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IoT-based low-cost prototype for online monitoring of maximum output power of domestic photovoltaic systems

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This paper presents a low-cost prototype for monitoring online the maximum power produced by a domestic photovoltaic (PV) system using Internet of Things (IoT) technology. The most common tracking algorithms (P&O, InCond, HC, VSS InCond, and FL) were first simulated using MATLAB/Simulink and then implemented in a low-cost microcontroller (Arduino). The current, voltage, load current, load voltage, power at the maximum power point, duty cycle, module temperature, and in-plane solar irradiance are monitored. Using IoT technology, users can check in real time the change in power produced by their installation anywhere and anytime without additional effort or cost. The designed prototype is suitable for domestic PV applications, particularly at remote sites. It can also help users check online whether any abnormality has happened in their system based simply on the variation in the produced maximum power. Experimental results show that the system performs well. Moreover, the prototype is easy to implement, low in cost, saves time, and minimizes human effort. The developed monitoring system could be extended by integrating fault detection and diagnosis algorithms.

KEYWORDS
internet of things, low-cost prototype, maximum power, monitoring, photovoltaic system

1 | INTRODUCTION

Over the past few years, the photovoltaic (PV) market has seen remarkable growth, mainly due to various factors such as the significant reduction in cost of the PV modules on the market and more effective subsidy policies. The total installed capacity worldwide has reached 512 gigawatts which is an increase of 27% [1], and about 1.7 million PV plants have been installed [2].

The Internet of Things (IoT) conveys information through networks of physical devices (connected devices or smart devices), cars, buildings (smart cities), and any other electronic chip found in software, sensors, and any type of objects capable of collecting and exchanging data [3]. IoT enables objects to be remotely recognized and controlled through an existing network infrastructure, creating opportunities for more direct integration between the physical world and computer systems [4,5].

In the literature, numerous online monitoring PV systems have been designed and developed. These systems are mainly classified into three classes: (a) stand-alone PV systems, (b) grid-connected PV systems, and (c) hybrid PV systems. As reported in [6], an effective online monitoring of grid-connected PV systems using ZigBee was proposed. In [7], a low-cost power-line communication for monitoring residential PV systems was designed. The system can monitor and observe the performance of PV system based on power-line communication. In [8], the authors presented a cost-effective method for online monitoring of a PV module (wireless PV monitoring module). Table 1 summarizes the recent published work on the monitoring of PV systems based on IoT technology (from 2018 to 2020), including the types of microcontrollers, transceivers, monitored parameters, IoT platforms, cost, and PV systems.

In the last two decades, many researchers have presented different algorithms to track the maximum PV power under uniform and non-uniform irradiance conditions. The available algorithms can be broadly classified into two groups: local and global maximum power point (MPP) algorithms. The first group can be used only to track the MPP of PV systems under uniform irradiance conditions, and they are called conventional methods; examples include perturb and observe, incremental conductance, and hill climbing. The second group concerns the global MPP algorithms based on soft computing and hybrid MPP tracking (MPPT) to track the MPP in the case of partial shading conditions (non-uniform irradiance) [9]. However, MPPT based on advanced techniques, such as machine learning and heuristics, have not been examined in real-time applications, although there have been a few attempts to implement and verify the algorithms in dSPACE and FPGA for real-time applications [10,11].

The main objective of this work is to develop and realize a low-cost prototype for online monitoring the maximum power produced by a PV system. The prototype is also equipped with a web page that helps users to check in real time the changes in the power produced by their installations without any additional effort and cost. An additional objective is to verify experimentally the performance of some existing MPPT algorithms in real time based on IoT technology. The following points summarize the main differences between the present work and other related work: (a) the equipment used (low cost), (b) the number of implemented MPPT algorithms (users have more choices), and (c) the designed web page, which is rich in information and flexible (most published studies use the available ThingSpeak platform).

A detailed description of the implementation platform, including the design and development of the hardware and software, is presented. To the best of our knowledge, this application, that is, integrating IoT in monitoring the maximum power in PV systems based on low-cost system, which can help users to check the system evolution and possible faults detection in real time, has not yet been deeply investigated [12].

The paper is organized as follows: Section 2 describes the monitoring system components. A detailed description of the hardware platform and web page development process is provided in Section 3. Finally, the results and discussion are given in Section 4.

TABLE 1 PV monitoring system based on IoT technology

References	Year	Controller	Transceiver	Monitored parameters	IoT platform	Cost (EUR)	Uses and type of PV system
[17]	2018	Arduino Uno	Wireless: Ethernet	I_{pv}, V_{pv}, T, G, and others	ThingSpeak web page	Expensive 300.71	A novel monitoring and data logger of a solar home system
[18]	2018	PIC18Fxx5x	Wireless: Raspberry	I_{pv}, V_{pv}, T, G, and others	Web page	Not declared	Real-time monitoring of renewable energy system based on the Raspberry PI
[19]	2019	Arduino Uno	Wireless: RFM95W (LoRa)	DC current, DC voltage, DC power, Irradiation	Web page	Low 39.26	Data monitoring and management for a PV power plant using LoRa technology
[20]	2019	Node MCU ESP8266	Wireless: ESP8266	PV current, PV voltage, PV power, and Irradiation	ThingSpeak	Not declared	Real-time monitoring of the parameters of a PV panel using an Android application
[21]	2019	ADC1115 module	Wireless: Raspberry	DC current, DC voltage, DC power, Irradiation,	Web page	Low 55.87	A new methodology-based IoT technology for detecting uniform and non-uniform operating conditions for grid connected PV
[Our Work]	2020	Arduino Mega	Wireless: ESP8266	I_{pv}, V_{pv}, T, D, V_L, I_L, P_{mpp}, G	Web page	Low 63.04	Online monitoring of domestic photovoltaic system

