Low-cost web-based Supervisory Control and Data Acquisition system for a microgrid testbed: A case study in design and implementation for academic and research applications

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ABSTRACT

This paper presents the design and implementation of a low-cost Supervisory Control and Data Acquisition system based on a Web interface to be applied to a Hybrid Renewable Energy System (HRES) microgrid. This development will provide a reliable and low-cost control and data acquisition systems for the Renewable Energy Laboratory at Universitat Politècnica de València (LabDER-UPV) in Spain, oriented to the research on microgrid stability and energy generation. The developed low-cost SCADA operates on a microgrid that incorporates a photovoltaic array, a wind turbine, a biomass gasification plant and a battery bank as an energy storage system. Sensors and power meters for electrical parameters, such as voltage, current, frequency, power factor, power generation, and energy consumption, were processed digitally and integrated into Arduino-based devices. A master device on a Raspberry-PI board was set up to send all this information to a local database (DB), and a MySQL Web-DB linked to a Web SCADA interface, programmed in HTML5. The communications protocols include TCP/IP, I2C, SPI, and Serial communication; Arduino-based slave devices communicate with the master Raspberry-PI using NRF24L01 wireless radio frequency transceivers. Finally, a comparison between a standard SCADA against the developed Web-based SCADA system is carried out. The results of the operative tests and the cost comparison of the own-designed developed Web-SCADA system prove its reliability and low-cost, on average an 86% cheaper than a standard brandmark solution, for controlling, monitoring and data logging information, as well as for local and remote operation system when applied to the HRES microgrid testbed.

1. Introduction

Electricity demand has steadily increased due to the growths of the population around the world. In parallel, conventional grids have evolved into intelligent grids, better known as Smart Grids, and the renewable energy sources participation in the electricity generation has increased, in many cases in the form of microgrid systems. This penetration of decentralised renewable sources in the grid, like microgrids, has produced the inclusion of Information Technologies for the last decade to provide management of energy, data and communications issues for those systems, but this massive inclusion has a lack of standardisation [1, 2]. Because microgrid systems are themselves, the integration of many renewable energy sources and energy storage systems, a microgrid can be designed following one of two main control topologies: centralised or decentralised. No matter which topology is selected, data flow and communications are essential for any decision-making controller [3, 4]. Conventional microgrid controllers are often based on Programmable Logic Controllers (PLC) [5], dedicated computers microgrid simulators [6] and microcontroller-based devices [7, 8]. Selection of a proper controller should be addressed accordingly to the microgrid application, financial budget and security issues. Due to the lack of standardisation on control topology and controller hardware technology, there are many communication protocols available and very different characteristics should be considered [9].

In this paper, the methodology for the development of a low-cost SCADA system for an experimental microgrid test-bed for academic and research proposes is presented, as well as the results of the operational tests and the required investment for the system implementation.

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Since SCADA systems are nowadays becoming an essential part of electric power systems, such as microgrids, it is essential to consider an accurate testbed development. Five main approaches for testbed developments, shown in Table 1, can be considered [10].

The low-cost SCADA system developed in this paper is intended to operate over a physical replication of a microgrid, so the fidelity and reliability conditions could be excellent, according to the evaluation of Table 1. Conventional SCADA systems for a microgrid are expensive due to the need for data loggers, controllers, sensors and other devices. Therefore their use is limited to industrial applications. Therefore, the development of a low-cost SCADA system development and integration methodology should improve the cost-effectiveness and repeatability associated with the deployment of SCADA systems in microgrid physical testbeds.

