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THE DEVELOPMENT OF AN ADVANCED IT SYSTEM DEDICATED TO A PHOTOVOLTAIC PUMPING STATION

[1]L. ELMAHNI, [2]L. BOUHOUCH, [3]A. MOUDDEN
[1,3]LMTI, Department of Physics, Université Ibn Zohr, Agadir, Morocco.
[2]ERTAIER, School of Technology of Agadir (ESTA), Université Ibn Zohr, Agadir, Morocco.
E-mail: [1]elmahni.lah@gmail.com, [2]bouhouch.esta@yahoo.fr, [3]a.moudden@uiz.ac.ma

ABSTRACT

Smart Meters (SM) are one of the first bricks in the case of Smart Grids. Indeed, the control of flows in real time contributes to the efficient management of energy and enables consumers to identify their energy-intensive appliances and, subsequently, to change their consumption practices. However, the large-scaled deployment of intelligent measurement systems will require huge investments, which will directly affect the final consumer. This paper presents the design, implementation and realization of an intelligent electricity meter. This counter is based on low cost, open hardware and software structures. It is intended to monitor, manage and control a photovoltaic water pumping station. The intelligence faculty is, indeed, due to the fact that this meter is communicating thanks to the use of new information and communication technologies (ICT).

Keywords: *Smart Meter, PanStamp, Raspberry Pi, Energy Measurement Processor, Photovoltaic*

NOMENCLATURE

Dp	Flow meter
EMP	Energy Measurement Processor
GPIO	General-Purpose Input-Output
GPS	Global Positioning System
MPPT	Maximum Power Point Tracking
L1	Low level tank
L2	High level of reservoir
Lp	Level of the well
ICT	Information and communications technology
IDE	Integrated Development Environment
IEA	International Energy Agency
IT	Information Technology
PV	Photovoltaic
PVG	Photovoltaic generator
SG	Smart Grid
SM	Smart meter
SWAP	Simple Wireless Abstract Protocol
RF	Radio Frequency
RPi	Board card Raspberry Pi
PSt	Board card PanStamp

1. INTRODUCTION

According to the International Energy Agency (IEA), the growth of energy consumption from 1990 to 2012 is 43%. The energy sector is changing in such a way that, in the future, researchers will have to find answers to such challenges as the reduction of the greenhouse gases emissions [1], the increase in the proportion of renewable energy sources and electric vehicles, the improvement of energy efficiency, the quality of the services and the safety of the electrical production systems [2].

In this context, active management is the fastest, most, the most economical and the most efficient to reduce energy costs and CO_2 emissions while supporting the growth of demand and industrial production. This would be possible by (i) installing low-energy equipment; and (ii) introducing tools that have a high level of control, real-time supervision, and a very large capacity for information technology and communication (ICT). This can be achieved through an advanced metering infrastructure, capable of providing billing on an hourly basis, allowing consumers to choose the best price from different electricity producers, but also to play on consumption hours [3], allowing data exchanges between the various stakeholders, in real time, with perfect precision and with absolute respect for consumer privacy [4]. The development of these smart meters (SM) is one of the most important aspects of current research in the field of energy and this is the cornerstone of Smart Grids [5].

Some authors [6], claim that SMs which communicate bi-directionally, corresponding to advanced energy meters, can measure a user's energy consumption and provide relevant

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information to electricity companies. While other authors [7], list the main functions of SMs, their communication technologies, and the classification of the latest products in the market. Also, some authors [8], present the role of SM in the architecture and in the functional modules of energy management systems for intelligent home (HEMS). Furthermore, the paper authors [9], propose the design and implementation of an intelligent power meter, based on ZigBee. But this meter is a little more expensive than the solution we developed.

Our work revolves around a contribution to this theme with the design of a smart meter based on the following electronic modules: The Raspberry Pi (RPi) development board [10], the PanStamp module (PSt) [11] and the 78M6610+LMU circuit [12]. This measurement system that we have developed, has the advantage of being the cheapest on the market while ensuring the communication of various measured data to the Manager of the installation, all through a developed Web application residing in the RPi, in order to ensure the reception and presentation of the results in graphic form.

After this introduction, this paper is organized as follows: a description of our project presented in section 2. Then section 3 exposes the measurement bench used with introducing the principle of operation of different blocks forming the project under test. In section 4, we treat the software part of this project. Section 5 describes some theoretical elements associated with a few components of this project. Finally, discussion of obtained results, conclusion and the perspectives are outlined in the last sections.

