Smart Grid Infrastructure Using a Hybrid Network Architecture

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***Abstract*—Smart grid can be defined as a modern electric power grid infrastructure for improved efficiency, reliability and safety, with smooth integration of renewable and alternative energy sources through automated control and modern communications technologies. The increase need for more effective power electrical systems control turned the development of smart grids, the main object of study for many researchers. This paper proposes a digital system for condition monitoring, diagnosis and supervisory control applied to smart grids. The system is based on hybrid network architecture (HNA), consisting of a wired infrastructure, a wireless sensor network (WSN), a power line communications (PLC) and a controller area network (CAN). The system is based on three hardware topologies: remote data acquisition units (RDAUs), intelligent sensors modules (ISMs) and a PLC modem. The basic characteristics are: a) easy/low cost implementation, b) easy to set up by user, c) easy implementation of redundant routines (security), d) portability/versatility, and e) open system. To validate the developed system, it was implanted in one underground electric substation power distribution, characterized as an extremely hostile environment for supervisory control applications. In this application, the main challenge is to establish a communication system installed inside the substation with the outside (operations center—OC) considering that there are not commercial solutions appropriate to solve completely this problem.**

***Index Terms*—Architecture, communication systems, hybrid network, monitoring, power distribution, smart grids.**

I. Introduction

SMART GRID IS A modern electric power grid infrastructure for improved efficiency, reliability and safety, with smooth integration of renewable and alternative energy sources through automated control and modern communications technologies. In the smart grid, reliable and real-time information becomes the key factor for reliable delivery of power from the generating units to the end-users [1].

Embedded systems can be found everywhere in daily life, from electrical commodities and appliances, to nonlinear compensation mechanism, complex automation systems and adaptive control systems [2], [3].

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Hybrid network architecture (HNA) is a network architecture that utilizes both, wired and wireless infrastructure for communication. The use of HNA is interesting in many ways, including: i) the possibility of implantation redundant structure (the same information is sent over two or more different communication media) increasing reliability; ii) adding a few wires to a wireless sensor network can not only reduce the average energy expenditure per sensor node, but also the non-uniformity in the energy expenditure across the sensor nodes resulting in a better life network [4].

Also, smart grid enable new network management strategies provide their effective grid integration in distributed generation (DG) for demand side management (DSM) and energy storage for DG load balancing [5].

According with [6], there is a variety of researches which shows that more active participation in the market by the demand side could have significant benefits for the whole market. In particular:

- reduction in the energy cost for consumers who shift their demand from periods of high prices to periods of lower prices;
- reduction in the overall generation cost of the system because this demand shifting will flatten the overall demand profile;
- even consumers who do not adjust their demand will make a profit if this reduction in cost translates into a reduction in prices;
- avoiding price spikes (i.e., very large increases in price over short periods of time);
- reduction in the ability of generating companies to exert market power.

Integrated systems avoid severe economic losses, resulting from unexpected failures, and improve system reliability and maintainability [7]. There are several hardware and software solutions for implementing smart grids for the most varied scenarios [1], [7], [8]. Integrated systems can consist of a number of devices connected to a computer through a local area network (LAN), usually consists of a shields twisted pair of wires [9].

According to [10], the PLC application in smart grid power consumption field, demonstrate the favorable prospect. In [11] the authors investigates the effects of load impedance, line length and branches on such systems, with special emphasis on powerline networks.

There is an increasing interest in applying technology to protect and control electric utilities. At present many power utilities are being faced with the reality of conventional centralized control systems limitations, as they can greatly degrade due to the complexity of dealing with network events that would require

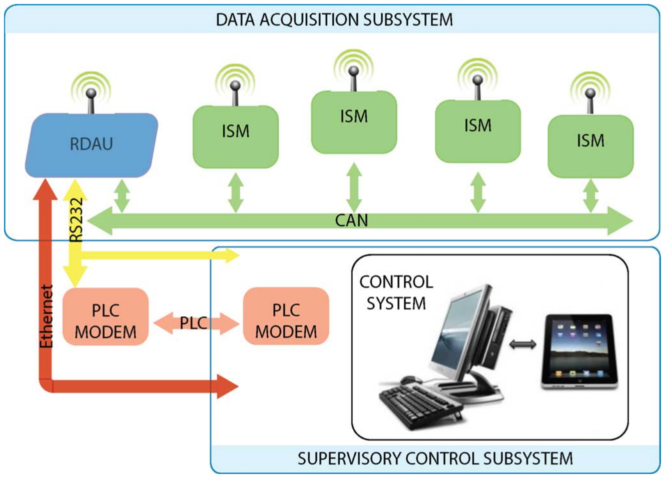

Fig. 1. Complete monitoring system.

