Photovoltaic Systems and Equipments for the Rural and Urban World

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Mustapha Melhaoui, Kamal Hirech, Ilias Atmane, and Khalil Kassmi

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Abstract

Climate change and emissions of certain gaseous pollutants due to the burning of fossil fuels have intensified the natural phenomenon of the greenhouse effect and led to an increase in temperature and environmental degradation. This phenomenon is likely to have significant impacts on the climate and ecosystems of the planet. The international community has therefore mobilized to propose alternatives to limit atmospheric concentrations of greenhouse gases, with the objective of halving global emissions by 2050.

M. Melhaoui · K. Hirech · I. Atmane · K. Kassmi (✉)
Faculty of Science, Department of Physics, Team: Materials, Electronics and Renewable Energies MERE, Laboratory Electromagnetism Signal Processing and Renewable Energy LESPRE, Mohamed Premier University, Oujda, Morocco

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The problems of energy resources and the environmental impacts thus constitute one of the major concerns of the world organizations. The alternatives to be developed are the use of clean energies and the implementation of energy politics that use renewable energies (solar and photovoltaic energies, wind, biomass, etc.).

Our proposal aims to facilitate the sharing of information on current techniques in terms of photovoltaic renewable energies, under development, between scientific actors and civil society. It contributes to improving the knowledge of all actors concerned about climate change – means of improving the living conditions of populations in order to achieve sustainable development.

In this context, our objective, in collaboration with the socioeconomic partner sectors concerned with energy and environmental issues, is the development and promotion of renewable energy installations and the use of necessary applications such as lighting, water pumping, solar ovens, and solar desalination.

In this chapter, we present:

– Introduction on the environment and renewable energies
– Structure, operation, and results on optimized systems for the production of electrical energy
– Equipment for acquisition, control, and energy management control

Keywords
PV system · MPPT · Charge controller · System monitoring · Remote system control

Abbreviations

CU	Control unit
PV	Photovoltaic
DC/DC	Direct current/direct current converter
MPPT	Maximum power point tracking
MPP	Maximum power point
HMI	Human machine interface
MSS	Management and supervision system
VCO	Open circuit voltage
PWM	Pulse width modulation
Vpv	PV panel voltage (V)
Ipv	PV panel current (A)
Ppv	PV panel power (W)
Vbat	Battery voltage (V)
Ibat	Battery current (A)
Pbat	Battery charge power (W)
Ioct	Over charge terminate current (A)
CC	Short circuit
CO	Open circuit

Introduction

In order to deal with the alarming depletion rates of the main conventional energy resources such as coal, oil, and natural gas, and with the environmental degradation caused by the process of exploiting these sources of energy, it has become necessary to invest into other type of energy such the renewable energy resources. Such investment in the world could face the world's ever-increasing demand for energy, without degrading the environment by greenhouse-gas emissions causing an increase in the level of global warming (Valkila and Saari 2010; Moosaviann et al. 2013).

Research centers in the renewable energy sector have been developing in all regions of the world for several years, leading to the improvement of renewable energy technology, competitiveness between the various players in this field sector, and thus the reduction of energy production costs.

Photovoltaic energy is one of the solutions that can face challenges of future energy transition. It has become a widely used source in stand-alone installations and isolated sites for low and medium power and connected to the grid for high power installations.

Like any industrial processes, a photovoltaic (PV) system may be subjected, during its operation, to different anomalies leading to a system performance reduction or even total unavailability of the system. This reduces the productivity of the PV system and thus reduces the profit of the installation, not to mention the cost of maintenance (De la Casa et al. 2003).

In order to increase the reliability of the photovoltaic system, it is important to understand the technologies and manufacturing processes of the entire energy production chain. The PV system improvement requires:

- The improvement of different photovoltaic cell manufacturing technologies and processes
- The enhancement of the power bloc functioning (DC/DC converter – DC/AC inverter, Solar batteries . . .) (Lin and Lu 1999; Lin and Chen 2008; Tseng et al. 2006; Melhaoui et al. 2014)
- The optimization of control signals functioning (MPPT control, battery controller, etc.) (Fan and Yu 2011; Lin and Lu 1999; Lin and Chen 2008; Tseng et al. 2006; Melhaoui et al. 2014; Salas and Olí 2006; Xin-chen Cai 2011)
- Better management of the energy flow in the photovoltaic system (supervision management system, etc.) (Melhaoui et al. 2015; Melhaoui et al. 2016; Zahran and Yousef 2014; Tsagaris and Triantafyllidis 2012)

In this context, our team conducts research on PV systems and on all applications related to the PV production (solar oven, desalination system, pumping station, etc.). Special attention is focused on performance improvement, increasing energy production, and reducing the energy cost.

In this chapter, we will present the design and validation of the management and supervision system of a modern stand-alone PV installation. More precisely, we will present our contribution on the improvement of control systems (MPPT regulator) and on the development of a performant management and supervision software for the PV system, which can be controlled locally or remotely to improve the energy saving with low cost.

PV System Structure

The PV system developed during this work in the LETSER laboratory is shown in Fig. 1 This system is designed to deliver an electrical power generated by the PV panels, which can reach 300 W in order to supply a DC load (solar battery, etc.). This prototype is equipped with a management and supervision system to control the energy flow in the system, to ensure adaptation between the different power blocks and to monitor in real time the state of the whole system (data acquisition, remote control, and monitoring). It is also equipped with a safety and protection system to protect the PV equipment against malfunction. The different blocks of this system are:

- PV generator formed by PV panels
- Adaptation quadrupole represented by a DC/DC Boost/Buck converter, whose function is to adapt the PV generator to the load using the MPPT control
- DC load formed by solar battery

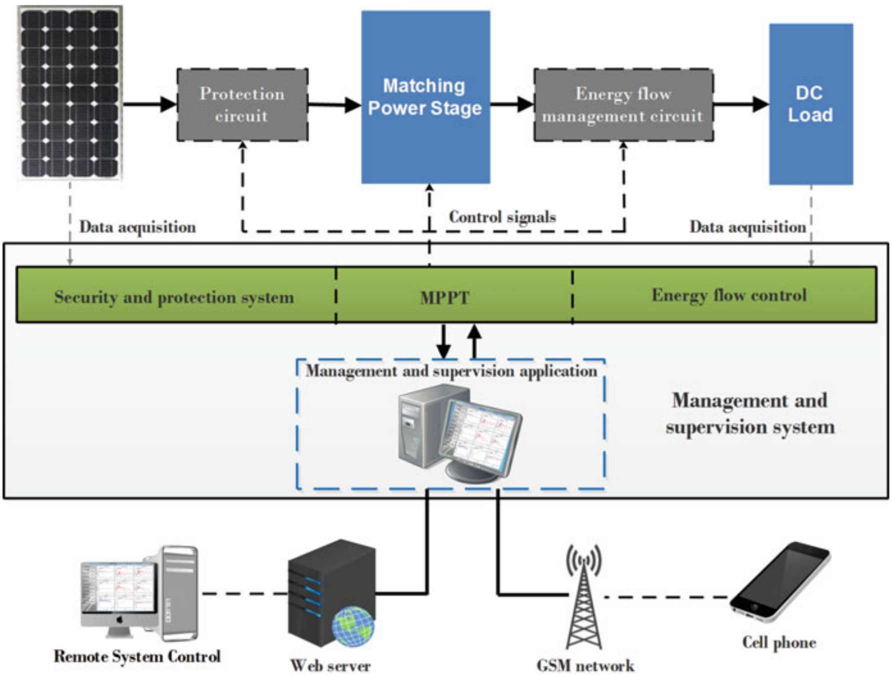

Fig. 1 Synoptic diagram of the PV system controlled by the management and supervision system

- Management and supervision software used to manage the entire PV system, to visualize and represent in real time plots the electrical quantities, to calculate the overall efficiency of the system, and to represent the state of charge of the batteries. The software can also store the data into a database and export them into a text or Excel file for further study (Melhaoui et al. 2015; Melhaoui et al. 2016)
- New strategy of signals control implemented in a microcontroller: MPPT control that ensures optimal operation of the PV system around the MPP in all weather conditions (Melhaoui et al. 2014), and charge/discharge controller that controls the use of the batteries (Hirech et al. 2013; Hirech et al. 2015)

PV System Operation

MPPT Control

Principle of the Functioning

The purpose of the MPPT control is to control the DC/DC power switch, in order to produce and provide the maximum power from the PV panels to the load. The MPPT algorithm is implemented on a microcontroller, which provide a PWM signal whose duty cycle is set according to the MPPT algorithm, to converge the operating point of the PV panels to its maximum power point (PPM) (Fig. 2).

To optimize the functioning of the MPPT control and increase the reliability of the PV system, we used the characteristics of the PV panels (voltage optimal operating range) in the MPPT algorithm in order to increase the precision and the search speed of the point PPM.

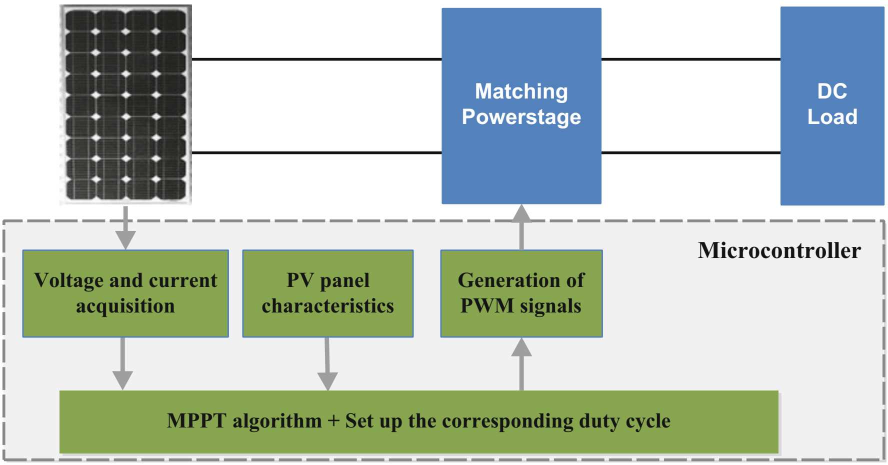

Fig. 2 Synoptic diagram of a single-stage PV system equipped with the MPPT control

MPPT Control Algorithm

The algorithm used to track the maximum power point is based on the Hill Climbing algorithm, taking into account the optimal electrical characteristics of the PV panels. Our contribution on the MPPT algorithms consists on looking for the MPP of PV panels using the optimal voltage range (Vmin and Vmax) of the PV panels. This range is only relative to the PV panels used in the system.