2. PROJECT DESCRIPTION

The overall project is described in Figure 1. Its constituents are identified in table 1.

Table 1 : Pumping station components

Designation	Reference
60 Solar Modules	REC235PE
Frequency Inverter	MITSUBISHI FR-E740-230SC-EC
Motor pump	Grundfos SP 30-9 - 13A01909

In this station, the inverter is a variable frequency "Inverter". Its role is to transform the direct current produced by the solar generator "PV" in a three-phase AC variable frequency f. This will vary the pump speed "PUMP". In this case, the ratio of the AC voltage to frequency (U/f) is constant. In the case of this station, the inverter used is programmed to operate in the frequency range between 20 Hz and 50 Hz.

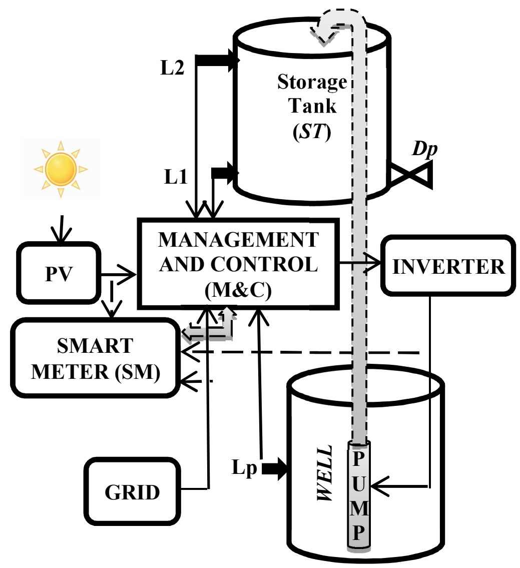

Figure 1: Description of the photovoltaic pumping station

The block of management and control "Management and control" (M&C) allows, if necessary, to supply this inverter directly by the public network (GRID) during the night or when the photovoltaic (PV) is very low.

The "Smart Meter" block (SM) is an electronic card to measure in real time the power produced or consumed and sends them to "M&C" block. Thanks to a web application whose functions will be enumerated below, the "M&C" block then ensures the supervision of the station various devices as well as the management of water and electricity consumption.

Components L1 and L2 are low level detectors and the top of the water in the "ST" tank, while the Lp component detects the low water level in the well "WELL". Dp is the general water meter to measure the amount of water supplied to the tank outlet. In addition to the global water smart meter Dp, each consumer has a water smart meter communicating with the block "M&C", thus forming an intelligent and communicating system with the aim of minimizing water leaks and achieving water savings and, therefore, energy ranging from 5 to 15%.

The choice of this station's equipment is based on economic and technical considerations such as the price of batteries and the cost of investment and maintenance. As a matter of fact, to reduce these costs, we would rather use water storage than electricity.

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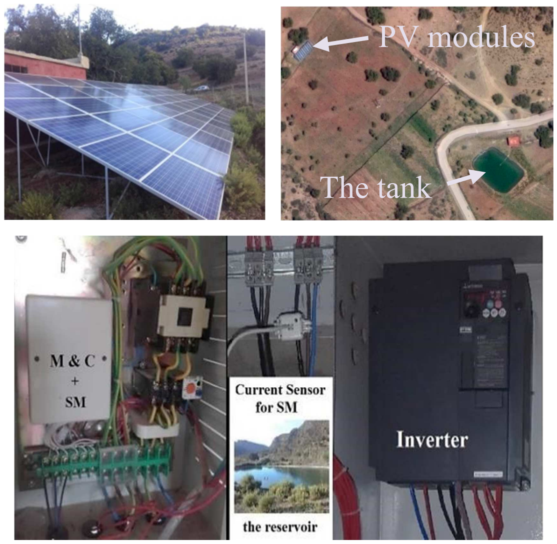

Figure 2: Project site

Our study focuses on the practical realization of a "SM" for the management and control of a pumping station of water for irrigation in the small village of Tazentout in the South of Morocco, where the GPS coordinates are 30.646884°, -9.376587° (Figure 2).

3. MEASUREMENT BENCH AND HARDWARE DESCRIPTION

3.1 Measurement Bench

During our investigations, we have made use of the measuring devices used to estimate the following parameters:

- The solar irradiation.
- The flow of pumped water.
- The AC voltage *U* and its frequency *f* to the output of the inverter.
- The current consumed by the pump.