A microgrid management system should be aware of the current status of the system, including sensing, data collecting, and communications. Standard parameters to be measured in microgrids are environmental variables such as solar irradiance, temperature and wind speed. Also, electrical parameters such as frequency, apparent, active and reactive electric powers should be collected. Some SCADA systems are specialised in this type of monitoring [11, 12], and, by measuring such electrical parameters, they allow for a forecast of the microgrid operation and also for the microgrid health and ageing assessment, as presented in [13, 14]. Low-cost monitoring systems is a relevant topic, especially for academic and research applications where financial budgets are often limited. Therefore, efforts have been made for a cheaper solution to collect and display data from electricity, gas or environmental sensors in experimental microgrids [15, 16, 17, 18], given industrial solutions are often expensive and not suitable for small scale applications.

An additional improvement to these control and data systems is the possibility to be accessed from any place with internet access. In this case, every device should be connected to “the Cloud”. Therefore, electronic devices must send data via Internet by means of a communication protocol to keep them stored on a Web database that enables to display them on a Web page [19, 20], allowing microgrid interoperability [21]. Several papers mentioned the integration of the Raspberry Pi with Arduino [22, 23]. The development of a low-cost SCADA system for a stand-alone photovoltaic system is presented in [24], where the authors measured environmental variables and power generation from the photovoltaic system using an Arduino UNO development board. The cost of development reported is as low as $62. However, this system was limited only to monitoring a single renewable energy source and to wired communication [25]. presents a low-cost SCADA system for wireless remote control and monitoring for a single power inverter. The hardware used by the authors includes an Arduino development board, a Raspberry development board, an ESP12E wireless transceiver and a Wi-Fi shield for Arduino.

This paper presents the design and implementation of a low-cost SCADA system applied to an experimental microgrid. The system presented is more complicated than considered in [24] and [25] because it integrates wireless control and monitoring for several renewable energy sources and an energy storage system. The proposed system is an alternative for commercial SCADA and a solution for modular affordable monitoring and control systems for small to medium scale applications in renewable energy laboratories.

| Testbed approach     | Fidelity | Repeatability | Accuracy | Safety | Cost-effective | Reliability | Scalability |
|----------------------|----------|--------------|----------|--------|----------------|-------------|-------------|
| Physical replication | Excellent| Poor         | Moderate | Poor   | Poor           | Excellent   | Poor        |
| Simulated            | Low      | Moderate     | Poor     | Excellent| Excellent     | Poor        | High        |
| Virtual              | Moderate | High         | Moderate | Moderate| Moderate       | Moderate    | Moderate    |
| Virtual-Physical     | High     | High         | Excellent| Excellent| High          | High        | Moderate    |
| Hybrid               | High     | High         | Excellent| High   | High           | High        | Moderate    |

Fig. 1. Overall system architecture.
2. Design

The low-cost Web-based SCADA system was implemented in a microgrid at LabDER-UPV [26, 27] composed by a photovoltaic (PV) array, a small-power wind turbine, a biomass gasification plant, a battery-based energy storage system and a fuel backup generator. All the energy sources, as shown in Fig. 1, are connected to a hybrid inverter, which allows the microgrid to operate in both ways: stand-alone or grid-tied to feed a programmed load. Table 2 shows the main features of the microgrid.

The renewable and backup energy sources are connected to an AC bus managed by a Xantrex XW hybrid inverter, which communicates wirelessly to the Arduino-Raspberry Pi base station for data acquisition and control signal management. Remote control and monitoring of the microgrid is available through a Web host with a MySQL database. The Web hosting platform used is PLESK, which allows users to set up Websites and configure a Web server through a control panel with a simple, intuitive and easy-to-use interface. PLESK bases its programming language in PHP and MySQL, versions 7.1 and 5.5, respectively.

3. Methodology

The implemented low-cost experimental microgrid platform has a functional cloud-based own-developed SCADA system, as previously shown in Fig. 1.