The improved algorithm (Fig. 3) is based on the calculation of the PV power and with its derivative to determine the evolution of power point. The algorithm is also based on the calculation of the voltage derivative of the PV panels and on the use of the optimal voltage range in order to improve the search time and increase the stability of the system around the PPM.

The algorithm performs with the following steps:

- If the power derivative is positive, the system thus evolves toward the maximal power point. The algorithm makes no change and let the PV system maintain its evolution
- If the power derivative is negative: the PV system loses the power and two cases are possible: (1) external cause (change of the illumination, the variation of the temperature), of which our algorithm is going to find another maximum power point; (2) internal cause, the system did not still find the MPP or it oscillates around MPP. According to the study made on the photovoltaic systems (Mrabti et al. 2009), we conclude that the optimal voltage of PV panels, used in the laboratory, varies between Vmin =12 V and Vmax = 15 V, regarding the intensity of the illumination or the temperature (Fig. 4). Thus, the algorithm forces the search for the MPP using the voltage range [Vmin, Vmax]:
  - If Vmin < Vpv < Vmax: the system oscillates all around or close to the maximum power point. In this case, we fixed a temporization during every change of the evolution of the PV system. This temporization determines oscillation frequency around the MPP and eliminates false acquisitions of the electrical quantities due to the system noise or to sudden variation of the illumination to maintain the PV system stable. To provide the precision and the stability of the system, we fixed the increment and the decrement steps of the PWM duty cycle (Inc) to 0.01. Depending on the time delay (TMP), we process as follow:
    - If (TMP = 1) (temporization or delay elapsed): we invert the Vstate signal and reset the timer (the evolution state includes two states: 1 or 0). This signal allows us at the end of the algorithm to increment the duty cycle if Vstate = 1 or decrease the duty cycle if Vstate = 0.
    - Otherwise, no operation is performed.
  - If $V_{PV} < V_{min}$ or $V_{PV} > V_{max}$: The PV system is distant from the maximum power point. In this case, the PV system is close to short circuit state or to the open circuit. The algorithm bring quickly the system to the optimal range by imposing an important variation steps of the duty cycle (Inc = 0.05). All this will prevent far oscillations from the MPP and allow the PV system to always convergence toward the MPP. This process is realized with the following operations:

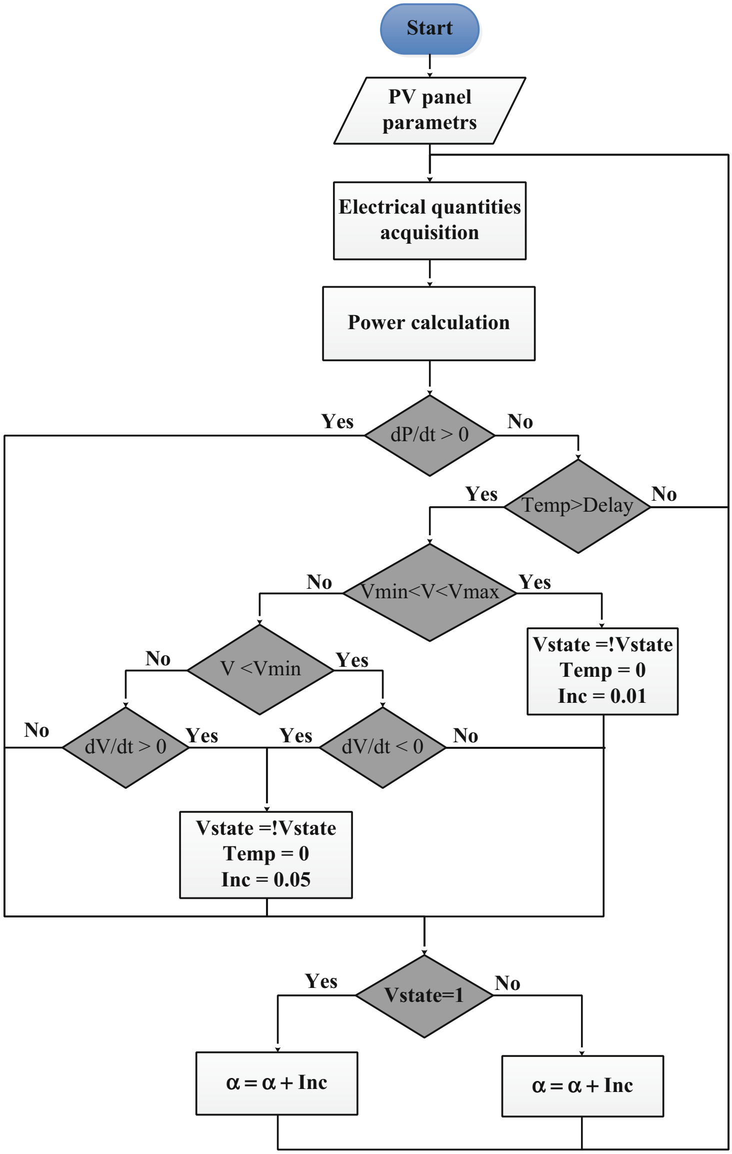

Fig. 3 Enhancement of the MPPT algorithm

- If ($V_{PV} < V_{min}$): We calculate the PV voltage derivative to determine the evolution of the PV system (The PV system evolves toward or away from the MPP):
  - If ($\Delta V < 0$) and if TMP $= 1$: The Vstate signal will be inverted and the timer will be reset to zero.
  - If ($\Delta V > 0$): no operation is performed.

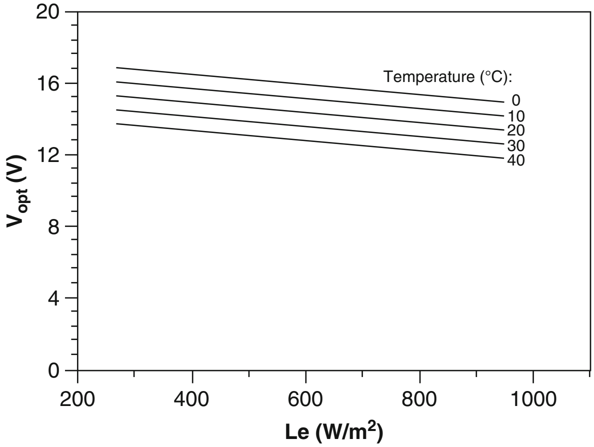

Fig. 4 Optimal voltage characteristics of SP75 PV panels according to illumination and temperature

- If ($V_{PV} > V_{max}$): We calculate the PV voltage derivative to determine the evolution of the PV system:
  - If ($\Delta V > 0$) and if TMP = 1: The Vstate signal will be inverted and the timer will be reset to zero.
  - If ($\Delta V < 0$): no operation is performed

At the end of the algorithm, we increase the duty cycle if Vstate = 1 or decrease the duty cycle if Vstate = 0, with the fixed step (Inc) determined by the algorithm.

Thus, unlike to the classic algorithms that take into account in their processes only of the power value (Algorithms Hill Climbing) or of the voltage value (Algorithms VCO), our algorithm takes several parameters into consideration (PV panels power, PV panels voltage, and the characteristics of the PV panels), which makes the PV system dynamically stable and faster.

Solar Charge Controller

State of Charge Estimation

In order to accurately estimate the state of charge of the batteries throughout the functioning of the PV system and taking into account the faradic efficiency (Ausswamaykin and Plangklang 2014), we established the algorithm shown in Fig. 5c using the following methods (Hirech et al. 2013, 2015):

- The first method is based on the calculation of the initial state of charge SoCi from the open-circuit voltage VOC (Patangia et al. 2010). This requires that the battery be at rest for a long time to stabilize the battery voltage V_{BAT}.
- The second method is that of Coulomb counting (Ausswamaykin and Plangklang 2014) to calculate the quantity of energy injected or subtracted from the batteries. This method is based on the integration of the charge current (Ibat) and the discharge current (Idech), taking into account the faradic efficiency η.

Regulator Operation

To optimize the charge controller of the battery, we used the technical characteristics of the battery, and we proposed a method based on the control of the energy supplied by the PV panels by hashing the current using power switches. The charge of the battery is processed through three phases (Hirech et al. 2013; Hirech et al. 2015), and the surplus of the energy produced is injected into another DC load (Fig. 5).