Concerning the measurement of instantaneous irradiation Gd, it is carried through the SL200 Solarimeter KIMO (Figure 2) [13]. This is a monitoring tool and portable investigation, providing the values of the irradiance while memorizing them in W/m^2.

For the measurement of the flow of pumped water, it is realized, for more precision, with the help of two flow devices: Primeflo-T and Transport® PT878 (Figure 4). These portable devices integrate a DSP (Digital Signal Processing) for the measurement of water flow by exploiting a principle based on an ultrasonic technique.

Figure 3: Solarimeter KIMO SL200

To follow the evolution of the AC voltage U and its frequency f out of the inverter, we have used the Agilent Technologies 34970A Data Acquisition / Data Logger Switch Unit [14] (Fig. 5).

For measurement purposes, it is necessary to first lower the voltage u(t) to output the three-phase inverter, which is of the order of 400 V. For this, three single-phase transformers 52 V are wired according to Figure 6.

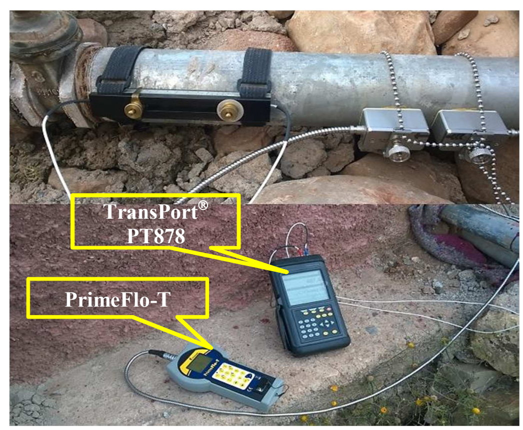

Figure 4: The flow meters PrimeFlo-T and TransPort® PT878

Regarding the measurement of the current i(t), it is done using a hall-effect sensor that will be described in the next section.

The average power consumed by the pump is given by the following relationship:

$$P = \frac{1}{T}\int u(t)i(t)dt \qquad (1)$$

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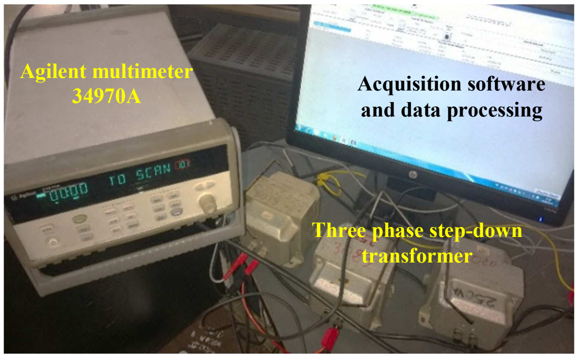

Figure 5: Agilent 34970A Data acquisition / Switch unit with its operating software and the three-phase step-down transformer

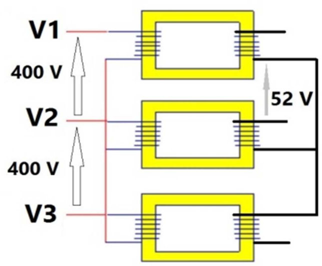

Figure 6: Wiring diagram of the three-phase step-down transformer with three single phase transformers

3.2 Hardware Description

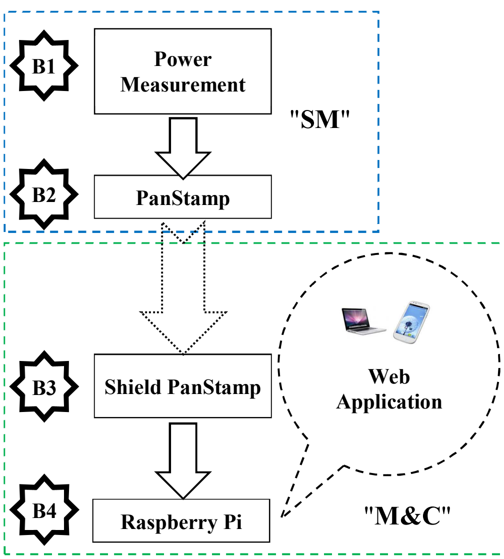

Figure 7: Project description

The operating principle of our project is described in Figure 7. The latter highlights the two blocks: "SM" and "M&C". The "SM" assures the measuring by the B1 block of the electrical power produced or consumed and transmits it by the B2 block. This emission is done via radio frequency (RF) via "PSt" block "M&C".