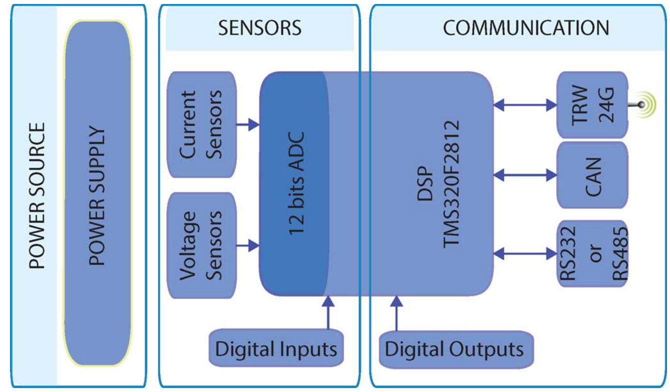

Fig. 2. Remote data acquisition unit (RDAU) block diagram.

enormous amount of data to properly manage them. Nowadays, intelligent electronic devices (IEDs) and robust communications processors contain large amounts of valuable data that have been available for years, but largely overlooked. Initial integration efforts by most vendors focused solely on providing data access, supervisory control and data acquisition [7], [8], [12], [13].

Wireless sensor networks (WSNs) will play a key role in the extension of the smart grid towards residential premises, and enable various demand and energy management applications. Efficient demand-supply balance and reducing electricity expenses and carbon emissions will be the immediate benefits of these applications [1], [7], [14].

The objective of this study is developing a system that integrates a set of smart sensors and communication systems for different applications in smart grid. A HNA combine wired communications [serial bus, ethernet, power line communication (PLC), controller area network (CAN)] and wireless communication (WSN), which enables real-time monitoring of the system under the developed/implemented supervision.

To validate the developed system it was implanted in underground electric substation power distribution, characterized as an extremely hostile environment for supervisory control applications. In this application, the main challenge is to establish a communication system installed inside the substation with the outside [operations center (OC)] considering that there are not commercial solutions appropriate to resolve this problem.

The concept of smart grid lies in the fact that turns an existing structure, old, in a structure of power distribution that provides various information to the OC, without the need to make any significant change in it.

The designed system in Fig. 1 is based on the concept of intelligent sensors. The intelligent sensors modules (ISMs) may acquire up to four magnitudes, i.e., two analog and two digital, communicating by wireless and/or physical network. A second module is designed to be used in the acquisition of quantities with fast dynamic and need read more than four quantities, e.g., secondary voltages and currents of the transformer. This device is referred as remote data acquisition unit (RDAU).

The developed/proposed system is subdivided in two subsystems: a) data acquisition—DAS; b) supervisory controller—SCS. The data interchange, among the subsystems and among the modules, is based on a hybrid communication.

II. Data Acquisition Subsystem

Automation processes are extremely associated to instrumentation and control. The concept normally used for data acquisition in process control is usually accomplished by placing sensors close to the actual phenomenon [12]. Data gathered by the sensors are then transmitted through a wired communication infrastructure to the processing place.

The evolution of sensor technology and communication networks has allowed to employ intelligent sensors for improving the processing control. In this case, sensors not only collect data, but they also perform some local processing and transmitting their results through: wireless communication (i.e., radio transmission), or for wired communication infrastructure avoiding data redundancy [15].

Concerning to this idea, the system is using two platforms to data acquisition: remote data acquisition units (RDAUs) and intelligent sensor modules (ISMs).

A. Remote Data Acquisition Unit (RDAU)

Different RDAUs are responsible monitoring rapid dynamic data and fault detection. For this purpose, the RDAU provides six analog inputs and four digital inputs, transmitting the data to a supervisory controller, and if required, the platform can operate based on digital outputs. RDAU system is illustrated in Fig. 2.