3.1. Design of measurement and control devices

To collect weather data and measure the electrical parameters of the microgrid, detailed at Tables 3 and 4, an Arduino wireless power meter

| Table 2 |
| LabDER-UPV microgrid main features. |
| Description | Main features |
| Photovoltaic array | 2.1 kW, 12 solar panels. Connected to a Xantrex GT grid-tied inverter. |
| Wind power system | 3.5 kW @ 12 m/s wind speed. Installed on a 24-meter tower from ground level. |
| Biomass power plant | 10 kW @ 30 Nm3/h from syngas. 13 kg/h biomass consumption from wood chips and pellets. |
| Battery bank | 12 kWh power capacity, four batteries from 12 V @ 250 Ah. |
| Fuel backup generator | Petrol 9 kW, 230 VAC @ 50 Hz PRAMAC S12000. |
| Test-load bank | 10 kW, 240 VAC @ 50 Hz resistive load bank (30 x 330W resistors) |

| Table 3 |
| Meteorological parameters measured in the microgrid understudy. |
| Environmental measurements | Units | Sensor | Measuring range |
| Solar irradiance | W/m² | CEBEK C0121 Solar cell | 0–1100 W/m²; ±40W/m² |
| Environmental temperature | °C | DHT22 | -40 to 80 °C; ±0.5 °C |
| Wind speed | m/s | FGHGF Anemometer | 0–32.4 m/s; ±1 m/s |
| Relative environmental humidity | % | DHT22 | 0–100%; ±5% |

| Table 4 |
| Electrical parameters measured in the microgrid understudy. |
| Electrical measurements | Units | Sensor | Measuring range |
| Current | A | YHDC SCT-013-030 | 0–100 A; ±3% |
| Voltage | V | PCB Mount Transformer VB 2.3/2/12 | 200–260 V; ±1V |
(AWPM) is designed and built. Other related parameters were calculated from those measurements by using the energy-monitoring library also mentioned in Tables 3 and 4. The device manufacturer has recommended these libraries, but some of them have been modified to obtain more information from the measuring devices, according to the work goal to create a single complete system. An integrated Arduino-based base station broadcasted these data via wireless, using the radio frequency transceiver module NRF24L01 through the SPI (Serial Peripheral Interface) synchronous protocol. The whole system is displayed in Fig. 2.

Fig. 3 shows a flowchart of the process to store the measured variables by using the AWPM. Calibration of the current and voltage measurements is an essential issue for the AWPM implementation; this task is carried out by adjusting calibration coefficients included in the code. These coefficients are deduced by the calibration of the AWPM with a commercial Sentron PAC3200 Power Meter up to reach a precision of ±5% on average.

The AWPM designed, operates with a voltage transformer and an SCT-013 non-intrusive current transformer sensor. The transformer ratio is 12:1, reducing the grid voltage to a safe level that can be adjusted by a voltage divider to operate at the Arduino analog input voltage level (0–5 VDC). The analog input A2 is used to measure the voltage. The current transformer SCT-013 measures the instantaneous current, and the Arduino reads the value through the analog input A1. Fig. 4 shows the connection of the AWPM main components.

The phase difference between voltage and current phase displacement is determined by using a zero-crossing detection algorithm, programmed in the power calculations library used for the AWPM. This algorithm is based on the work of [28, 29], and [30] where the interaction between continuous-time functions and the discrete event is modelled. Active, apparent, reactive power and power factor are calculated employing Eqs. (3), (4), (5), and (6) respectively, taken from [31] for AC circuits analysis.

\[
V_{\text{RMS}} = \sqrt{\frac{1}{N} \sum_{n=0}^{N-1} V^2(n)} \tag{1}
\]

\[
I_{\text{RMS}} = \sqrt{\frac{1}{N} \sum_{n=0}^{N-1} I^2(n)} \tag{2}
\]

\[
P = \frac{1}{N} \sum_{n=0}^{N-1} V(n) \cdot I(n) \tag{3}
\]

Fig. 4. AWPM main components connection diagram.