The heart of the B1 block is the processor for measuring energy (EMP) type MAXIM 78M6610+LMU. The B2 block receives the value measured through its serial port and sends it to the B3 block via RF.

The B4 block "RPi" is responsible for various treatments, such as viewing and recording in a database, while ensuring control of the circuit breakers. This last block, B4, offers us a nice solution, allowing the access to numerous data via the web. This block "RPi" is, in fact, a mono Nano-computer card; revolving around the ARM processor, it runs the free operating system Raspbian based on the Debian GNU/Linux distribution optimized for the "RPi".

Figure 8 shows the block diagram describing the circuit for measuring the electric current I into play in our resort. The EMP is driven by a 20 MHz quartz and includes an ADC (Analog to Digital Converter) with a resolution of 24 bits. This ADC is multiplexed on 4 channels. The intelligent part of the ADC is a microcontroller providing the measuring current instantaneous values I. This component also includes type serial links SPI, I²C or UART allowing a communication with the PSt.

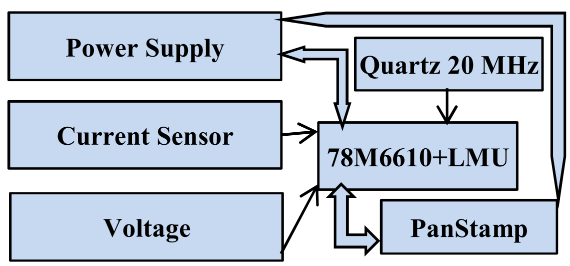

Figure 8: The power measurement block diagram

The used PSt is a module (Shield) of type NRG 2.0 compatible with the Arduino IDE 1.6.x development tool. It uses the Open Source technology and communicates in the free frequency band (868-915 MHz) using the SWAP (Shared Wireless Access Protocol) Protocol. The latter is an Open Source Protocol created to maximize benefits of the Panstamps hardware. The PSt is presented, as shown in Figure 9, in the form of a box type DIP 24 containing the MSP430 microcontroller and an RF interface of type CC1101 capable of providing a communication on a range up to 100 m in open spaces. The PSt is able to exchange information with its environment via external sensors or control loads through input/output cards. This PSt module

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allows to release the card processor RPi radio aspects and communications at low level.

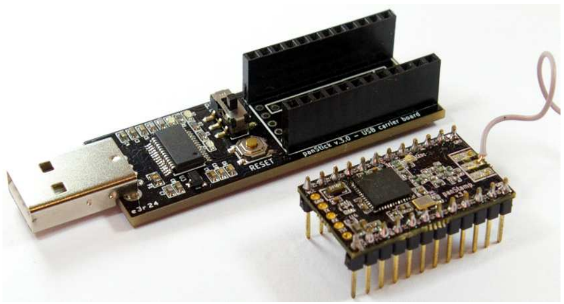

Figure 9: Module PanStamp at the bottom with its programming adapter

The powers brought into play in the pumping system are, therefore, deducted from the values of I and U, thus leading to the evaluation of energy consumption.

At the installed application in the RPi, it offers various services to users; namely the configuration and monitoring of the smart meter. It also provides archiving of measurements in a database and display of power variation graphs consumed in real time daily, weekly, monthly and yearly. Furthermore, it allows calculating the cost as well as periods and usage times of the pump in the day. Moreover, one can not only access the application but also receive configurable notifications by Smartphone, Android or IPhone.

4. PROJECT SOFTWARE DESCRIPTION

The software side of the project is divided into two parts; one to programming PanStamp modules and the other is dedicated to web application development, under the Raspbian operating system running in the RPi card.

4.1 Programming of the Modules PanStamp

PSt modules programming consists of developing a code to read the powers issued and transmitted by the EMP from MAXIM.

This programming can be carried out according to three different methods; Serial bi-Wire, flash with SWAP firmware loader or via the port series using a USB/UART converter. The latter technique is the one we have advocated in our project. It involves placing a PSt in a visible programming at the top of Figure 9 (PanStick) adapter. This adapter provides USB/UART conversion. Then, it loads a program into the memory of the PSt from the Arduino programming environment.