1) Analog Inputs: Transformers are used for the voltages measurements with a 11:1 relation, and HAIS100 (LEM™) for measuring the currents. The RMS voltage value in the primary supervision transformer is 75 V. Considering 50% overvoltage, the system is able to measure up to 110 V. The current sensor has 100 A of nominal primary current. The same can measure currents up to ±300 A. To achieve better resolution for the current measure, two conditions were developed, one for maximum current of 5 A (low power circuits) and another for 100 A (high power circuits). The transition between the resolutions is implemented by software.

2) Digital Inputs and Outputs: Besides the common analog voltage and current inputs, the RDAU has also the capability to analyze four digital inputs: low level, ranging from 0 V to 75 V, and high level, ranging from 95 V to 127 V. For the actuation in power systems, the RDAU provides four digital outputs that can be used whenever necessary.

3) TMS320F2812: The TMS320F2812 microprocessor operating at 150 MHz clock frequency (i.e., 6.67 ns/instruction). The memory architecture is organized as follows: 64 kB program memory, 64 kB data memory, RAM, one external memory interface with 1 MB, and 128 kB Flash ROM. The system also provides an analog-digital converter (ADC), PWM, and timers.

4) Software: The software was developed based on the C++ language, using the Code Composer Platinum platform (Texas Instruments). The main routine configures peripherals and interruptions, enabling data acquisition, data processing and data transmission. The data acquisition subroutine uses the internal ADC of the DSP. The DSP has two parallel sample-and-hold channels that connect at one ADC with a 12 bits resolution, working with maximum conversion rates of 25 MHz/channel. The sampling is simultaneously for each pair of inputs.

The sampling time was adjusted for 7680 samples/second, representing 240 samples/cycle for each voltage and current of the phases R, S, and T. Aiming at improving the system's performance, some data processing is performed locally to reduce the number of data packet transmissions.

The RDAU processing data subroutine performs the computation of the RMS values for the voltage and current phases, active, reactive and complex three-phase power and power factor, in addition to the computation of fast Fourier transformer (FFT). From the RMS values, the operator can analyze the power system behavior (i.e., fault analysis), allowing covering all rules and international standards. Given that the system has some processing power, it allows running several control algorithms and the implementation of fault detection techniques.

All the results obtained from the data processing unit are transmitted through a "transmission data subroutine" to the supervisory controller (SC). This subroutine configures the RS232 communication with two stop bits, no parity, eight data bits, and 115 200 bps data rate, based on the MODBUS protocol [16]. Besides RS232, RDAU communicates to SC by Ethernet. To send/receive data from the ISMs, RDAU uses CAN and radio frequency (RF) communications.

In the next item the possible communication scenarios will be explained. Concerning to the protocol, transmission rate and that data process occurs in the TMS320F2812, the using of the transmission channel is 15%. The implemented prototype is illustrated in Figs. 3 and 4.

Fig. 3. RDAU prototype.

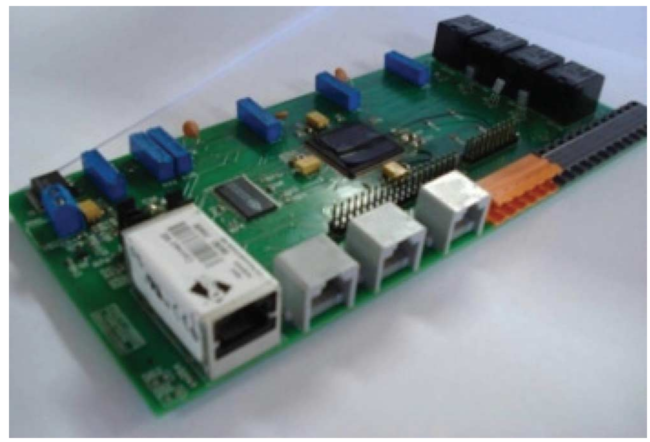

Fig. 4. RDAU hardware.

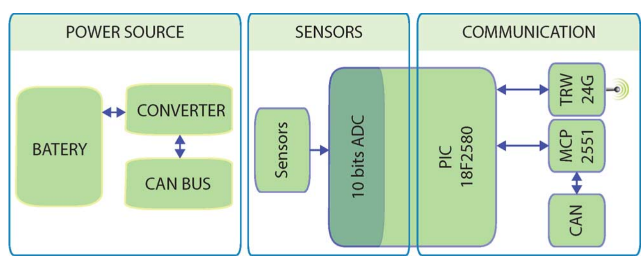

Fig. 5. ISM architecture.

