_{s1}} = 6000.\mathrm{I_m} \quad (3)$$

2.7. ACS712 current sensor

The ACS712 current sensor is employed [33] to quantify the output current of the PV module. This current sensor exhibits the capability to accurately measure both direct current (DC) and alternating current (AC) currents, with a maximum capacity of 5A; the utilization of the Allegro ACS712ELC chip is observed, which offers a notable level of sensitivity and accuracy [34]. The sensor demonstrates a precision level of ±1.5% and a sensitivity of 180 mV/A; this indicates that the analogue voltage output of the sensor undergoes an increase of 180 millivolts for every ampere of current that traverses through it.

The ACS712 current sensor module functions at a voltage of 5 V, provided by the Raspberry Pi. The sensor's output reference voltage is configured at 2.5 volts; this implies that the analogue voltage output will stabilize at the reference voltage level 2.5 V without electrical current passing through the sensor. The ACS712 current sensor's output is linked to the CH1 analogue input channel of the MCP3008; the Raspberry Pi can interpret and transform the analogue voltage output of the ACS712 into a digital representation, facilitating subsequent analysis and monitoring of the current generated by the PV module. Integrating the ACS712 current sensor with the MCP3008 enables precise measurement and monitoring of the current produced by the photovoltaic panel; this facilitates the acquisition of significant data that can be utilized for many applications and analytical purposes.

2.8. Solar radiation sensing

A pyranometer is used to measure global solar radiation placed on the surface of the PV panel; we utilize the following equation, as represented by (4), to convert the electrical response into solar radiation [35].

$$\mathrm{E_g} = \frac{1000}{101.5}\mathrm{V_{mes}}(\mathrm{w/m^2}) \quad (4)$$

To obtain accurate solar radiation measurements, it is possible to incorporate a TL084 operational amplifier (AOP) with a gain of 30 between the pyranometer sensor and the ADC; this setup modifies the voltage applied to the input of the MCP3008 circuit ADC. Previously, the voltage was 101.5 mV per 1000w/m², but with the addition of the TL084, the voltage becomes 3045 mV per 1000 w/m²; the output from the TL084 is then connected to the CH3 analogue input channel of the ADC MCP3008. The diagram is depicted in Figure 2, and the voltage applied is represented by (5).

$$v_s = \mathrm{v_e}.\left(1 + \frac{\mathrm{R6+R7}}{\mathrm{R2}}\right) = 30.\mathrm{v_e} \quad (5)$$

2.9. Photo-resistor sensor

Photoresistors, sometimes called light-dependent resistors (LDRs), are electronic components that exhibit sensitivity to light and variations in resistance in response to changes in light intensity [36], the LDR in question possesses a light resistance value of 10 kΩ. When the LDRs are illuminated, the sun sensor generates voltage outputs from 0 to +5 Volts; this voltage range can be traced to the utilization of a +5 Volts power source to energize the sun sensor. Subsequently, the output signal generated by the LDR is linked to the CH4 analogue input channel of the MCP 3008; the diagram is depicted in Figure 2.

2.10. The real-time clock (RTC) DS1307

RTC DS1307 module comprises a crystal oscillator and a 3 V battery [37], the battery ensures that the RTC module remains powered even when the Raspberry Pi is turned off, thereby preserving the time data in memory. We need to follow these steps to establish a connection between our RTC and the Raspberry Pi: first, connect the Raspberry Pi power output pin (5V) to the module; next, connect the serial data line (SDA) pin to GPIO2 and the serial clock line (SCL) pin to GPIO3 on the Raspberry Pi.

3. RESULTS AND DISCUSSION

Our project aims to generate a graphical depiction of real-time measurements acquired from various sensors and save this data in a database file situated on a Raspberry Pi device. The measurements were conducted using Python programming, and the data was stored using the SQLite database management system; the integration of HTML code with a library from the Google Chart API graphical interface facilitated the generation of the displayed graph. Furthermore, we utilized JavaScript, jQuery, and CSS to create dynamic and engaging web pages, and we employed the Nginx HTTP web server to facilitate uninterrupted data transmission between the client and the server.

The program's primary objective is to configure the Raspberry Pi card as a web server, generating an HTML page that allows monitoring of the responses of different sensors connected to the photovoltaic panel from the client's browser. The "client/server" exchanges are presented on a web page; when you enter the IP address of the Raspberry Pi 'Server' card into your browser, a Wi-Fi network is created between the PC and the server. First, identify the computer's IP address that will be used to create the network and the subnet mask, open a browser and enter the server's IP address, 192.168.1.11. Once you've entered the address, the received request will be displayed on the web page, as shown in Figure 3. By implementing this setup, users can easily monitor and visualize real-time sensor data from the Raspberry Pi on their browsers, creating a seamless experience for data analysis and interpretation.