1.1 | Related work of MPPT-based IoT

Few studies can be found in the literature on the online monitoring of maximum PV output power based on IoT technology. For example, in [13]; the authors presented a process for integrating the IoT architecture with MPP tracking in a PV system. They discuss clearly the complexities in demonstrating an IoT compatible with the MPPT of PV system. In [14], the authors exhibited a complete PV power harvesting system with a low-overhead adaptive MPPT scheme for IoT nodes. A strategy including IoT application in tracking the MPP was proposed and presented [15]. In [16], the authors presented MPPT based on an automated solar battery charge controller for controlling the overcharging and deep discharging of a battery using the PIC 16F877a controller. The monitored parameters were the voltage, current, temperature, and state of the battery.

2 | MONITORING SYSTEM DESCRIPTION

2.1 | PV module

The PV module used in this study is a BP Solar MSX-120 manufactured by multi-crystalline technology; its electrical specifications at standard test condition (STC: 1000 W/m^2 and 25°C) are presented in Table 2.

TABLE 2 Electrical specifications of BP Solar MSX-120 at STC

Maximum power (P_{max})	121.41 W
Voltage at MPP (V_{mp})	17.1 V
Current at MPP (I_{mp})	7.1 A
Short-circuit current (I_{sc})	7.98 A
Open-circuit voltage (V_{oc})	21.2 V

2.2 | DC/DC boost converter

A DC-DC boost converter was used for controlling the electrical power in DC circuit with great flexibility, reliability, and high efficiency. The electrical circuit of the boost converter is given in Figure 1. This structure consists mainly of an inductance (L), two capacitors (C_{int} and C_{out}), and two switches (a MOSFET and diode). Table 3 summarizes the values of the used components. For more information about the conception of the DC/DC boost converter, see our last work [22].

Figure 2 illustrates the block diagram of the designed monitoring system, which is composed of PV modules, a DC/DC boost converter, two voltage sensors, two current sensors, one module temperature sensor, and one reference solar cell for measuring solar irradiation, two microcontrollers (Arduino Mega 2560), a Wi-Fi module (ESP-8266), and an LCD display (16 × 4).

Table 4 gives more details about the different components used for the monitoring system (the name of the components, principal features, task, cost, and figures).

TABLE 3 DC/DC boost converter [22]

Elements	Ratings	Cost (USD)
Capacitors (Cint, Cout)	220 µF	The total cost of DC-
Babine	1 mH	DC boost converter:
MOSFET	IRFP540N	20
Lamp (Load)	36 W	
Diode Schottky	1N5824	
Driver	IRF2121	

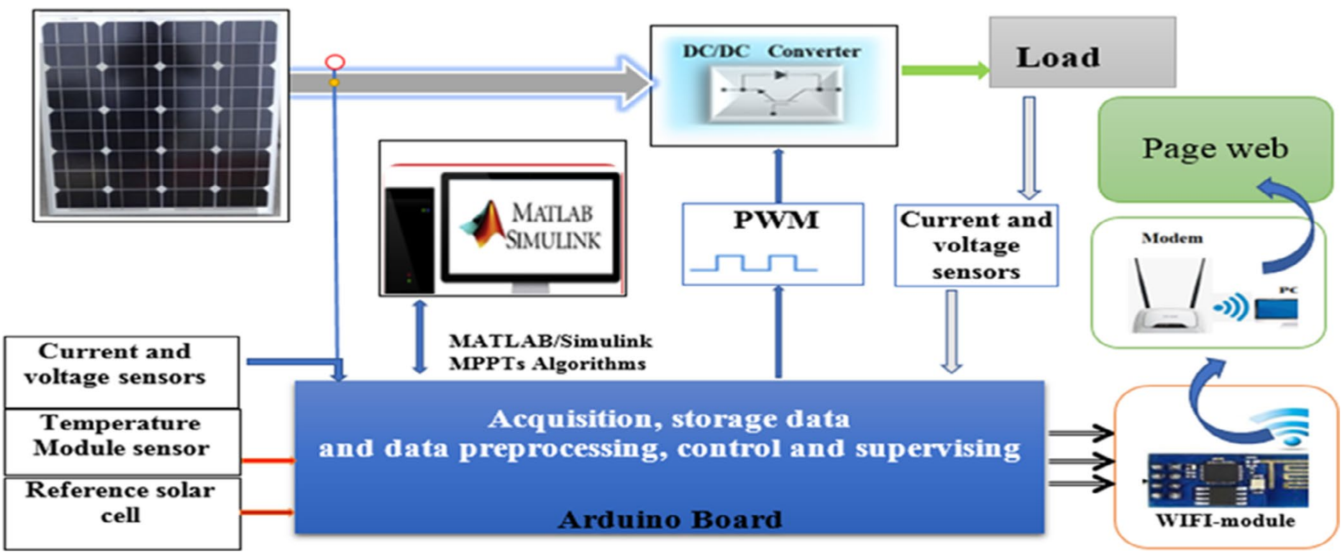

FIGURE 1 Block diagram of the designed monitoring system [22]