4.2 Development of a Web Application

The development of the web application under the Raspbian operating system running in the Nano-computer RPi, requires the use of some development tools, such as the CherryPy (Framework minimalist web), Python and service line as ThingSpeak. This allows visualizing measurement data [15].

The web application developed accordingly provides opportunities for device control and real-time monitoring of water consumption and electricity as well as the consultation of their historical, from a computer, iPhone or Android smartphone type. This application is implemented in the core of the RPi card that consumes less than 3 W, while offering the possibility of a direct control of devices through its inputs / outputs named GPIOs.

The functions performed by this application, we can mention:

- The choice of the optimal operation mode: According to climate data and energy prices, the station is to be supplied by the public network or the photovoltaic system.
- The management of water levels in the wells and the reservoir to ensure the pump control and protection and also avoid starts / repeated stops of the pump.
- Receiving notifications, like in cases where the maximum or minimum volume of the tank is reached, or when the water level in the wells tends to its minimum value.

5. THEORETICAL ELEMENTS

However, the sizing of photovoltaic pumping systems is not what this paper is about, the research work in this respect being very abundant in the literature [16]-[22]. Though, some expressions prove to be essential; expressions such as the one estimating the average water flow produced by the pump in m3/h. in addition to the one assessing the maximum electrical power in W, PM produced by the photovoltaic generator (PVG).

5.1 Calculating the Volume of the Pump Flow

The pump implementation in the PV pumping under test is of centrifugal type. This pump applies a couple of load CR proportional to the square of the speed of rotation of the motor, such as [23]:

$$C_R = K_{ch}\,\omega^2 = k\,f^2 \qquad (2)$$

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With:

K_{ch}, k ou k' : Proportionality constants.

ω et f: Motor rotation speed (rad/s) and frequency of the inverter output voltage (Hz).

Regarding the powers involved; as well as that consumed by the pump than that delivered by the PVG, they are defined by equation (3). The latter is approximately valid assuming that there are no losses in the engine and those of the power converter are neglected. [23].

$$P = K_{ch}\,\omega^3 = k'\,f^3 \tag{3}$$

According to the equations (4), knowing the performance of a centrifugal pump (Q Flow, Total head H and power consumed by the pump P) for the N rotation frequency, similarity laws to determine other performance (Q', H' and P') to another frequency N' [23]:

$$Q' = \frac{N'}{N}\,Q \;\; , \; H' = H\left(\frac{N'}{N}\right)^2 \; , \; P' = P\left(\frac{N'}{N}\right)^3 \tag{4}$$

In reality, due to mechanical and thermal losses, the P power consumed by the pump is related to the PM power issued by the PVG by the following relation [24]:

$$P = P_M\,\eta_{MP}\,\eta_{ond} \tag{5}$$

With:

η_{MP} : Performance of the pump unit (30 to 45%, depending on the type of pump and engine).

η_{ond} : Performance of the inverter (95%).

As a result, relations (5) will be slightly corrected.

5.2 Mathematical Models of Maximum Power Production

The literature offers several models for determining the maximum power provided by a PVG, depending on the variation of solar irradiation and the ambient temperature; we propose to treat two models that best describes the behavior of the maximum power output of a PV module.

5.2.1. First approach

In the case of this first approach, PM power produced from PVG can be calculated from the following equation [25]:

$$P_M = \eta_{PV}\,A\,N\,G_d \tag{6}$$

With the terms representing:

η_{PV} : Instantaneous efficiency of the generator in the operating conditions.

A : Active surface of the generator (m^2).

N : Number of PV modules.

G_d : Incident instantaneous global irradiation on the PV modules.

The PV array efficiency is represented by the following equation [25]:

$$\eta_{PV} = \eta_R\eta_{PT}[1 - \beta_T(T_C - T_R)] \tag{7}$$

Where parameters, depending on the type of PV module and some of which provided by manufacturers, are: η_R is the efficiency reference of PVG, η_{PT} is efficiency of tracker, which is equal 1 if a perfect maximum power point tracking system is used, β_T the coefficient of efficiency of temperature ranging from 0.004 to 0.006 (°C^{-1}) for Silicon PV cells, T_C (in °C) the temperature of the cell PV and T_R (= 25°C) the temperature of the PV cell reference.