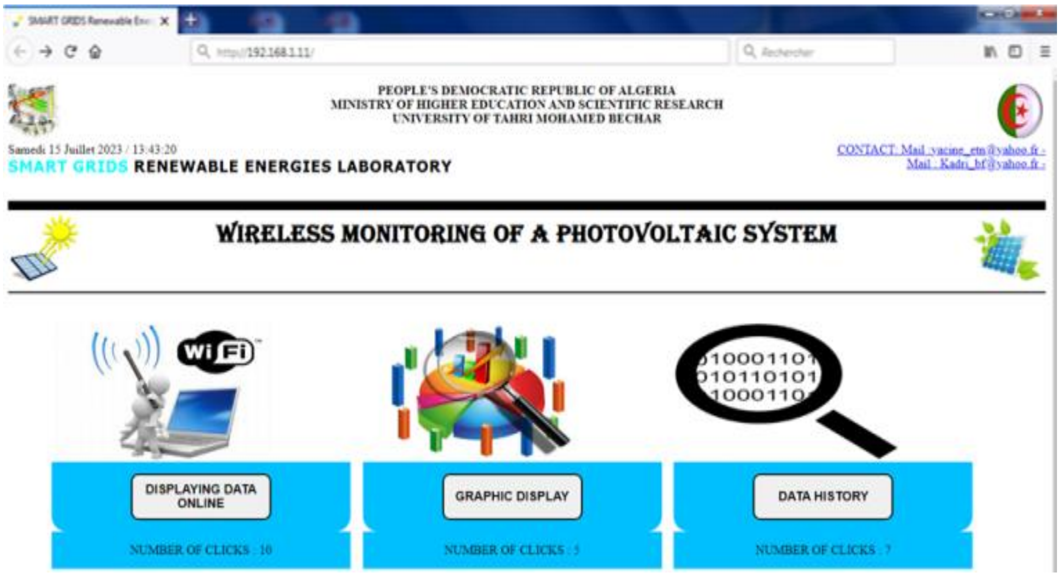

Figure 3. Online web page view on 15/07/2023 at 13:43:20

Upon clicking the "Displaying Data Online" button, the web page titled "acq.html" is opened. Figure 4 illustrates the presentation of real-time data on the web page in a tabular manner. The data undergoes continual updates, and the page is programmed to automatically reload every 30 seconds, showcasing the most recent measurements obtained from the sensors.

On the other hand, when the button (Data History) is clicked, it leads to the "his.html" web page. Figure 5 illustrates this page, which presents a comprehensive view of all the measurements collected from the various sensors. These measurements are stored in a file with the format ".db" on an SD-type memory; the data in this file covers the period from 15th to 19th October 2022.