The algorithm used to charge the battery, which takes into account its characteristics, follows the steps mentioned below (Fig. 5a):

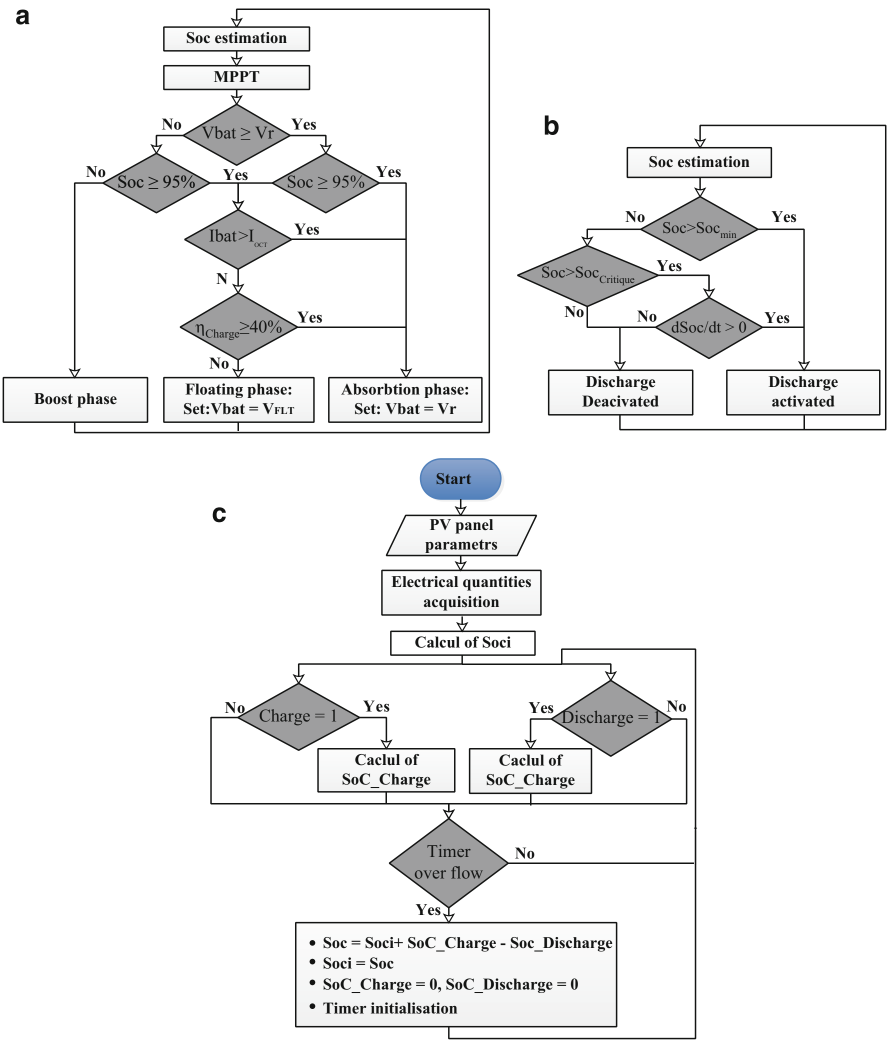

Fig. 5 Control algorithms to charge and discharge the battery. (**a**) Battery charge control algorithm. (**b**) Battery discharge control algorithm. (**c**) Algorithm for estimating the state of charge of the battery

- Boost phase: During this phase the battery is charged with full energy supplied by the PV panels until the battery voltage (Vbat) reaches the regulation voltage V_R (regulation voltage).
- Absorption phase: The algorithm regulates V_{BAT} around V_R, when the charge current I_{BAT} gradually decreases until reaching I_{OCT}, and consequently the energy absorbed by the battery decreases progressively. At this point, the battery is fully charged, the charge efficiency is less than 40% and the SoC is estimated at 95%. The energy not absorbed by the battery is then transferred to another DC load.

On the other hand, the charge current can sometimes decrease due to a low lighting intensity. Therefore, to estimate the operation mode of the battery, we use the notion of the energy efficiency absorbed by the battery:

- If $I_{bat} \leq Ioct\ and\ \eta_{absorbed} > 40\%$: Then, much of the energy produced by the PV panel is absorbed by the battery. In this case, we can conclude that the end of charge is not yet triggered and therefore the absorption phase is maintained.
- If $I_{bat} \leq Ioct\ and\ \eta_{absorb\acute{e}} < 40\%$: In this case, the battery absorbs less energy, which means that the battery is charged. The battery charge can pass to floating phase.
- Floating phase: To compensate the self-discharge phenomena, the battery absorbs a minimum of energy to set V_{BAT} around V_{FLT} (floating voltage). During this phase, almost all the energy produced by the PV panels is transferred to a DC load.

The discharge control of the battery operates according to the algorithm proposed on Fig. 5b, in order to protect the battery against the deep discharge. This process is activated or deactivated according to the state of charge estimation (SoC):

- If the Soc reaches the critical value $Soc_{Critical}$ (40%), then the discharge process ends.
- If the Soc is greater than Soc_{min}, then the discharge process activates.
- If $Soc_{Critical} < Soc < Soc_{min}$: The activation/deactivation of the discharge process is established according to different scenarios.
  - If during the normal operation, the SoC did not reach $Soc_{Critical}$ yet, and $\frac{dSoc}{dt} < 0$, then the battery continues the discharge until $Soc \leq Soc_{Critical}$, to protect the battery from deep discharge.
  - When the discharge process is blocked, it will not be activated until the Soc is greater than Soc_{min} in order to ensure a minimum amount of energy to the user.

Management and Supervision Software

System Description

The management and supervision software that manages the energy flow and monitors the PV system in real time has different functionalities (Fig. 6):

- Real-time display of the electrical quantities of the PV system with graphical forms
- Real-time PV system animation presenting the system status information

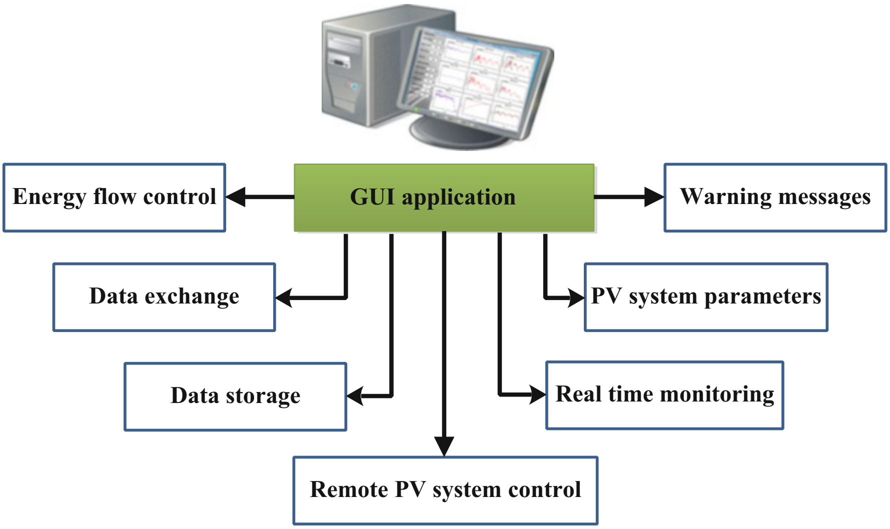

Fig. 6 Functioning diagram of the MSS

- PV system data recording by creating a complete database to study the reliability of the system
- Facilitate the implementation of the entire system by presenting a clear electrical diagram showing the different components of the sensors used
- Ability to set the PV system parameters used by the control algorithms (MPPT and regulator), in order to avoid reprogramming of the microcontroller in each change on the same
- Energy flow control via the power switches installed in the system
- Display of error messages if a problem is detected by the security and protection system on the PV system (short circuit, load disconnected, etc.)

Functioning Principle

The software is developed via Visual Studio C++ and MySql for database management, following the simplified algorithm shown in Fig. 7. The software provides real-time PV system management and monitoring, strong interaction between the windows from the software and between the microcontroller and the PV system.

The main window of the software presents the synoptic diagram of the PV system. It displays a dynamic diagram of the PV system in real time with the PV panel electrical quantities (Vpv, Ipv, Ppv) and the solar battery electrical quantities (Vbat, Ibat, Idech). We can visualize a real-time system efficiency and the duty cycle of signals controlling the power switches (MPPT, solar charge control). Besides, the software monitors the evolution of the PV system by displaying the state of charge of the batteries, as well as the energy efficiency of the whole system. Finally, it is possible to connect or disconnect PV power blocks (or isolate a block) on the case of

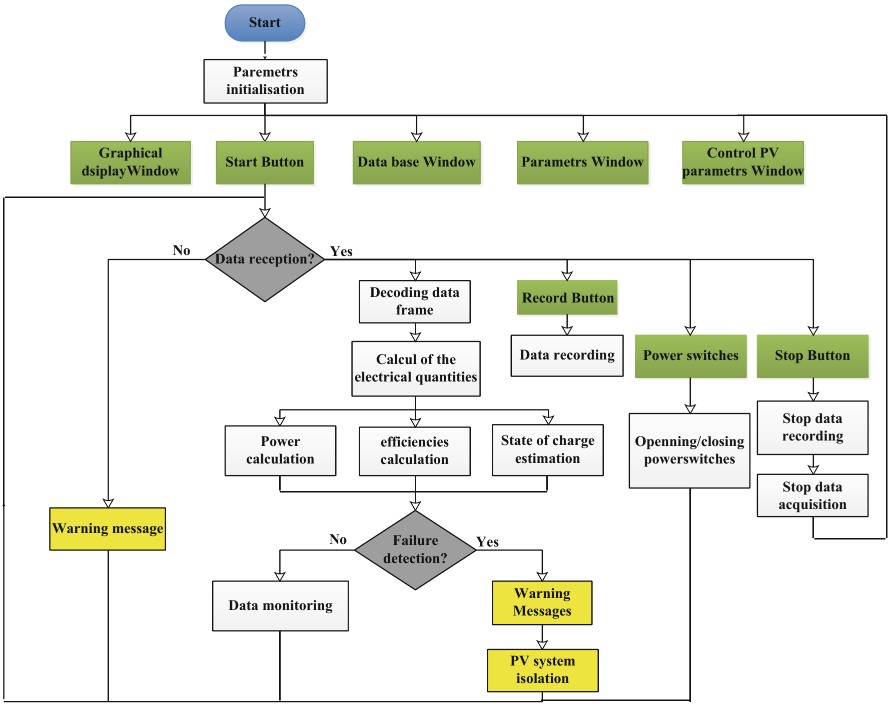

Fig. 7 Graphical user interface algorithm

a malfunction to secure PV equipment and to prevent the shutdown of the system, by controlling the control switches in the PV system.

Figure 8 shows the management and supervision software developed during this work, which includes:

- Main window (Fig. 8a): This module displays a real-time animation of PV system operation and the electrical quantities of each block (PV panels, batteries, etc.), including information about control signals (MPPT, solar charge control). This window indicates in real time the state of charge of the batteries, and it controls the energy flow or isolates the PV system by closing and opening control switches. Finally, this window displays error messages if the PV systems fails, to which the security and the protection system can act automatically accordingly to the fails nature. From this window, we can access other windows: Archive, Graphical Visualization, PV System Parameters, etc. This window has three important buttons to start or to stop the application and to save data into local or distant database:
  - *Start button*: starts the acquisition of the electrical quantities and the real-time animation of the PV system.
  - *Record button*: allows storing the data in a local or distant database every 5, 10, or 20 mn. This database is developed by Mysql and contains the date, time, and data related to PV systems.