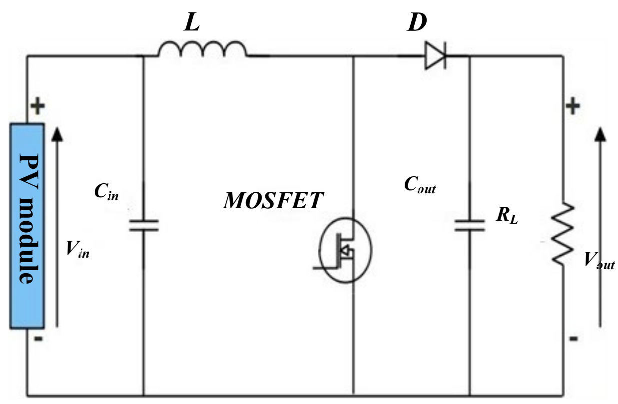

FIGURE 2 DC/DC boost converter

3 | METHODOLOGY

In this work, we do not intend to present the theoretical background of the used algorithms: perturb and observe (P&O) [23], incremental conductance (InCond) [24], hill climbing (HC) [25], variable step size incremental conductance (VSS InCond) [24], and fuzzy logic (FL) [26], as these algorithms have already been developed and simulated. There have also been some attempts to verify experimentally the MPPT algorithms using, for example, microcontrollers [27], dSPACE, and FPGA [28], but not for online monitoring. Hence, in this study, we focus more on the experimental implementation and online monitoring of the maximum power produced by a domestic PV system. It should be noted that these methods have not been well examined for online and real-time applications (eg, domestic applications less than 10 kWp). Of course, some industrial equipment has been studied, for example, charge regulators with MPPT, MPPT integrated with inverters, and supervisory control and data acquisition systems; however, these kinds of systems are more expensive, and there is no way to modify or update the integrated algorithms.

3.1 | Hardware design

This subsection presents a detailed description of the components used in the designed system and their experimental realization. The hardware configuration setup is shown in Figure 3. The designed prototype consists of two electronic boards: a DC/DC boost converter and a data-acquisition sensing board. The monitoring board consists of two voltage sensors, used for measuring

TABLE 4 Summary of the employed components

Component	Principal features	Task	Cost (USD)
Sensor current AllegroACS712	Output sensitivity: from 66 to 185 mV/A Total output error: 1.5% Size: 31 mm × 13 mm Weight: 2.8 g (approx.)	Measuring output current from the PV module and output current from the DC/DC converter	2.00
Sensor voltage 4PCS 25 V	Max voltage range: 25 V Analog input voltages up to 5 V Size: 27 mm × 13 mm Weight: 3 g (approx.)	Measuring output voltage from the PV module and output voltage from the DC/DC converter	2.50
Microcontroller Arduino Mega 2560	Microcontroller: ATmega2560 Digital I/O pins: 54 (15 pulse width modulation outputs) Size: 101.52 mm × 53.3 mm Weight: 37 g	Receiving and transmitting information from sensors	10.67
Module Wi-Fi ESP 8266-01	Operating Voltage: 2.5 V–3.6 V Operation current: 80 mA Size: 14.3 mm × 24.8 mm Perfect and simple at commands	Transmit the monitored data on the Internet (web page)	1.30
LCD DISPLAY	Type: 16 × 4 size: 70.6 mm × 60.0 mm Visual Area: 61.70 mm × 25.20 mm Weight: 7 g	To show the parameters monitored in real time	4.10
MAX 6675 K	Supply current: 1.5 mA Range: 0°C–1024°C Accuracy (20°C–80°C): ± 3°C Resolution: 0.25°C	Measuring module temperature	2.10
Reference solar cell	Isofoton	Measuring the solar irradiation	5.20
Total cost = 63.04 USD			