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$S = V_{RMS} \cdot I_{RMS}$  

$Q = \sqrt{S^2 - P^2}$  

$\cos \phi = \frac{P}{S}$

$V_{RMS}$ is the voltage root mean square value (Eq. 1); $I_{RMS}$ is the current intensity root mean square value (Eq. 2); $P$ is the active power (Eq. 3); $S$ is apparent power (Eq. 4); $Q$ is reactive power (Eq. 5) and $\cos \phi$ is the power factor (Eq. 6). Based on Eqs. (3), (4), (5), and (6), Fig. 5 shows the code dedicated to calculating the active, reactive and apparent power and the power factor.

The Emonlib. h library for Arduino performs the rest of the calculations. This library has been modified to measure frequency additionally. Fig. 6 shows the flowchart for the calculation of the grid frequency. After reading the analog pin reference and using the voltage transformer connected to the Arduino board, the algorithm detects every time an AC signal crosses zero. Given the 10-bit resolution range of the analog to digital converter (ADC), if a value is between 512 and 520 (intermediate range of the $2^{10} = 1024$ possible values) means that the signal has crossed the zero reference of the AC voltage.

Fig. 7a shows the general scheme of the Arduino wireless power meter (AWPM), and Fig. 7b displays the Arduino board responsible for the meteorological data collector (AWMDC) that compiles wind speed, solar radiation, environmental temperature and humidity with a DHT22 sensor. Again, a base station receives the data and broadcasts them via wireless communication, using the NRF24L01 Radiofrequency transceiver module.

The operation of the microgrid requires connecting and disconnecting the different renewable sources according to the preprogrammed load and the amount of energy coming from those sources. The Arduino wireless switch controller (AWSC) accomplishes this task. Fig. 7c shows its overall structure that an Arduino Mega board, a radiofrequency transceiver module NRF24L01 and a Relay module. Its operation depends on commands sent by the Arduino-Raspberry Pi 3 wireless base station (ARWBS), shown in Fig. 7d.

ARWBS is based on the integration of an Arduino board and a Raspberry Pi, allowing the system to log data and store it into a local DB, as well as in a cloud DB. The communications of the Arduino and Raspberry Pi 3 use the I2C serial protocol. With this structure, the Arduino is acting as an interface between the Raspberry Pi and all the other Arduino-based data collectors. A SCADA system Website user interface has been developed to control and monitor the entire microgrid.
This interface is linked to the ARWBS by TCP/IP communications and hosted in PLESK Web using a MySQL DB.

3.2. Communications and data logging

An NRF24L01 Radiofrequency transceiver, operating at 2.4 GHz and using an SPI protocol to manage the communication with an Arduino board, carries out the wireless communications. AWPMs, AWMDC, and AWSC are wirelessly linked to the ARWBS by using radiofrequency, as shown in Fig. 8. The users interact with the microgrid Web SCADA interface by using HTML5, JavaScript and PHP programming languages, hosted on the PLESK Web server. Cloud DB reads and writes data, updating continuously at specific sample rates, for each variable following the data refresh and operation commands sent by the ARWBS to each microgrid device. Besides, a local DB records the information as a backup for preventing data losses due to wireless communication or internet connection failures.
3.3. Cloud DB and web SCADA

Users interact with the microgrid using a Web SCADA interface that operates over a MySQL cloud DB, writing and consulting data using an own-developed Graphical User Interface (GUI). PHP makes queries from Web SCADA GUI through the PLESK platform and, subsequently, modifies the MySQL cloud DB, updating data, according to user commands or the automated data refresh option. Fig. 9 shows the general data transmission process.

Once communication is established between Plesk web server and MySQL DB, the next step is to generate a table, adequately fetched, from AWPM in a real-time monitoring process with data on power, meteorological measurements and status of the microgrid components. The communication between the DB and the raspberry pi is carried out using a 3G modem using a SIM card, but it is also possible to use a wifi network. As time progresses, more data will be recorded, increasing the size of the table and, therefore, the space memory could reach the maximum storage permitted by a Plesk regular account (6 GB). Moreover, it will require more data if the sampling rate is very high, in the order of 1 s for all variables. Annual maintenance is programmed; it includes a back up of the stored data and memory clean up, avoiding to overcome the maximum storage permitted. Fig. 10 represents the information obtained from the grid-tied PV inverter. Such data are stored in the MySQL DB.