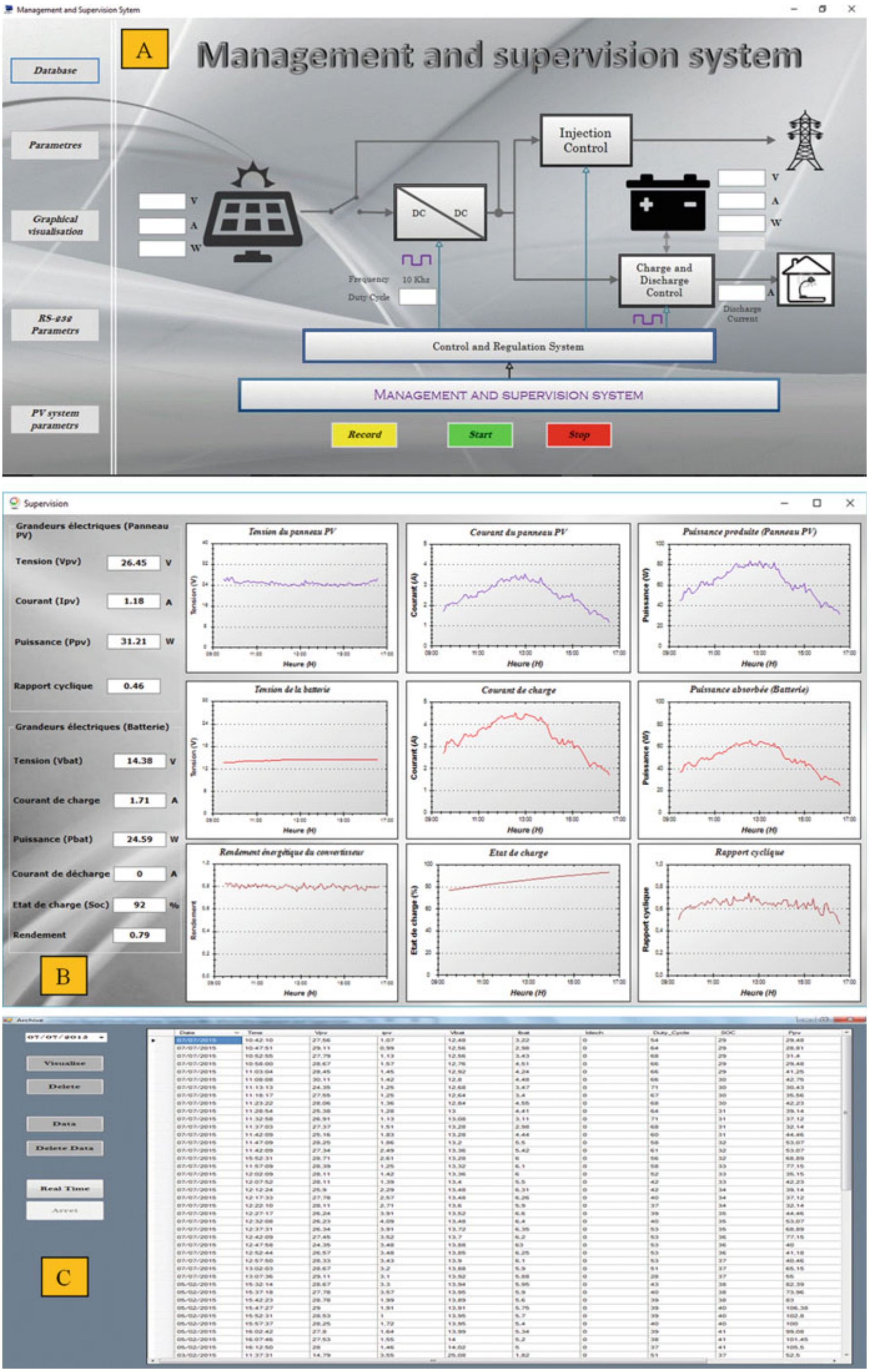

Fig. 8 (continued)

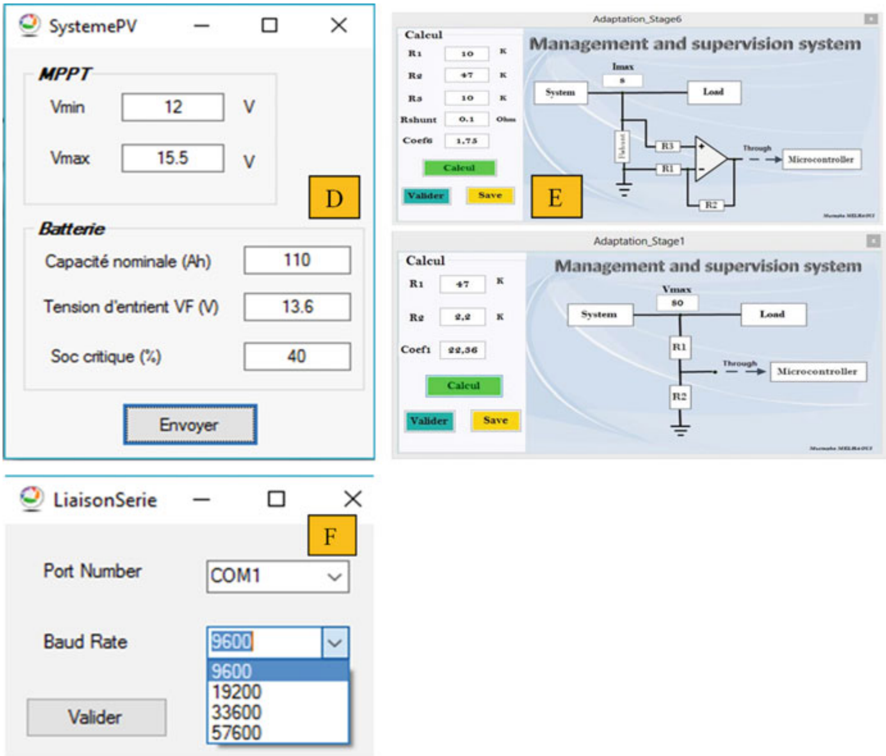

Fig. 8 Management and supervision software. (**a**) Main GUI window. (**b**) Supervision window. (**c**) The archive window. (**d**) PV system parameter window. (**e**) Parameters of the adaptation setting. (**f**) RS232 setting

  - *Stop button*: Stops the use of the application.
- Supervision window: This window presents graphically the real-time evolution of all electrical quantities of the PV system. Numeric values are displayed on the left, and the real-time plots of electrical quantities are displayed on the right: voltages, currents, power, energy efficiency, duty cycle, and the state of charge (Fig. 8b).
- Archives: Storage and data consultation of PV system operating are very important features in a PV system. Thanks to the data acquired, we can study the reliability of the system and the performance of the PV system designed to improve the energy efficiency of the PV system, which allows us to reduce the cost of maintenance considerably during a malfunction. A PV system that does not have this feature makes it less reliable and less robust. By selecting this menu from the main interface, a new window containing all the electrical quantities of the PV system stored in the SQL database will appear. On this new window, we will have access to all the electrical quantities stored in the database. We can

choose the data by day, month, or year (Fig. 8c). Finally, the stored data can be imported into a text or Excel file as required by the user.

- Control PV parameters window: This window set the parameters required for control algorithms implemented in the microcontroller and which ensures optimal system operation. Among these parameters, we have the optimal voltage range that the MPPT algorithm uses during its functioning, and which is unique for each type of PV panels. We also have battery settings such as its charging capacity and operating voltage that are used by the battery charge process. This data is then sent to the microcontroller and allow us to avoid its reprogramming whenever the nature or the topology of the PV panels or batteries are changed (Fig. 8d);
- Parameters: We propose in this window the different elements of the adaptation stages to be implemented between the PV system and the acquisition board (Fig. 8e). This window facilitates the interaction between the application and the PV system. Indeed, the system designed is set by default to acquire voltages less than 100 V and currents less than 10 A. For a user who prefers to change its setting, he must therefore change the adaptation settings between the PV system and the microcontroller. We have therefore proposed a tool allowing users to define their adaptation settings by calculating and proposing the values of the optimum resistances to be placed in the electrical circuit for the correct functioning of the system.
- RS232 setting: The microcontroller sends data to the computer with a user-defined transmission setting. This window allows to specify the parameters of the serial link used between the acquisition board and the computer to communicate with the microcontroller (Fig. 8f).

Remote Management and Monitoring System Control

Remote Control Using SMS

The key element of the remote supervision system via the SMS is the telecom module represented by a GSM modem. To be able to communicate with the GSM modem, we will need to use Hayes AT command (http://www.sparkfun.com/datasheets/Cellular%20Modules/AT_Commands_Reference_Guide_r0.pdf). In general, these two codes (AT + command) are used to synchronize the speed of the modem. The commands act on internal registers that can be directly manipulated.

In order to send and to receive an SMS message, the GSM modem must be properly configured. This task is performed automatically by our application, which sends a sequence of AT commands that must be successfully executed (Fig. 9).