B. Intelligent Sensor Module (ISM)

The ISMs are devices capable of performing data acquisition functions, data processing and transmitting/receiving data. Its low cost architecture Fig. 5 consists of a power subsystem, a sensor subsystem and communication subsystem.

The subsystems, sensors and communication are managed by a PIC18F2580 microcontroller. This was chosen because of design requirements and also has the same integrated hardware dedicated to CAN (controller area network). In addition, supports various peripherals, e.g., 10 bits ADC, four timers, universal synchronous asynchronous receiver transmitter (USART) as serial interface, among others.

The power subsystem is responsible for powering the ISM. The primary source of energy comes from the CAN bus and/or battery pack. When necessary, the CAN bus system also feeds back into recharging of batteries. This system consists of a battery with 900 mAh capacity and 7.2 V.

The ISM is equipped with four sensing inputs, two digital and two analog. The analog inputs designed to operate with signals in the range of 0 to 5 V or 4 to 20 mA, depending of characteristic of the sensor connected. If the sensor attached to the ISM need power, it is provided with the signal connector.

The ISM send/receive data in two distinct ways: via wireless network or through physical network. The physical network is primarily intended for the redundancy, the wireless network is the principal communication to exchange information.

Fig. 6. ISM hardware.

The device used to radio frequency (RF) communication is the TRF-24G module, which employs the nRF2401A transceiver and a physical bus based on CAN communication.

A ISM prototype was developed to experimental validation Fig. 6. Each ISM has an address assigned by the Gateway when installing the network, organizing themselves autonomously (plug and play).

III. Supervisory Controller Subsystem

Nowadays different equipment has an integration technique for each vendor, which does not communicate to equipment from other vendors. Like this, once an organization commits to a vendor proprietary integration solution, it is difficult to change or extend capabilities without the vendors involvement [17].

The SC Subsystem was developed in order to emphasize data presentation versatility. It runs on standard PC architecture using Linux or Windows OS, once the interface was developed using JAVA language, and IBM-DB2 Express-C and MySQL to database. The application was developed to support online data presentation through reading of the received data files, including as well as a Database system, which stores the data [18]. Since the main function of the SC subsystem is receive and store the data derived from the RDAUs, it can process and present them to operators through: i) SCADA (proprietors systems); or ii) human machine interface (HMI) specially designed for this purpose.

A. Human Machine Interface (HMI)

The HMI, Fig. 7, used in the SC as mentioned before, was developed in JAVA language and is divided in four parts described as follows:

1) Part 1 Monitoring: Allow the user to show the graphical representation of all the variable of the platform, with real time values of voltage and current as well as powers values, Fig. 7.

2) Part 2—Alarms: Include a sequential listing of alarms and changes of state. This list allows the operator notice of any disturbance of the power system, as sag, swell, overcurrent, and overload. The list of alarms can be seen in Fig. 7; however, the meters issue alerts in real time, shown in Fig. 8.

3) Part 3—Database: The measurement of voltage and current are stored in a hard disk (HD) permitting after analyzes anytime that is necessary.

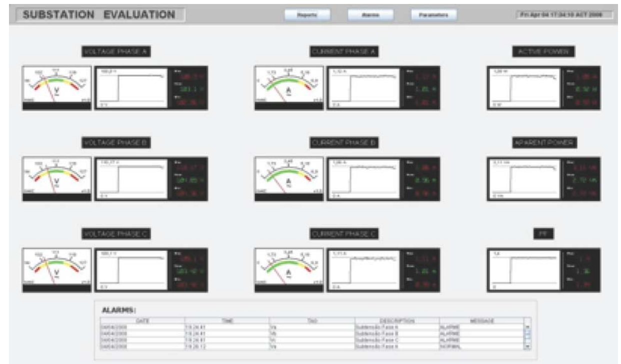

Fig. 7. HMI main interface.