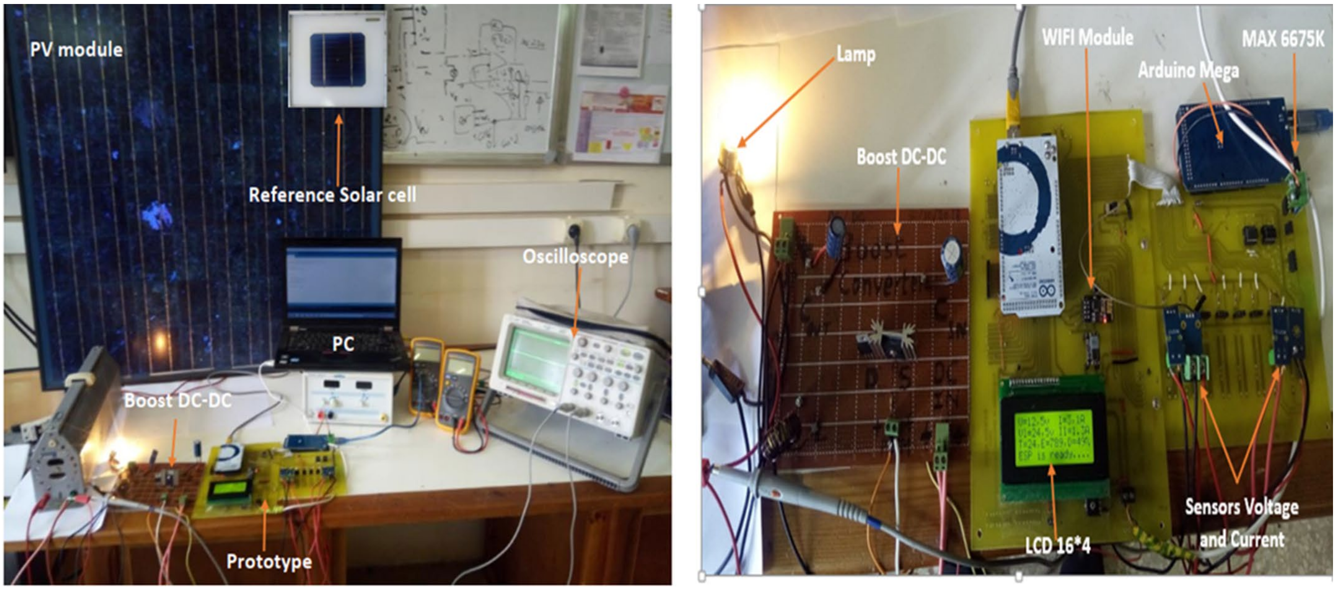

FIGURE 3 (A) Components of the PV system implemented at Jijel University and (B) the designed prototype under test

TABLE 5 Fuzzy rules [26]

ΔE / E	NB	NS	ZE	PS	PB
NB	*PS*	*PS*	*PB*	*PS*	*PS*
NS	*PS*	*PS*	*ZE*	*NS*	*ZE*
ZE	*NS*	*ZE*	*ZE*	*NB*	*PB*
PS	*ZE*	*ZE*	*NS*	*NS*	*PS*
PB	*ZE*	*NS*	*NS*	*NS*	*PS*

the output voltage from the PV module and the output voltage from the DC-DC converter; two current sensors, for measuring the output current from the PV module and the output current from the DC-DC converter; a MAX 6675 K sensor for measuring the module temperature; a reference solar cell for measuring solar irradiation; and two microcontrollers (Arduino Mega 2560) for acquisition, control, and supervision. To display the results, an LCD displayer is used to show the monitored data in real time as well as the system status. In addition, a Wi-Fi module (ESP-8266) is used to transmit the monitored data: current (I_{PV}), voltage (V_{PV}), load current (I_L), load voltage (V_L), power at MPP (Pmpp), module temperature (T), in-plane solar irradiance (G), and duty cycle (D) to the Internet. The load consists of a lamp of 36 W.

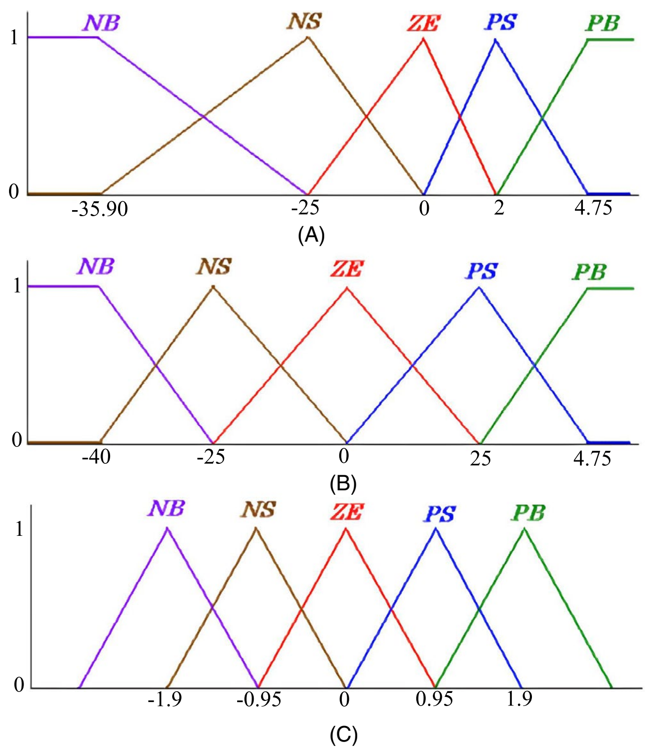

FIGURE 4 Membership functions (A) error, (B) error change, and (C) duty cycle

3.2 | Software design

3.2.1 | MPPT algorithm implementations

The FLC algorithm uses two inputs, the tracking error E and the change in the error ΔE, which are defined by the following equations [26]:

$$E(n) = \frac{P_{pv}(n) - P_{pv}(n-1)}{V_{pv}(n) - V_{pv}(n-1)}, \tag{1}$$

$$\Delta E(n) = E(n) - E(n-1), \tag{2}$$

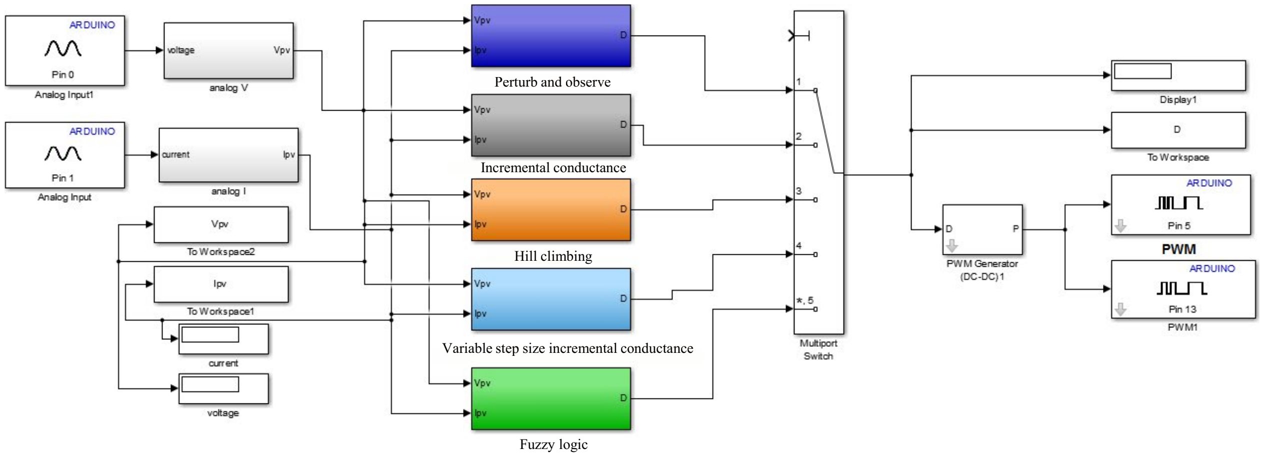

FIGURE 5 Different algorithms MPPT implemented in Arduino board under MATLAB/Simulink

where n is the sample time and $P_{pv}(n)$ and $V_{pv}(n)$ are the instantaneous power and voltage of the PV generator, respectively. The input/output variables are divided into the following five linguistic variables: *NB*: "Negative Big", *NS*: "Negative Small", *ZE*: "Zero", *PS*: "Positive Small", and *PB*: "Positive Big". Therefore, in this fuzzy logic controller, we used 25 fuzzy control rules. The fuzzy rules are reported in Table 5, and Figure 4 shows the membership functions.

The MATLAB/Simulink block diagram developed for different algorithms is depicted in Figure 5. The aforementioned MPPTs are incorporated in the block diagram. As can be seen in Figure 5, the user can select easily a suitable algorithm.

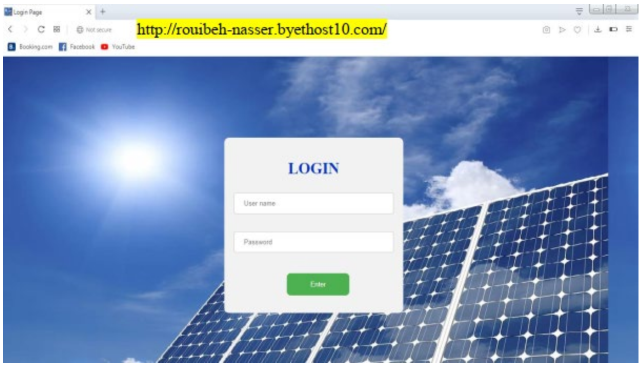

FIGURE 6 Login web page

3.2.2 | Web page development

In order to develop the web page for this application (formatting and displaying data on the web page), we used HTML and JavaScript languages. The web development process includes two sides: the client side and server side. More details about the developed websites can be found in our last work [29]. The web page was developed in order to enable administrators to view the monitored parameters in real time as well as the curves of the point selected by the administrators. Figure 6 depicts the login web page.

In the literature, various transmission technologies can be utilized for monitoring purposes; for example, ZigBee wireless network [6], wireless communication [30], wired communication [31], and power-line communication [7]. In this work, a Wi-Fi module (ESP-8266) is utilized for the PV system monitoring. The integrated code in the Arduino Mega board is written using the Arduino IDE.

As mentioned previously, we used two boards (Arduino Mega), for acquisition, control, and supervision. The first board is used to implement the MPPT algorithms and control the MOSFET transistor of the DC-DC boost converter, and the second board is used for data acquisition and supervision. Figure 7 illustrates a block diagram of the process for monitoring data. The process begins with the initialization Wi-Fi module ESP-8266 and LCD display, if the Wi-Fi module ESP-8266 connect to the router. The monitored parameters are saved as strings and shown on the LCD screen. More details about the process can be found in [29].

For data transmission, the ESP-8266 creates a TCP/IP connection to the server. The data are transmitted as an HTTP request. The monitored data, stored as strings, are concatenated with the base HTTP request to form an HTTP request containing the monitored data values. The final HTTP request is similar to "get/web/get_data.php, Host: http://nassirrouibah.net." After sending the final HTTP request, the TCP connection to the server is closed and the process is repeated [29].

4 | RESULTS AND DISCUSSION

4.1 | Simulation results

The simulation was carried out based on different MPPT algorithms under constant atmospheric conditions using real