Among these commands, we can cite:

- AT + CMGF = 1: Setting the message format in text mode.
- AT + CNMI = x,x,x,x,x: Set the notification type when receiving a new message. In our case, we chose the direct reception of the message on the

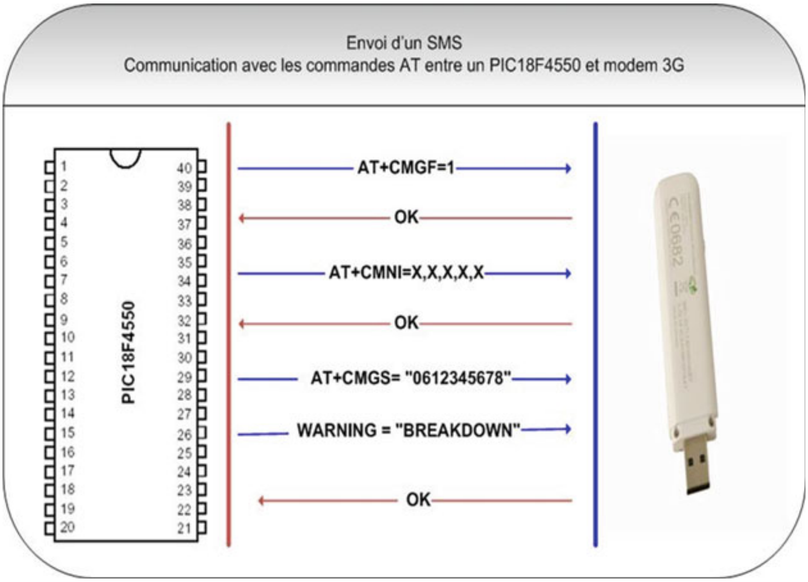

Fig. 9 SMS message sending via the AT commands

USB port. The choice of the reception mode is made by replacing the "X" with the appropriate digits.

- To send an SMS message, the appropriate command can be presented as follows:

AT + CMGS = ["Tel Number" + <CR > Message < CTRL + Z/ESC>].

For example, to send a warning message of a PV station failure, we can set the following instruction:

AT + CMGS = "+212,612,345,678" < CR>.

"ALERT: FAILURE OF PV STATION" < CTRL + Z/ESC>.

The main role of the modem is to receive instructions sent by the manager to switch on/off the station and to send fault identification messages (when a problem occurs on the PV station) or to send electrical quantities to the user manager. This method has enabled remote control of the PV station by any simple GSM phone.

Remote Control Using Internet

The purpose of this method is to connect the laboratory PC to the one installed at the PV station, to control the PV station, and on the other hand, to monitor remotely the whole installation. To achieve that goal, we set up an apache web server (https://projet-plume.org/files/apache_josy_plume.pdf) with fixed IP address (http://whatismyipaddress.com/dynamic-static). This server will be responsible for sending/receiving instructions and data as well as storing data in a MySQL database.

We also created web pages (Figs. 10 and 11) containing PHP forms (http://www.toutjavascript.com/savoir/savoir24.php3), in which we will insert data that will be

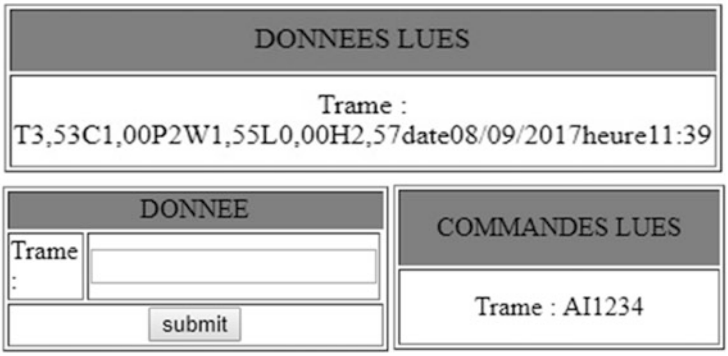

Fig. 10 Pages made to send and to receive data frame

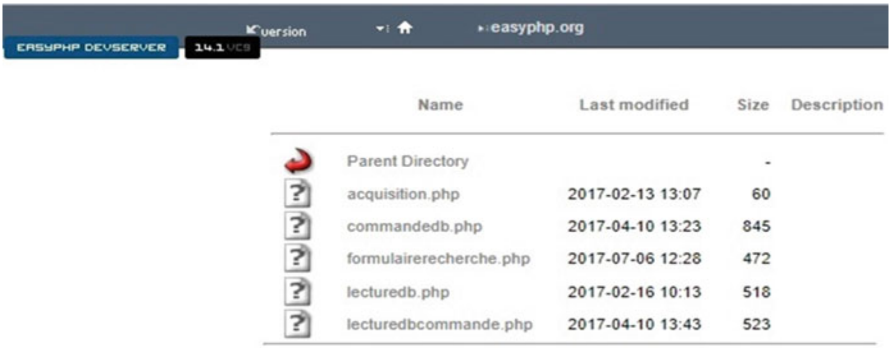

Fig. 11 Web pages made for data exchange

sent by the POST method (https://www.apprendre-php.com/tutoriels/tutoriel-12-traitement-des-formulaires-avec-get-et-post.html). The data is inserted automatically by filling the input field with the data from the PV station (electrical quantities) to be sent to the computer installed in the laboratory. The data sent is then stored in the server database. This storage will allow us, on the one hand, to share the information with the other interfaces connected to our server, and, on the other hand, to have a history of measurement to obtain the energy balance during the operation of the PV station in order to estimate its performance.

The web server, the MySQL database, as well as the database management program are all configured by easyPHP software (https://si405c.files.wordpress.com/2007/11/cours_esayphp.pdf).

In order to save data, we created two databases managed by the program PHPMyAdmin available also on easyPHP. The first will store instructions and the second will store electrical quantities (Fig. 12).

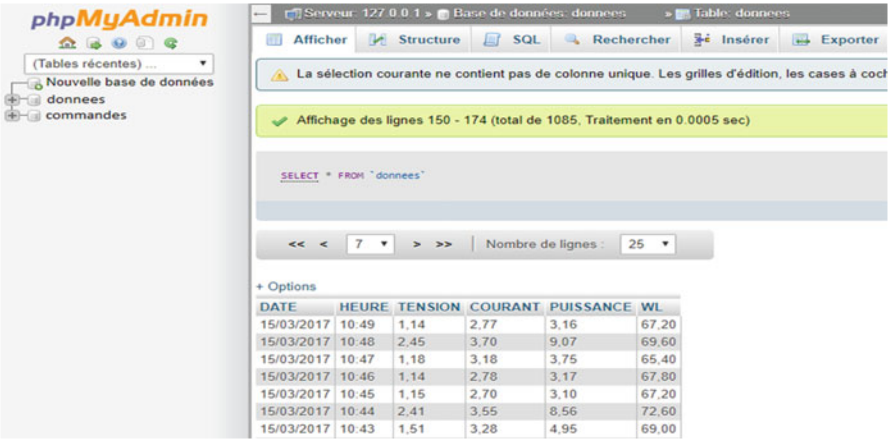

Fig. 12 Databases of electrical quantities of the PV system

Results and Discussions

Test Bench

The PV system, which is the subject of our study, and the fully automated test bench are displayed on Fig. 13. This system is composed by:

- Four monocrystalline PV panels, delivering under optimal conditions, energy power of 62 W, a voltage of 14.2 V, and a current of 4.4 A each (http://www.abcsolar.com/pdf/sp75.pdf)
- DC/DC Boost or Buck converter designed to operate at a frequency of 10 kHz with a maximum power of 200 W and a current of 12 A
- DC loads: A resistive load which support a current of 6.5 A, and solar batteries with 24 V nominal voltage and a capacity of 110 Ah
- Power switches to control energy flow and protect the PV system
- Acquisition and energy management system based on the use of a microcontroller and performs different algorithms:
  - MPPT control which determines the duty cycle and generates a PWM signal with a frequency of 10 kHz to control the power switch of DC/DC converter (Melhaoui et al. 2014)
  - Battery charge control to generate different signals controlling the power switches for enhance the functioning of the PV system (Hirech et al. 2013; Hirech et al. 2015)
  - Power switches control to manage energy flow in the PV system and to protect its equipment
- Management and supervision software: allows the control of the energy flow, real-time monitoring of the electrical quantities, and calculation of the energy efficiency

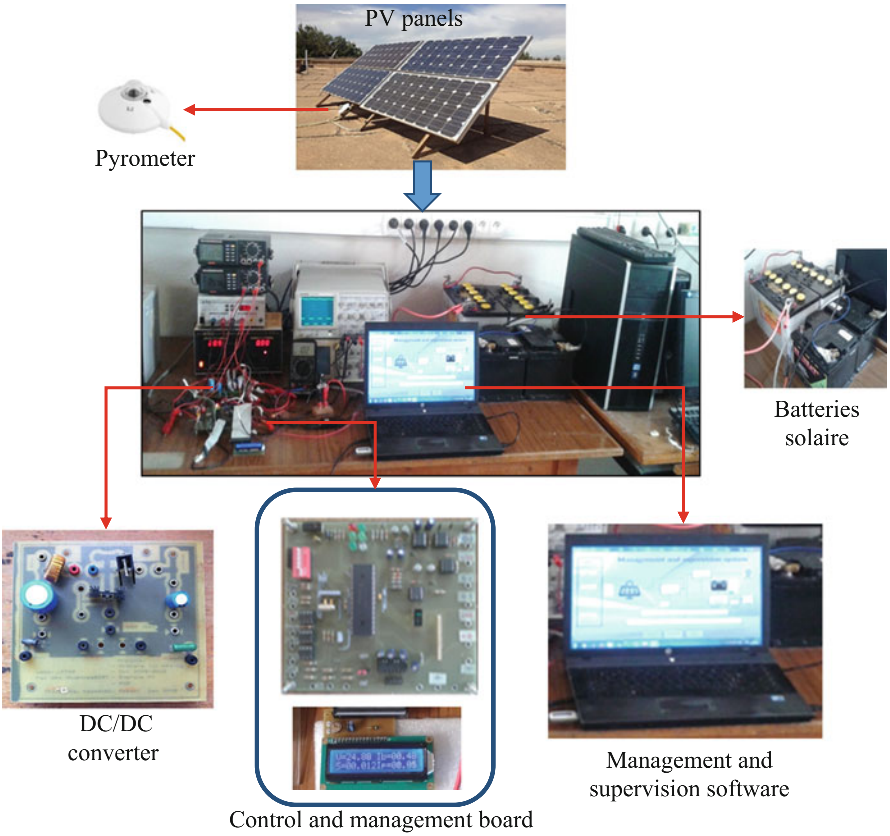

Fig. 13 PV system and bench of measurements used for the experimental procedures

and the estimation of the state of charge of the batteries. It also displays warning messages and indicates the failure or malfunction nature, and isolates the PV system during a failure of the functioning of the PV system. Finally, the software can store data in a database and export them into a text or Excel file (Melhaoui et al. 2015; Melhaoui et al. 2016)

- A weather station formed by a pyrometer CMP6 and a temperature sensor to measure illumination and temperature. The station is connected to a digital multimeter (KEITLY 2700), and transfer the data to a PC via an RS232 serial link or a USB link

MPPT Control Functioning

Search Time and Power Losses

To validate the operation of the MPPT control, we tested two PV systems using a different MPPT algorithm (Fig. 2) (Hill Climbing algorithm and the MPPT algorithm developed during this work) under the following conditions:

- First, we fix the functioning point of the panel in several positions of the power-voltage characteristic of the PV panel.
- On each functioning point, we noted the electrical quantities of the PV panel (voltage, current, and power), and then we measure the convergence time to the PPM and the corresponding optimal electrical quantities. From those measures, we deduced the power losses values supplied by the PV panel, based on the optimal results of Pspice simulator.