The T_C temperature varies with illumination and the ambient temperature according to the linear relationship [21]:

$$T_C = T_a + G_d\left[\frac{NOCT-20}{800}\right] \tag{8}$$

Where:

T_a : Ambient temperature (°K).

$NOCT$: Nominal Operating Cell Temperature of a solar cell, given by the manufacturer [26].

After substitution of TC in the relationship (8), the instantaneous performance of the PVG can be expressed by:

$$\eta_{PV} = \eta_R\eta_{PT}\left[1 - \beta_T(T_a - T_R) - \beta_T G_d\left(\frac{NOCT-20}{800}\right)\right] \tag{9}$$

5.2.2 Second approach

In the case of this second approach, the model is based on the equivalent circuit known as "At one diode" (Figure 10). It was in 1978 that one of the first authors developed this model [27]. This model uses the specifications of photovoltaic modules supplied by the manufacturers, so it can offer a simple way to know the optimum power generated by photovoltaic modules [28].

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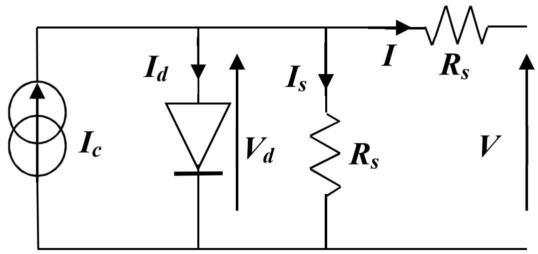

Figure 10: Equivalent to a single diode circuit [3]

The optimum power at the output of a PV module is determined by [28]:

$$P_M = V_M I_M \tag{10}$$

With:

$$I_M = I_{CC}\left[1 - \left[C_1 \exp\left(\frac{V_{MP}}{C_2 V_{OC}}\right) - 1\right]\right] + \Delta I \tag{11}$$

And:

$$V_M = V_{MP}\left[1 + 0.0539 \log\left(\frac{G_d}{G_0}\right)\right] + \beta_0 \Delta T - R_S \Delta I \tag{12}$$

With:

I_{CC} : Short-circuit current of the module (A).
V_{OC} : The module open circuit voltage (V).
V_{MP} : Maximum voltage of the module slot in the STC conditions (V).
β_0 : Voltage coefficient, depending on temperature (V/°C).
G_0 : Solar irradiation of reference (= 1000 W/m^2).
R_S : series resistance (Ω).

And where C_1, C_2, ΔI and ΔT are parameters calculated by relations 13, 14, 15, 16 and 17 [24]:

$$C_1 = \left(1 - \frac{I_{MP}}{I_{CC}}\right) \exp\left(-\frac{V_{MP}}{C_2 V_{OC}}\right) \tag{13}$$

$$C_2 = \left(\frac{V_{MP}}{V_{OC}} - 1\right)\left[Ln\left(1 - \frac{I_{MP}}{I_{CC}}\right)\right]^{-1} \tag{14}$$

$$\Delta I = \alpha_0 \left(\frac{G_d}{G_0}\right) \Delta T + \left(\frac{G_D}{G_0} - 1\right) I_{CC} \tag{15}$$

$$\Delta T = T_C - T_0 \tag{16}$$

Where:

I_{MP} : Maximum current in conditions STC (A).
α_0 : Coefficient of the current, dependent on the temperature (A/°C).
T_0 : Reference temperature (= 298°K).

According to the results of numerical simulations carried out by some authors [29, 30, 31], they claim that the values provided by the first model coincide strongly with experimentation, while with the second approach results are obtained with fewer errors when solar irradiance is greater than or equal to 900 W/m2 and above 27°C temperature.

6. RESULTS AND DISCUSSION

6.1 Experimental Measurements

Our main goal is to model the system under test using Matlab/Simulink software, and the theoretical tools considered above. But also, we compare simulation results with measurements on the ground using the communicating meter designed and validated by the measurements obtained using commercial tools, as it will be elaborated in this paragraph. Furthermore, we show the proper management of the pumping station under test through the different results described below. We will also present the benefits brought to the station manager by our advanced information and communication technology system.

Indeed, during a typical day of the spring season (May 27, 2016), resulting from a series of measures carried out by the Smart-Meter realized, Figures. 11 and 12 show an example of daily developments of flow Q (m3/h) water and electrical power P (in watts) consumed by the pump motor as well as variations in solar irradiance Gd (in W/m^2).