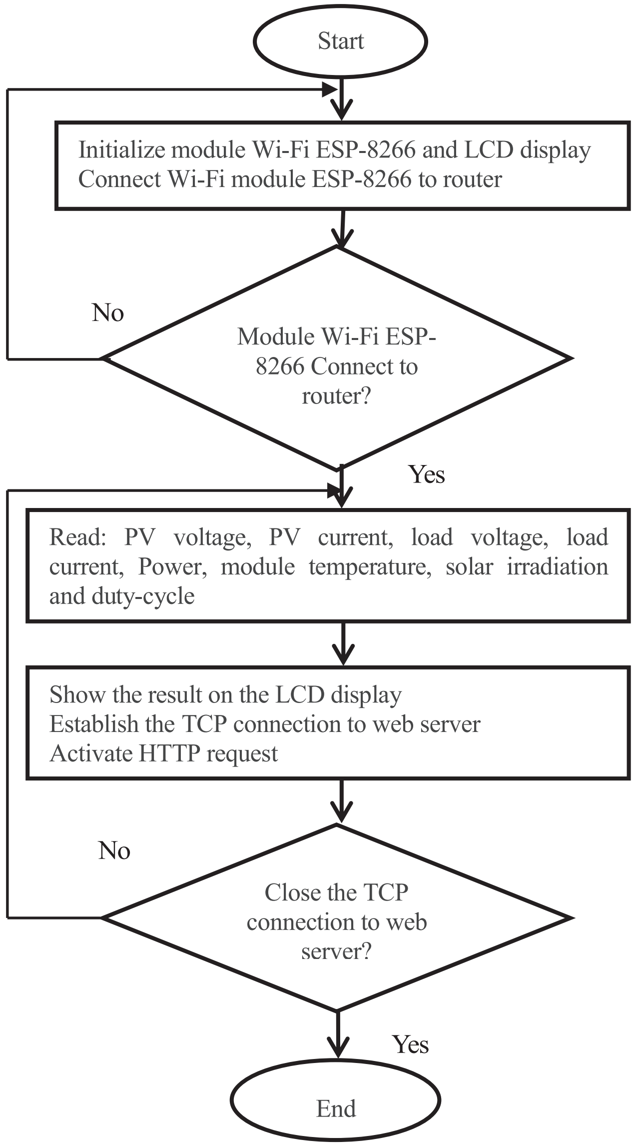

FIGURE 7 Block diagram of the data monitoring process

parameters obtained from the experiments (G = 870 W/m^2, T = 38°C). Figure 8 shows a comparison of the different MPPT algorithms obtained using MATLAB/Simulink software. The output power results obtained from the simulation at this condition using five MPPT algorithms are around 36 and 38 W. It can be noticed that all the MPPT algorithms have converged to the right MPP but with different performances.

4.2 | Experimental results

The experiments were carried out on 9 July, 2019 at RELab (Jijel University, Algeria). The simulated MPPT algorithms were evaluated with different values of duty cycle and controlled variations in the input and output voltage.

TABLE 6 Comparative assessment of different examined MPPT methods

Methods					
Evaluated parameters	**P&O**	**InCond**	**HC**	**VSS InCond**	**FL**
Power production (W)	32.65	33.48	32.73	32.65	33.54
Convergence time T_c (ms)	20.00	23.00	50.00	45.00	25.00
Efficiency (%)	85.62	97.29	83.58	97.76	99.23
Algorithm complexity	Low	Low	Low	Medium	Complex
Sensors used	I, V	I, V	I, V	I, V	I, V
Cost	low	low	low	low	low
Robustness	Yes	Yes	Yes	Yes	Yes
Control strategy	Sampling methods				Intelligent control

In this subsection, a performance comparison of different algorithms is presented by employing the most common assessment criteria, MPPT efficiency, convergence time, cost, required sensors, robustness, and complexity. The MPPT efficiency (static or dynamic efficiency) is an important parameter for assessing the performance of MPPT algorithms. The dynamic efficiency is calculated as follows [32]:

$$\eta_{\mathrm{MPPT}} = 100 \times \frac{\sum_{n=1}^{N} P_{\mathrm{pv}}(n) \cdot T_{\mathrm{s}}}{\sum_{n=1}^{N} P_{\max}(n) \cdot T_{\mathrm{s}}} = 100 \times \frac{\sum_{n=1}^{N} P_{\mathrm{pv}}(n)}{\sum_{n=1}^{N} P_{\max}(n)}, \tag{3}$$

where P_{pv} (n) is the measured output power of the PV under the control of MPPT, $P_{max}(n)$ is the output power at the true MPP, N is the number of samples, and T_s is the sampling period. The experimental curves of input voltage, output voltage, and output power of different MPPT algorithms (P&O, InCond, HC, VSS InCond, and FL) are depicted in Figures 9A-E and 10, respectively.

According to the curves presented in Figure 9, all investigated MPPTs converge to the vicinity of the exact MPP (33.256 W) but with different response times. It can be noticed that P&O, InCond, and FL exhibit fast convergences to the MPP of 20, 23, and 20 ms, respectively. On the other hand, the HC and VSS InCond algorithms exhibit convergence times of 50 and 45 ms, respectively, which is lower than that of the P&O, InCond, and FL algorithms. In addition, a small power ripple was observed in all investigated methods.

Table 6 reports the calculated power, convergence time, efficiency, and other parameters. With reference to Table 6,