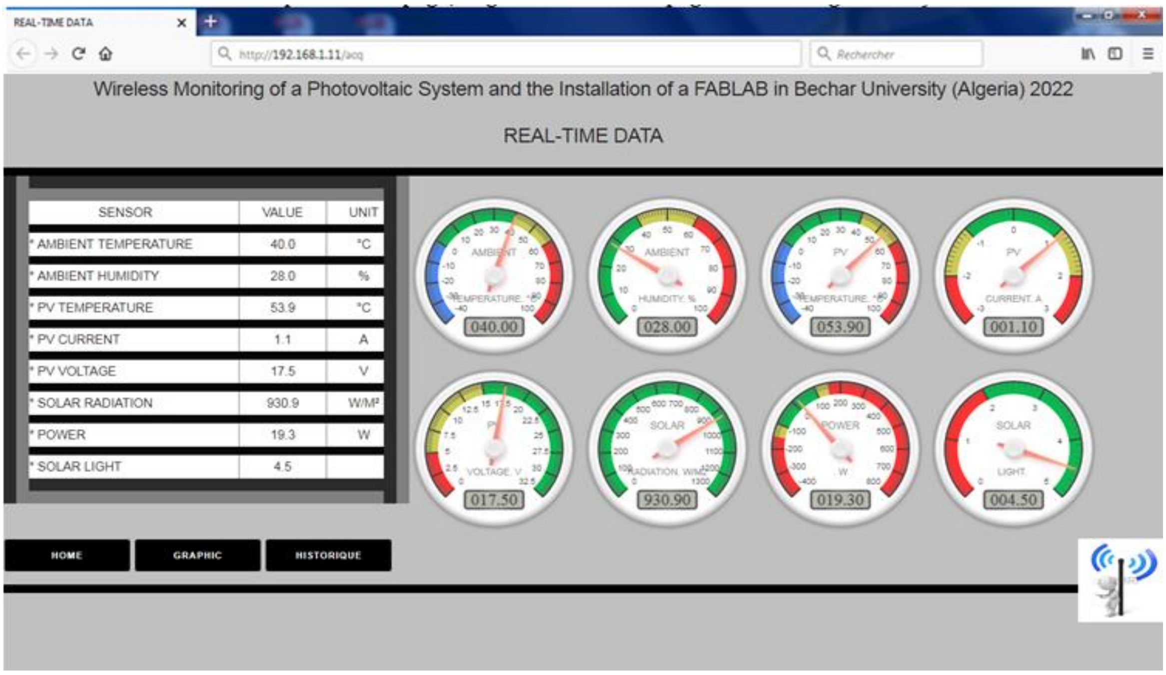

Figure 4. Real-time data

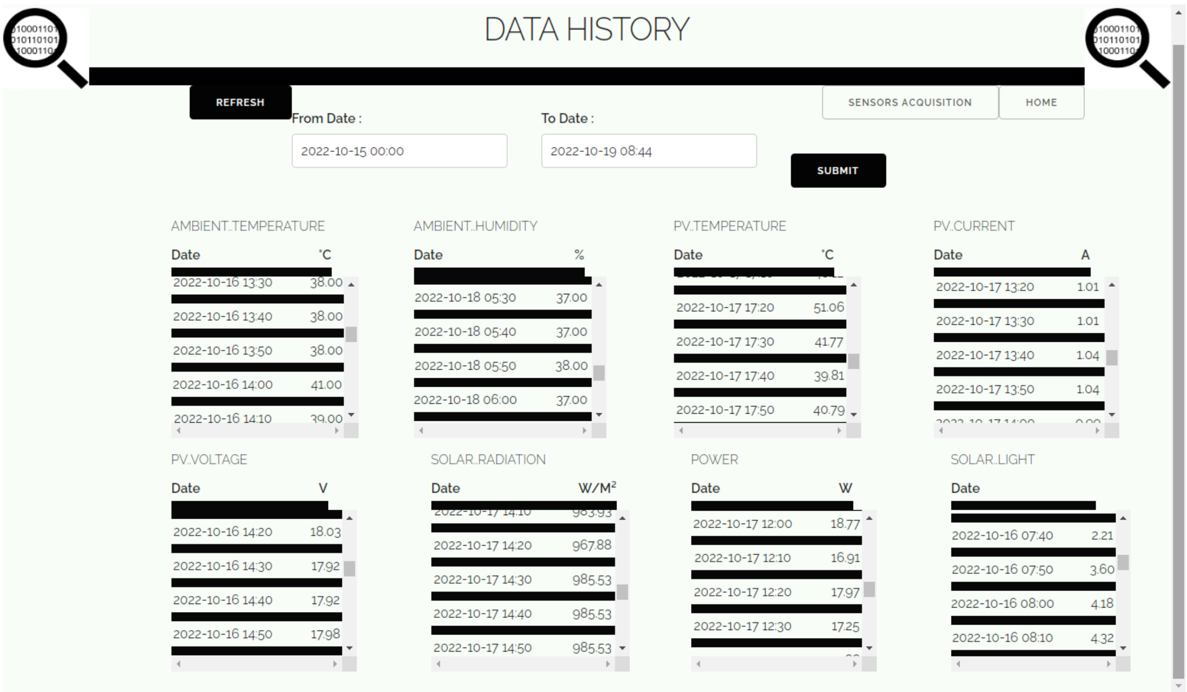

Figure 5. History display of values sensors

Furthermore, clicking on the button (GRAPHIC DISPLAY) launches the "gra.html" web page. Figure 6 depicts this page, allowing users to choose a specific display period. For example, in the displayed Figure 6, the chosen display period is 23rd October 2022, between 13:25 and 22:00; the (GRAPHIC DISPLAY) page offers a graphical representation of the monitored data, providing a visual understanding of the sensor readings during the selected time frame. This feature enhances the data analysis capabilities by enabling users to easily identify trends, anomalies, or patterns in the sensor data.