The curves of figure 11 show electrical and water productions, starting roughly around 7:30 and increases during the day to stabilize approximately from 10:30 to 15:00 to 25 m^3/h for flows, and around 9 kW for electrical power consumed by the pump. This stabilization is provided by one of the options of the inverter being implemented in the pump under test station. In fact, this option offers the possibility of limiting the output power of the inverter to a maximum desired value, for security purposes of the pump motor.

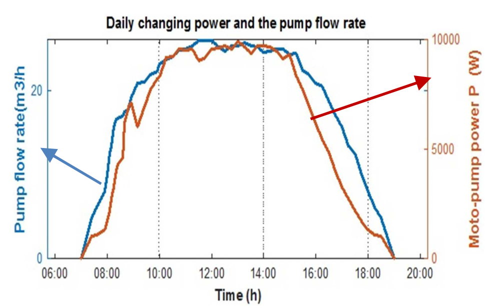

Figure 11: Evolution of Moto-pump power and the pump flow rate during May 27, 2016

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On the curve of figure 12 we see that, during the test day, measured irradiation increases with time and passes through a maximum of 1009 W/m2 around 13:02, and then it gradually decreases up to cancel approximately around 19:00. These very same values of solar irradiation have served for the theoretical calculation of optimum power delivered by the PVG using equation 6, and through equations 4, deduce flow solid theoretical Q values.

In addition, we can note from the results of figures 11 and 12 that, during a whole day, the power consumed by the pump and the pump have almost the same profile as that of solar irradiation.

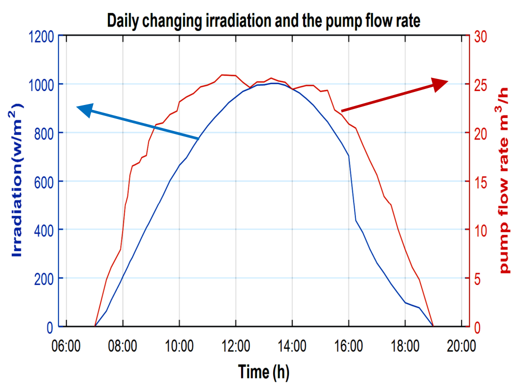

Figure: 12. Evolution of the volumetric flow rate of the pump, measured with PrimeFlo-T and instantaneous radiation during May 27, 2016

Figure 13 gives an example of a comparison of the theoretical volume flow (Eq. 4) and that observed experimentally, using commercial flow meter PrimeFlo-T [32], during the same day of May 27, 2016. We note an almost coincidence between these theoretical and measured flows.

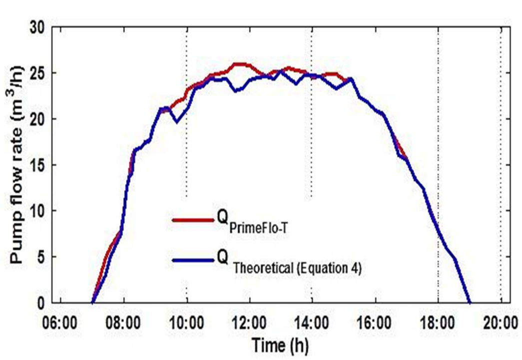

Figure 13: Comparison of measured and theoretical volumetric flow during 27/05/2016

We substitute PM (Eq. 6) and then we use the equation (5) to plot the curve of figure 14. This latter, shows an acceptable agreement between the models of the experimental power P and his estimated, by (Eq. 5) described by the first approach in paragraph 5.1. The limitation to the value Pmax = 9.5 kW of the inverter's power output is achieved through the option offered by the used inverter.

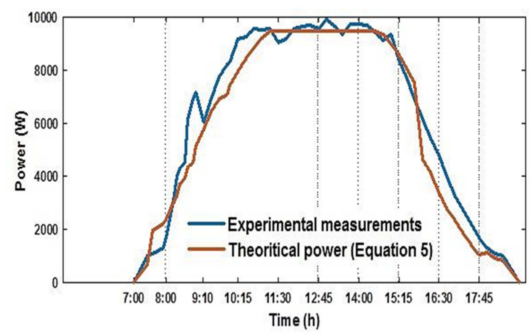

Figure 14: Comparison of the theoretical Moto-pump power P and measured powers during May 27, 2016

Concerning the variation P(f) approximate stated by equation 3, Figure 15 shows the curve fitting of the output power of the inverter according to its delivered voltage frequency. This adjustment is made using the CfTool tools of Matlab.