The obtained typical results are presented on Fig. 14. We can deduce that:

- The search time of the PPM strongly depends on the moving direction along the electrical characteristic of the PV panel (Fig. 14a). The search time from the initial functioning of the PV system to the PPM seems bigger when the initial PV system is close to the open circuit conditions than when it is close to the closed circuit conditions. These results are verified on both algorithms. In the case of the improved algorithm (Fig. 14a), when the functioning point is at 50% of PPM $\left(\frac{\Delta P_{PV}}{P_{Opt}} * 100 = 50\right)$, the search time is 150 ms (60 ms) when searching begins from the open circuit conditions (closed) to PPM. In the presence of the classical algorithm, the search time is in the order of 220 ms (125 ms).
- The search time ratio ($\frac{t_{\text{Improved}}}{t_{\text{Classique}}}$) of the classical and improved algorithms clearly depends on the illumination and the position of the functioning point of the PV panel. For strong illuminations (940 W/m2), the search times are virtually identical when the initial conditions are close to the PPM, that the initial voltage of the PV Panel is in the optimal range of panels (12 V–16 V). Outside this range, the improved algorithm is much faster and the search time can reach 50% compared to the search time using the classical algorithm. For low illumination, the improved

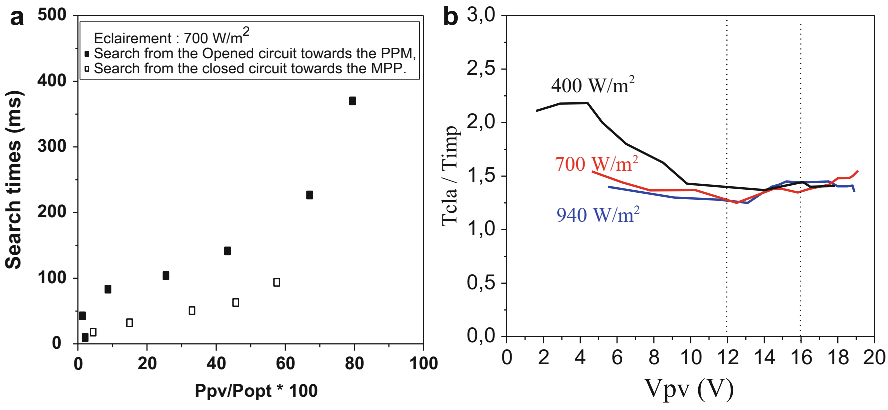

Fig. 14 Study of the use of the MPPT control. (**a**) MPP tracking time in the presence of the classic and the improved algorithm (Le = 700 W/m^2). (**b**) Relationship between the tracking times of the classic and improved algorithms in function of the initial PV panel voltage and illumination

algorithm is much faster compared to the classical. As shown on Fig. 14b, the search time ratio can achieve a factor of 2.5 (Tclassical/Timproved), which means that the improved algorithm can be 2.5 times faster than the classical one.
- The losses of the power supplied by the PV panel are significantly improved when we used the improved algorithm. This improvement is more marked when the MPPT control searches the PPM in the optimum voltage range. In the presence of the improved algorithm, the improvement can reach 4%.

The overall obtained results in this section show the best performance of the PV system in the presence of the improved algorithm: fast searching time of the MPP and power loss reduction supplied by the PV panels. The improvement is more marked for the low illuminations. In these low illuminations, the dynamism of the PV system is long (Mrabti et al. 2009); consequently, the search time for the PPM is also long. With the improved algorithm, the MPPT control is forced to search for the PPM in the optimal voltage range. This clearly shows the performance of the improved algorithm.

PV System Functioning during a Whole Day

For experimental validation of the PV system, we experimented and studied the functioning of the PV system with the MPPT control for a whole day. The PV system consists of a 50 Ω resistive load powered by a PV panel via a DC/DC Boost converter. The ambient temperature is around 29 °C in the morning and 32 °C in the afternoon. The sky in the morning was clear but from noon, we noticed the presence of clouds and therefore a great variation of the illumination (Fig. 15). Finally, as the meteorological conditions were unstable, we had the possibility to better study the reliability and the good functioning of the PV system whatever the meteorological conditions be.

During the operation of the PV system, we noted and presented on Fig. 15 the electrical quantities of the PV panel (voltage, current, and power) and the electrical quantities of the load (Vs, Is, and Ps). From these results, we obtained the energy efficiency of the panels (η_{PV}), the efficiency of DC/DC converter (η_{Con}), and the overall PV system efficiency (η_{Sys}). On the same plots, we also presented optimal results of all these quantities simulated under the same conditions via the Pspice simulator. The results obtained on Fig. 15 show:

- During the whole operation of the PV system, the illumination varies between 383 W/m^2 and 1000 W/m^2, and the temperature varies between 28 °C to 33 °C.
- A very good agreement between the experimental results and the optimal results is obtained via the Pspice simulation.
- The DC/DC converter efficiency is of the order of 86% throughout the whole operation of the PV system.
- Despite weather condition variations, the PV panel electrical quantities are always close to their optimal values. This shows the correct operation of the MPPT control, which forces the PV system to operate in optimal conditions without divergence at any weather conditions.

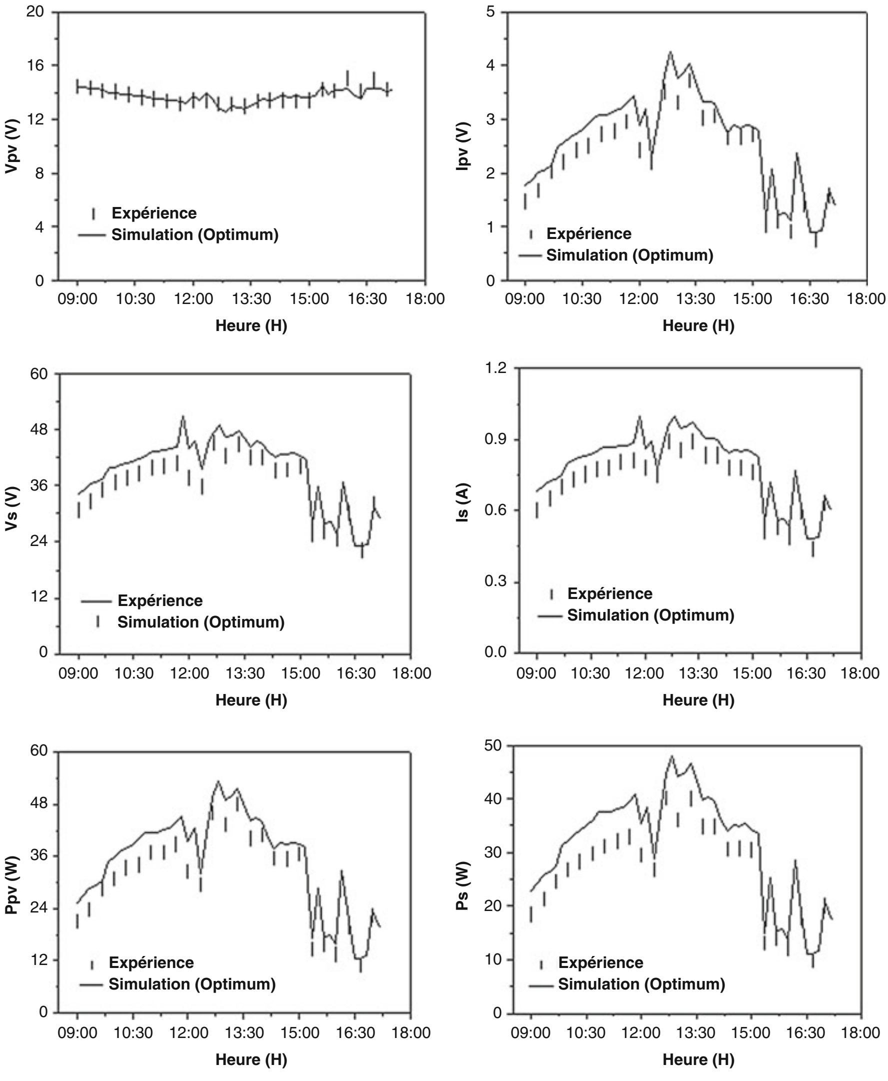

Fig. 15 Experimental and optimal electrical quantities of the PV system during full day operation

- The MPPT control efficiency is of the order of 98%. The power delivered by the PV panel is very close to the optimum power simulated by the Pspice simulator during the same conditions.
- The energy produced during this day is of the order of 200 Wh. From the optimal results obtained by the simulation, we estimated the energy losses by the photovoltaic module which are of the order of 10%.

The obtained results during a whole day show the good functioning of the PV system and in particular the operation of the MPPT control. Moreover, the good performance of the overall PV system shows that the system designed and analyzed during work can be used in PV installations.