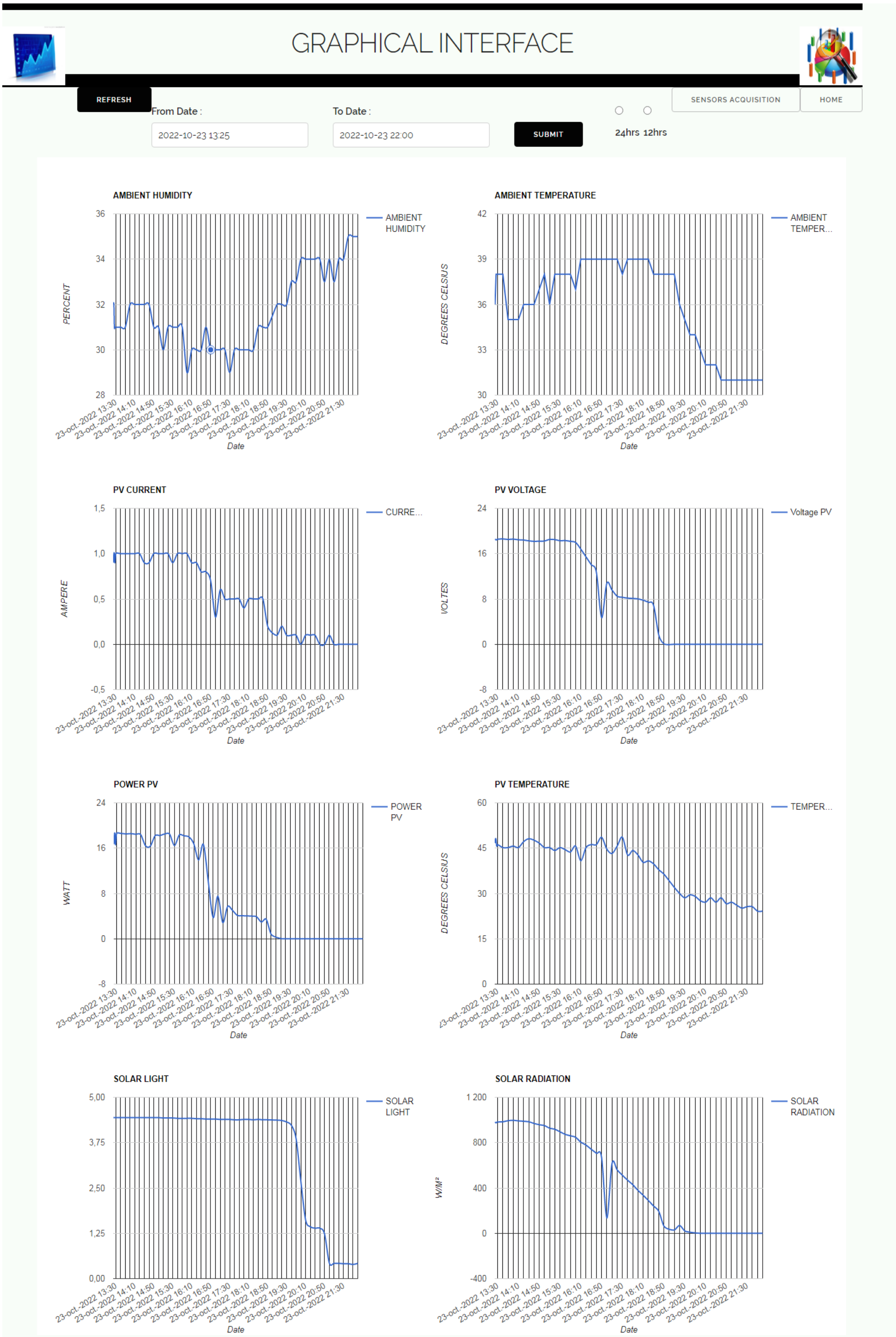

Figure 6. Web interface display of the wireless network system

4. CONCLUSION

The wireless monitoring system suggested in this study utilises Raspberry Pi and WiFi technology, presenting a viable and economical alternative for monitoring PV systems with enhanced efficiency and reduced costs. With real-time data acquisition, secure communication, and remote access, the system effectively empowers users to optimise their PV installations' performance and longevity. The proposed system lays the groundwork for further research and development in wireless monitoring for renewable energy systems. Future enhancements may include machine learning algorithms for predictive maintenance and integrating advanced communication protocols to accommodate various networking environments; for example, implementing an agent role within the system would enable it to handle issues autonomously, such as activating an alarm or reducing the charge, when necessary, this would enhance the system's capabilities and make it more versatile in addressing various scenarios and user requirements.

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