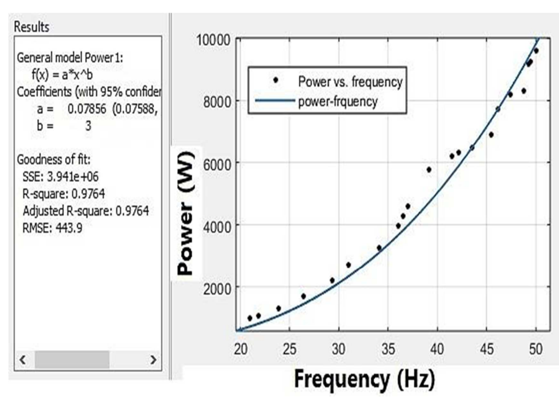

Figure 15: Relationship between power and frequency at the output of inverter

6.2 Communication of Information by Web

Figure 16 shows the interface of the web application with an example of visualization and monitoring in real-time of the power produced by the installation or consumed by a guest. Conversely, Figure 17 shows an example of a screenshot for a customer's management of power and water

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consumption, as well as various possibilities of visualization and treatment offered by this web application.

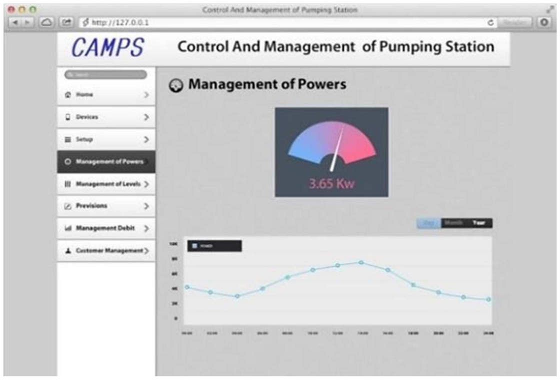

Figure 16: Web application screen in case of the powers management

Figure 17: Example of a guest consumptions and management screen capture

This web application is also accessible from any device, such as connected smartphone, by entering its URL in the address bar.

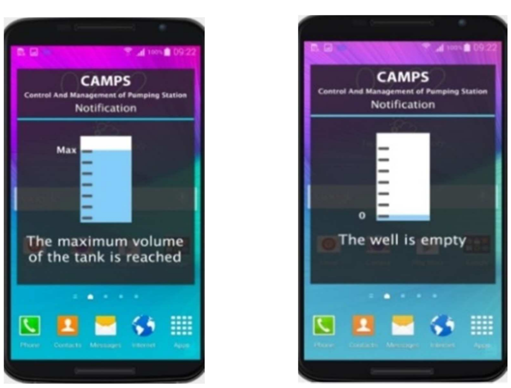

Figure 18: Example of notifications

Figure 18 illustrates the ability to receive notifications on a smartphone in particular cases of operation. For example, here the capture of left-hand side of this figure, a tank filling alert is sent to the engineer, and the right capture corresponds to another alert showing the exhaustion of the well's contents.

7. CONCLUSIONS AND PROSPECTS

In this paper, we have managed to put in place a coupling of the programmable stand-alone modules and open source. They are communicating and are characterized by low power consumption by using new information technologies and communication. Indeed, thanks to this association we have managed, in the case of a photovoltaic water pumping station, to design an electrical Smart-Meter, while interacting with the latter. This will, no doubt, have positive impact on the control and management of the PV pumping station, which allows, on the one hand, the important improvement of energy efficiency, ensuring, on the other hand, substantial savings and good management of supply and demand with regard to customers.

The present study is limited to the achievement of an electrical Smart-Meter. We intend, in future work, to proceed with the development of an intelligent water meter. The themes that will be the subject of our future research will be related to the deployment of a large-scale smart meter, which raises challenges, such as safety, security, privacy, and cyber-attacks. Indeed, several actors from various backgrounds and sizes (Oracle, Itron, Silver Spring Networks, Google, Cisco, ...) are positioned in the market of smart meters (SMs), to offer a set of hardware and software solutions in order to increase the reliability and security of the system, as well as the optimization of resources, namely; the automation of local stations, the effective deployment of the response to the demand, the distribution automation, the advanced energy management systems, the networking of "Smart Meters", etc.

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