Management and Supervision System Operation

MPPT Regulator Functioning

For the experimental validation of optimal control of charge and discharge of batteries, we experimented the PV system according to different operating modes to manage the transfer of energy between PV panels and batteries and between batteries and DC loads.

The PV installation is constituted of a PV panel (SP75 type), a lead acid battery (12 V, 110 Ah), and the MPPT regulator, which extracts the maximum PV power and controls the charge/discharge process of the batteries. A resistive load of 50 Ω is used for the discharge of the battery.

Figure 16 presents the experimental and the optimal results of the electrical quantities of the PV system. The charging current Ibat is approximately 4.5 A and the initial battery voltage is of the order of $V_{BAT} = 12.27$ V. During the operation of the system, equipped with the management and supervision system (MSS), we obtained:

- The initial state of charge is the order of SoCi = 57%. The Soci is estimated using the open circuit voltage of the battery at rest.
- During the charge cycle (0 to 3 h): The charge current is Ibat = 4.5 A and discharge current Idech = 0 A (Fig. 16a). We noticed during this cycle, an increase of battery voltage (V_{BAT}) and an increase of the state of charge from 57% to 67% (Fig. 16b).

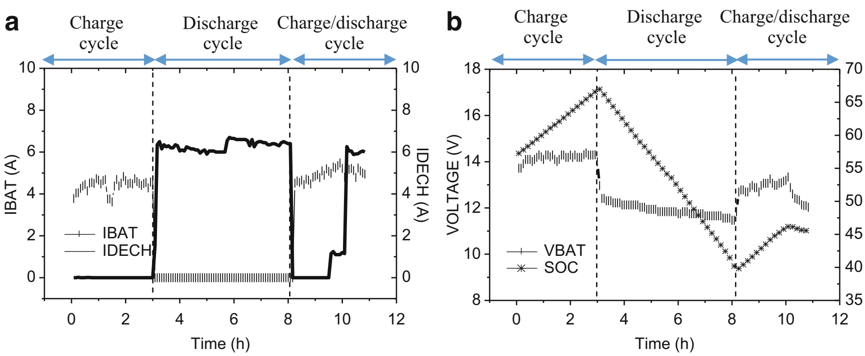

Fig. 16 The evolution of electrical quantities of the battery during charge/discharge cycles. (**a**) Variation of Ibat and Idech. (**b**) Variation of V_{BAT} and of SoC

- During the discharge cycle (3 to 8 h): The discharge current is of the order of Idech = 6.5 A and the charge current is Null Ibat = 0 A (Fig. 16b). We can notice from this cycle a decrease of V_{BAT} and of SoC (Fig. 16b). When Soc = $Soc_{Critical}$ = 40%, the system stops the discharge to protect the batteries (Idech = 0 A).
- During the charge/discharge cycle (8 to 11 h): As long as the SoC is lower than a Soc_{min} = 45%, the discharge is blocked (Fig. 16a). Above this threshold and depending on the energy demand, a discharge can take place. We notice that if the Idech < Ibat (9.5 h to 10 h) (Fig. 16a), V_{BAT} and of SoC increase slowly since the energy absorbed by the battery is bigger than the energy delivered to the load (Fig. 16b). When Idech > Ibat (10 h to 11 h), V_{BAT} and of SoC decrease, since energy delivered to the load is higher than the energy absorbed by the battery.

All the obtained results show the good control of energy transferred during charge cycle, discharge cycle, and charge/discharge cycle of batteries. This demonstrates the effectiveness of the regulation of the batteries, protecting them from deep discharge, and therefore increasing batteries life.

Optimal Operation of MSS

We experimented the PV system, equipped with the management and supervision system, during 8 days (10 h each day) to validate the overall functioning of the prototype developed during this work. The PV system consists of a PV panel (SP75 type), a DC/DC boost converter, two batteries in series, and a DC load.

We will study the influence of weather conditions and the different charge control (load/discharges) on the reliability of PV system.

We presented on Fig. 17 the experimental electrical quantities of the PV panels (voltage, current, and power) and the electrical quantities of the batteries during the operation of the system. In the same figures, we also presented the optimal electrical quantities simulated under the same conditions via the PSpice simulator. From these results, we have deduced the energy efficiency of the PV panel (η_{PV}), the DC/DC converter efficiency (η_{Con}), and the overall PV system efficiency (η_{Sys}) (Fig. 18). The obtained results show:

- The experimental electrical quantities of the PV panel are close to the optimal ones during the entire operation of the system (Fig. 17a, b, c). These results show the smooth operation of the MPPT control under the changes of the weather conditions during the whole system functioning.
- The DC/DC boost converter efficiency is of the order of 86%, and the overall installation efficiency is of the order of 9%. These quantities are stable throughout the whole operation of the PV system showing the reliability of the system (Fig. 18a).
- The correct functioning of the charge/discharge regulator of batteries ensures the good operation and a better management of the PV system within different scenarios:
  - During the charge cycle (0–38 h): The energy efficiency of the batteries is about 86% (Fig. 18b). During this cycle, all the energy produced by the panels is absorbed by the batteries.

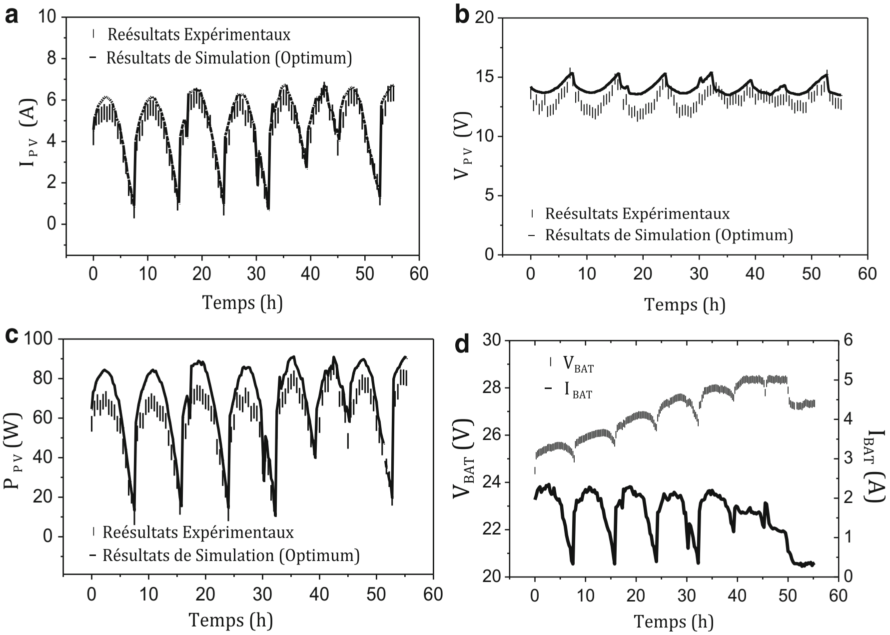

Fig. 17 Evolution of electrical quantities during optimal operation of the PV system. (**a**) Experimental and optimal results of Ipv. (**b**) Experimental and optimal results of Vpv. (**c**) Experimental and optimal results of Ppv. (**d**) Experimental results of Vbat and Ibat

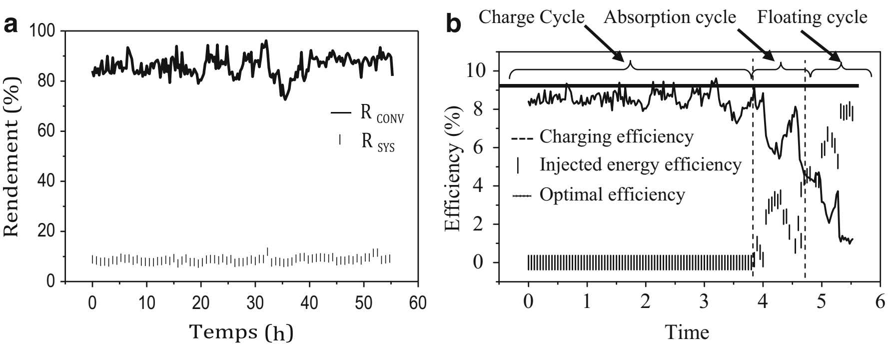

Fig. 18 Energy efficiencies of the PV system. (**a**) PV system efficiency and DC/DC converter efficiency. (**b**) Experimental and optimal energy efficiencies of batteries and the injected energy efficiency

– During the absorbtion cycle (38 h–48 h): the batteries absorb less energy, and the unabsorbed energy is injected to the DC load. This energy increases over time as the batteries approach full load, and therefore the energy absorbed by the battery decreases (Fig. 18b). The system regulates the battery voltage around $V_R = 28.4$ V (Fig. 17d).

  - During the floating cycle (48–55 h): The batteries are fully charged and absorb enough energy to maintain the charge of batteries. So most of the energy produced by the PV panels is injected to the DC load. In this cycle, the charging energy efficiency is low, and the injected energy efficiency is high.
- The good operation of the management and supervision software in terms of real-time monitoring of the entire PV system evolution without using measuring instruments (Voltmeter, multimeter, etc.):
  - The main window of the application shows a real time evolution PV system, as well as the electrical quantities essential to study the performance of the system (Fig. 19a).
  - Figure 19b presents real time graphical plots of the different electrical quantities of the PV system during the entire system operating. The data is saved and viewed via the access into local or web database (Fig. 19c).
  - The comparison of the electrical quantities acquired by the MMS and those acquired by the measuring instruments shows the proper functioning of the application designed for this work.

In this work, we have shown that the design and feasibility of a PV system equipped the management and supervision system. This system contributes to the optimization of the operation and the control of the flow of energy using algorithms taking into account the characteristics of the equipment used (PV panels, batteries). The experimental results obtained during the whole PV system operating show remarkable performances: tracking speed and operation around the MPP, minimization of energy losses, and the smooth battery charge control.