Data is collected every second and the Web SCADA fetch data from MySQL DB, written in SQL queries with PHP acting as a link of the remote web interface and DB server. The PHP query sentences aim to get access...
to voltage, current, power, and energy data located in their respective column of the table. Fig. 11 shows the flowchart for the code to read and update data register from the DB.

As previously mentioned, the user operates the microgrid through an own-developed Web SCADA interface that makes PHP queries to the PLESK server via port 443 and to the cloud DB using port 3306 through the ARWBS using TCP/IP. There are three different types of registered tables within the cloud DB: measured data, microgrid operation conditions and user credentials. The information displayed on the Web interface is timely refreshed according to the previous query requests, and, when the load or any energy sources is changed, the user or the preset programme sends a request to cloud DB utilising the Web SCADA. Such request is read by the ARWBS that sends the corresponding request to the AWSC to close or open the physical switches or relays.

All the devices connect to the remote PLESK server interact with the system employing an HTML5 graphical user interface that allows the user to set up operation parameters for the microgrid and monitoring and supervising data. Data available in the PLESK server can be exported in other formats, as shown in Fig. 12.

4. Results

Experiments were carried out in the Laboratory of Renewable Energies (LabDER) at Universitat Politècnica de València. Such experiments allowed to test the functionality and performance of the low-cost SCADA system, Fig. 1 displays the microgrid components, together with its energy, data and control signals flows. The figure also includes the storage of information in a remote database and the access to a remote monitoring and control graphical interface developed in HTML5 and JavaScript over an internet connection. Once all the components of the monitoring Arduino-based devices implementation, the software and the database development have been installed, a SCADA system was ready to be used in the microgrid. Fig. 13 shows some of the recorded data obtained in a microgrid experiment carried out in June 2018.

During the experiment, a load energy demand went from 800 W to a maximum of 3.97 kW, and it was covered with contributions from PV array, the utility grid and the battery bank. Details are presented in Fig. 13, where positive values correspond to the energy demanded by the system, and negative ones are those supplied by the energy sources. It should be noticed that the battery bank could work reversibly as a load or an energy source, as usual in energy storage systems in microgrid applications. PV power fluctuations are due to cloud appearance, as it was detected by the meteorological data gathered by the AWMDC, that also indicates that the maximum solar irradiance during this short test was 600 W/m² at 35 °C on the surface of solar panels (Fig. 14).

Medium and long-term tests in the microgrid using the SCADA system were also addressed. Fig. 15 shows the results for the medium term, one-day duration test. Power from the wind turbine and the PV array, accordingly to the current meteorological conditions during the day, and the power demanded from the microgrid are displayed. Power demand...
ranges on average from 0.3 to 3.3 kW, and it includes the use of lights, personal computers from researchers and the low-cost SCADA system-related devices.

The long-term test covers an entire week. Fig. 16 shows the obtained data for wind power, solar power, and users power demand. The reliability of the system is enough for obtaining the data required for analysing the system.

Table 5 shows the average standard deviation deduced from the difference between values obtained with the AWPM and a SIEMENS SENTRON PAC3200. For a set of 6,506 measurements, the AWPM