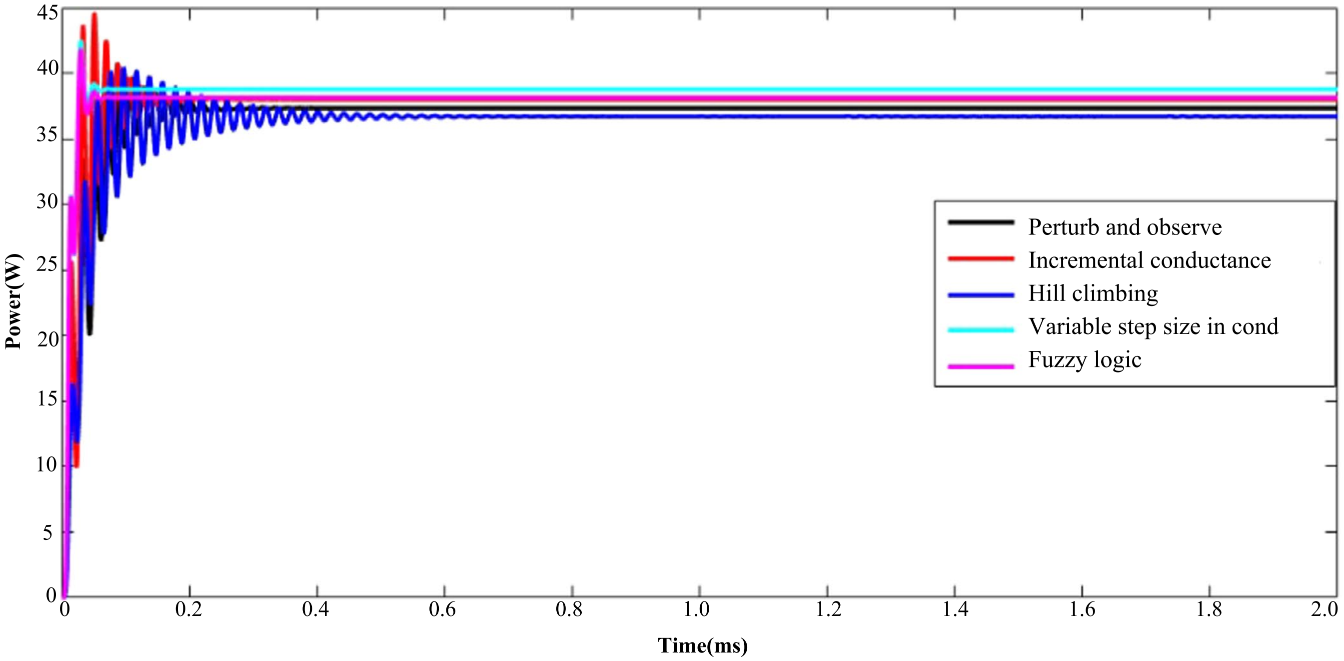

FIGURE 8 Simulation results of output power for different MPPT algorithms

it can be seen that the five MPPT methods take a short time for the convergence that is between 20 and 50 ms, and it is clearly observed that FL, InCond, and VSS InCond present good efficiency: 99.23%, 97.29%, and 97.29%, respectively. From the point of view of implementation, we can say that all investigated methods can be simply implement, except for FL, which needs some technical knowledge and skills.

Based on the comparison results, it can be concluded that the fuzzy logic MPPT can be considered a good MPPT controller for PV systems because it can improve the tracking performance in terms tracking efficiency (99.23%), short convergence time (0.025 s), and cost competitiveness.

4.3 | Web page results

In this subsection, we present the monitored data that can be observed on the designed web page. The web page is available at http://nassirrouibah.net. The web page is shown in Figure 6 (User name: Nassir, Password: aaaa), and the web page menu includes: (a) "Home," (b) "Monitoring system," (c) "MPPT," and (d) "partial shading." When "MPPT" is chosen, the web page shows a sub-menu containing the results of different algorithms used in this online monitoring, for example, when the user clicks on the buttons "P&O" and "graphs," another web page opens (Figure 11A-C), which gives real-time values of the monitored data.

The main contribution of this work is the remote monitoring of the product power and the parameters (I_{PV}, V_{PV}, I_L, V_L, P_{mpp}, G, T, and D) of the PV system in real time via the web page (http://nassirrouibah.net). The monitored parameters are handled and analyzed to deliver data that can be seen effectively by clients. The monitored parameters are represented in graphs. Figure 11A–D show screenshots of the monitored parameters after the "P&O" button has been clicked.

As depicted in Figure 11A, when the user clicks on the "P&O" button, we can observe the values of all monitored parameters (I_{PV}, V_{PV}, I_L, V_L, P_{mpp}, G, T, and D). When the user clicks on the graphical button, we can also visualize the changes in all monitored data, as shown in Figure 11B. Figure 11C depicts the produced output power based on the P&O tracking algorithm.

From the web page, we can easily download an XLS file containing all values of the monitored parameters, as shown in Figure 11D. The data, saved in XLS file format, can be easily exported to any software for further study. To obtain the XLS file, the user clicks the button marked with a red circle and chooses the "download XLS" option. Figure 11D depicts the XLS file with all the monitored parameters marked with blue circles. Moreover, users can export and print the data in different formats (for example, PNG, JPEG, PDF, and SVG for graphics and PDF, XLS, view table data, and CSV for documents).

The experimental results demonstrate that the realized monitoring system offers users a web interface in which users can monitor PV parameters (I_{PV}, V_{PV}, I_L, V_L, P_{mpp}, G, T, and D) in real time anytime and anywhere without effort.

From the obtained results, we can say that the monitoring system works correctly and tracks exactly the MPP. Hence,

FIGURE 9 Experimental curves of the PV panel output voltage (cyan), and input voltage (orange) with different values of duty cycle: (A) P&O, (B) InCond, (C) HC, (D) VSS InCond, and (E) FL

we can conclude that the online monitoring system-based MPPT for the domestic PV system based on IoT operates properly and enables users to check the evolution of the produced maximum power over time.

5 | CONCLUSION

In this paper, a prototype for the online monitoring of PV-maximum power using IoT technology was presented.