Remote Control of the PV System

In this section, we present the operation results of the PV system managed by the MSS and remotely controlled via the SMS messages according to different scenarios (Fig. 20):

- First scenario:
  - Once the PV station is activated via an SMS message, the microcontroller starts the acquisition, communicates with the MSS, and performs the MPPT/regulator algorithm. On the other hand, our application begins the real-time acquisition of the electrical quantities. A confirmation message of the PV station activation is sent to the person in charge via the SMS message (Fig. 21a).
  - As the PV station activation, it also can be switched off via the interface of the PV station or remotely via the laboratory interface or a GSM telephone. Once the station is deactivated, a confirmation message of the PV system deactivation is sent to the manager (Fig. 21b).
- Second scenario: During the operation of the PV system, the user can consult at any moment the PV station evolution (Current, voltage, power, illumination, and temperature). This can be done by sending SMS message to our application the corresponding code of consulting the electrical quantities. Then, the software sends back an SMS containing the electrical quantities values to the user (Fig. 21c).

Fig. 19 Management and supervision software during the operation of the PV system. (**a**) Main software window. (**b**) Graphical plots of electrical quantities. (**c**) Database of electrical quantities

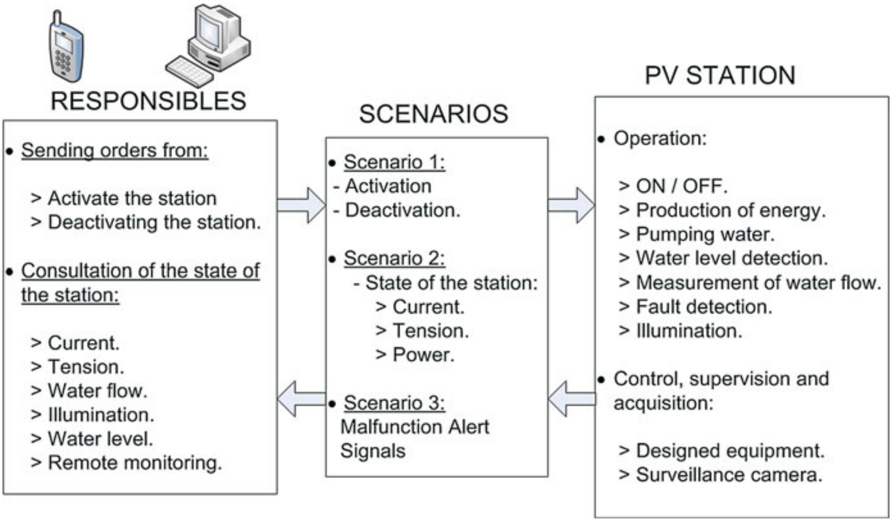

Fig. 20 Different scenario of remote monitoring of the PV system via SMS messages

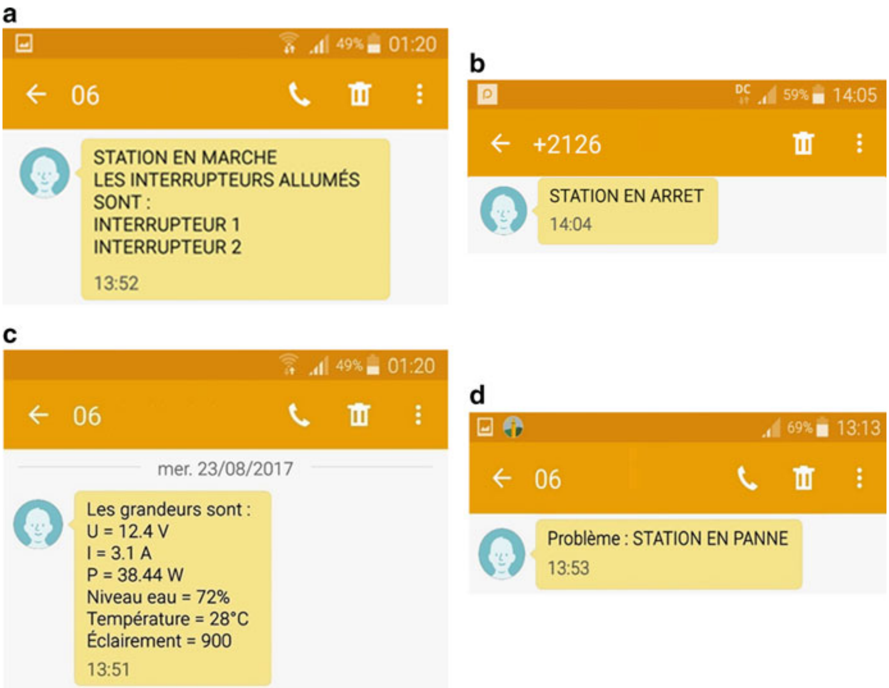

Fig. 21 SMS messages sent and received by the user. (**a**) Confirmation message to activate the PV station. (**b**) Confirmation message to stop the PV station. (**c**) Electrical quantities sent by the MSS. (**d**) Error message sent to the user

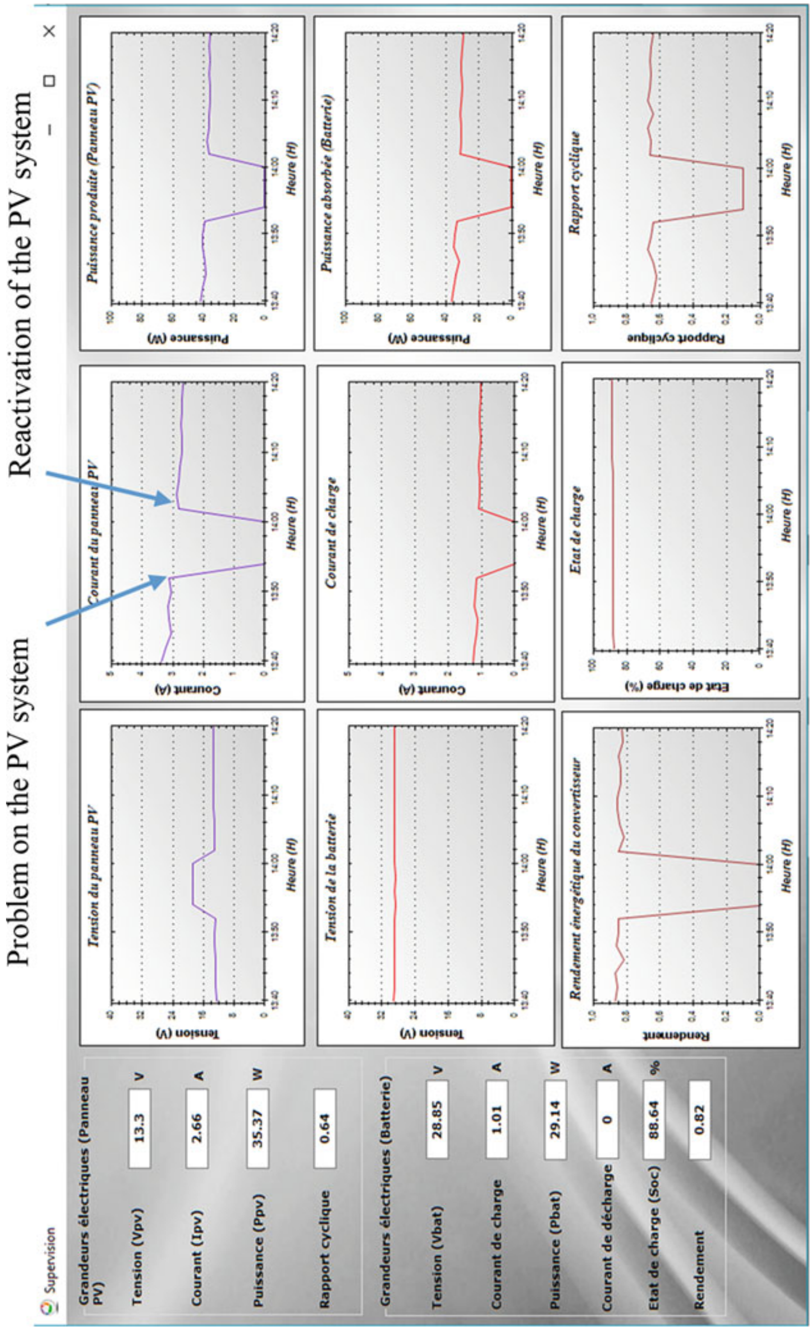

Fig. 22 The PV system operation monitored via the MSS

- Third scenario: If there is a problem at the PV station, an alert SMS message will be sent to the user (Fig. 21d), and the MMS will take an appropriate solution to the nature of problem occurred to maintain the PV production as possible, or otherwise it will isolate the PV system. Once the fault is set, the user will send an activation message, to reactivate the PV system (Fig. 22).

Conclusion

Our work in LETSER laboratory is carried out as part of the national and international projects on the field of modern autonomous photovoltaic systems. The main objective is to offer high-performance, reliable, optimized, and low-cost PV systems managed by the management and supervision application.

This work is mainly used to optimize the operation of the PV system, minimizing energy losses, and improving energy efficiency. The obtained results have clearly shown that:

- The use of the MPPT control, taking into account PV panel characteristics, has improved the operation of the PV system. The obtained results show that the experimental electrical quantities are close to the optimum results during the whole PV system operation with an MPPT efficiency of the order of 97%. We demonstrated that the PV system, throughout its operation, is more often stable with a tracking system significantly reduced compared to conventional algorithms.
- The use of the MPPT regulator, taking into account the characteristics of PV panels and batteries, improves the process of the battery charge. Using the voltage, current, and the state of charge of the batteries allows the system to charge and discharge the batteries intelligently, thus avoiding the deep discharge of the batteries and consequently to increase their lifetimes.
- The management and supervision system is important for real-time monitoring of the evolution of the PV system. More flexible and simple to use, this software offers a graphical animation of the state of the system, a control of the energy flow via the activation or deactivation of the power switches from the GUI interface.
- The combination of the two methods for remote PV system control allows us to fully exploit the PV station and make the global system more flexible and controllable from any station. In addition, we aim to create an android application for PV systems using the Internet to make control and supervision simpler and more convenient.

Cross-References

► Major Issues on Beneficial Utilization of Solar Energy in India
► Modeling the Feasibility of Employing Solar Energy for Water Distillation

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