| Variable          | Average standard deviation (grid-tied test) | Average standard deviation (stand-alone test) |
|-------------------|--------------------------------------------|----------------------------------------------|
| Active power      | 2.720                                      | 2.268                                        |
| AC bus Voltage    | 1.734                                      | 1.121                                        |
| AC bus Intensity  | 0.068                                      | 0.107                                        |
| AC bus Frequency  | 0.058                                      | 0.079                                        |
measurement performance test was carried for two different cases: grid-tied and off-grid operation mode of the microgrid. The highest deviation occurs in the active power measurements. It is also noticeable how the microgrid has a better bus frequency performance than the standard SCADA systems, in the order of 85% cheaper when compared with standard SCADA systems, and has high versatility, allowing the addition of new functions and interfaces. Finally, this system could be considered for other types of applications. Future projects related to open-source software should focus on the integration of new technologies, such as IoT (Sensors, devices and appliances connected to the internet), blockchain (for doing data transactions securely) and big data (Analysis of large volume of data efficiently) in Arduino and Raspberry projects.

5. Conclusions

Experiments prove that the proposed low-cost SCADA could monitor an experimental microgrid successfully. Several tests were carried out to validate the system robustness, data collecting and device communication efficiency with a remote DB. As a result, it was obtained a successful validation of the system operability. Measuring instruments were calibrated, reducing the error between the developed AWPM and a commercial Sentron PAC 3200 power meter, and the deviations were acceptable (Table 5). The system can be supervised both via a local computer or via the Web SCADA interface linked to a remote database. The implementation of the developed system microgrid has a low cost, in the order of 85% cheaper when compared with standard SCADA systems, and it has high versatility, allowing for the addition of new functions and devices. Finally, this system could be considered for other types of applications.

Table 6

| Device | Qty | Cost  | Total cost |
|--------|-----|-------|------------|
| Arduino based wireless single-phase Power Meter. Contains 1 Arduino UNO, 1 ethernet shield, 1 NRF24L01 transmitter, 1 SCT-013 current transformer, 1 VB 2.3/2/12 voltage isolated transformer, and miscellaneous accessories. | 9 | 100 € | 900 € |
| Arduino - Raspberry PI base station. Contains 1 Arduino UNO, 1 NRF24L01 transmitter, 1 Raspberry PI and miscellaneous accessories. | 1 | 80 € | 80 € |
| Arduino based wireless meteorological module. Contains 1 Arduino UNO, 1 NRF24L01 transmitter, 1 DHT temperature and humidity sensor, 1 solar irradiance sensor, 1 anemometer analog input reading. | 1 | 50 € | 50 € |
| Arduino based wireless switching module. 1 Arduino UNO, 1 NRF24L01 transmitter, 1 8-channel relay output relay. | 1 | 25 € | 25 € |
| PLESK Web server annual fee | 1 | 60 € | 60 € |
| Web SCADA system interface | 1 | Free | Free |
| Other components | 1 | 200 € | 200 € |
| TOTAL | | 1,315 € | |

1 Unitary cost prices as listed in Amazon.es Website.
2 Unitary cost prices as listed in Mouser.es Website.
3 Unitary cost prices as listed in Plesk.com Website.
4 Unitary cost prices as listed in PEC-instruments.com Website.

Table 7

| Device | Qty | Cost  | Total cost |
|--------|-----|-------|------------|
| SENTRON PAC 3200 Power Meter | 9 | 600 € | 5,500 € |
| Meteorological data logger | 1 | 200 € | 200 € |
| OMRON Programmable Logic Controller CJ1M with serial communication CJ1W-SCU31, ethernet communication CJ1W-ETHN21, relay output CJ1W-O2C11 and power source CJ1W-PAC20R modules. | 1 | 2,200 € | 2,200 € |
| PLESK Web server annual fee | 1 | 60 € | 60 € |
| CX-Supervisor SCADA system | 1 | 1,500 € | 1,500 € |
| Other components | 1 | 200 € | 200 € |
| TOTAL | | 9,360 € | |

1 Unitary cost prices as listed in PCE-instruments.com Website.
2 Unitary cost prices as listed in Mouser.es Website.
3 Unitary cost prices as listed in Plesk.com Website.
4 Unitary cost prices as listed in Amazon.es Website.

6. Additional information

No additional information is available for this paper.

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