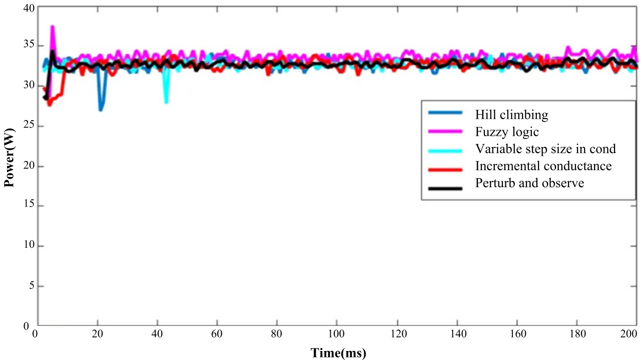

FIGURE 10 Experimental curves of the PV module power for the MPPT methods

Different MPPTs algorithms were implemented and tested under real environmental conditions. The effectiveness of each method in tracking the MPP was also presented. The designed prototype allows us to collect and transmit some parameters being measured in the investigated PV system, which enables us to verify and control the system operation online. The system is equipped with a web page to make it accessible at any time and any place via the Internet. Experimental results demonstrated that the system is able to operate with good performance. The main advantages of the designed prototype are easy implementation, low cost, acceptable reliability, time synchronization, minimization of human effort, time savings, enhanced data collection, and the ability to allow users to observe and control the performance of the PV system without any additional effort or cost. The designed prototype could potentially be adapted to support various types of PV systems to ensure data monitoring and control of the operation of the system online. We can say that the collection, transmission, monitoring, analysis, and observation of the parameters being measured in any PV system have now become an important aspect thanks to IoT technology. The limits of this work are as follows: (a) more knowledge and skills of computer science and mastery of programming languages (such as Java script or HTML) are needed, (b) the tested was only for a small-scale PV system, and (c) a data security system was not implemented in this work. The developed monitoring system could be further improved in the following ways: (a) the implementation of some algorithms that are able to track the MPP under partial shading conditions, (b) notifying the users via a simple SMS if any decrease is observed in the maximum output power, and (c) extensions for integrating fault detection and diagnosis algorithms.

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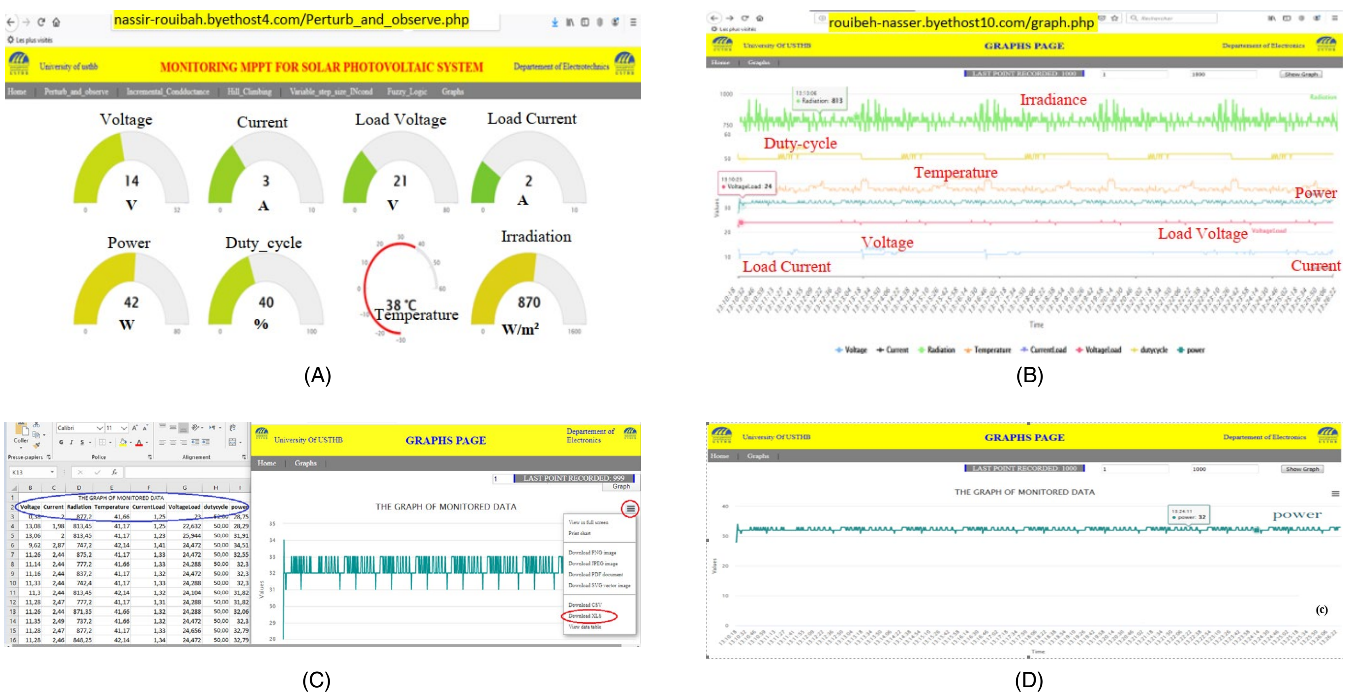

FIGURE 11 (A) Monitored parameters shown after the user clicks on the "P&O" button, (B) graphs of the monitored parameters, (C) graph of the output power, and (D) monitored parameters saved in an XLS file

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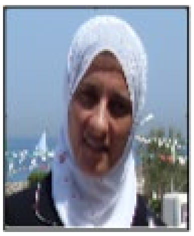

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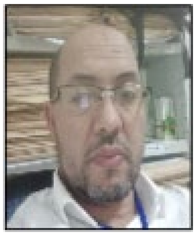

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