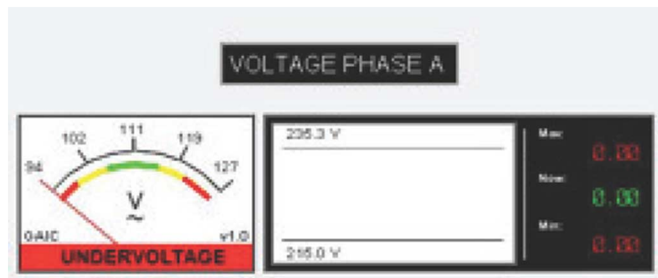

Fig. 8. Alarm warning of a meter.

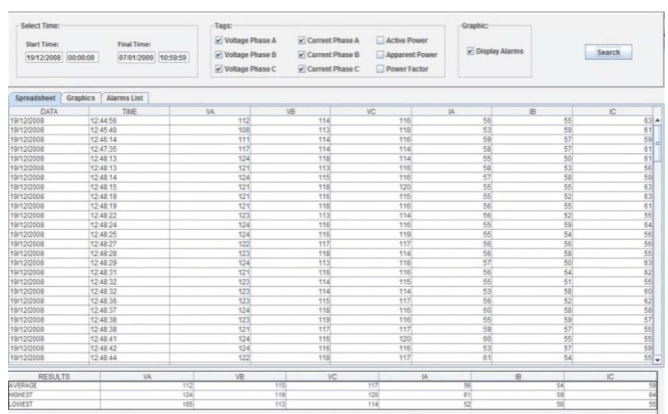

Fig. 9. Spreadsheet report.

4) Part 4—Historic Graphics and Reports: This function was developed for the user can observe the evolution of the current, voltage, and power values in a determined time (see Figs. 9 and 10).

5) Part 5—Parameters: To a better versatility the parameter of sag and swell can be configured by the user. In this form the nominal values and alarm enabling will run under the usual norms. The configurable parameters are: nominal voltage, maximum swell, minimum sag and overcurrent (see Fig. 11).

The SC can also be presented in WEB, iOS™, and Android™ platforms.

Fig. 12 presents the WEB application developed to access the data collected and stored in the database. Any user can to access this application from a computer with Internet access.

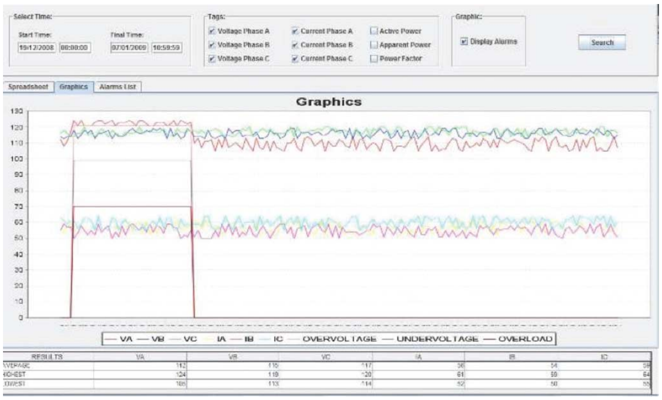

Fig. 10. Historic graphics.

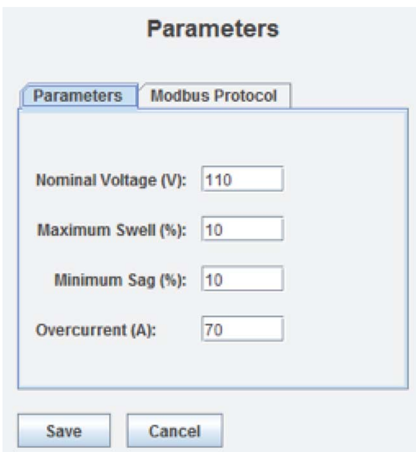

Fig. 11. Parameters.

Fig. 12. Real time interface for WEB.

Fig. 13 shows the application developed specifically to run on devices with iOS operating system (e.g., iPad™ and iPhones™).

Finally, Fig. 14 shows the application designed to run on devices with Android™ operating system.

IV. Hybrid Communication

Nowadays, there is a lack of communication ability in electric power systems. In smart grid concept, intelligent sensors should communicate to each other, local processing and advanced large computing power. For data transmission between smart meters and electrical utilities, different communication technologies can be used in infrastructure based on wired or wireless.

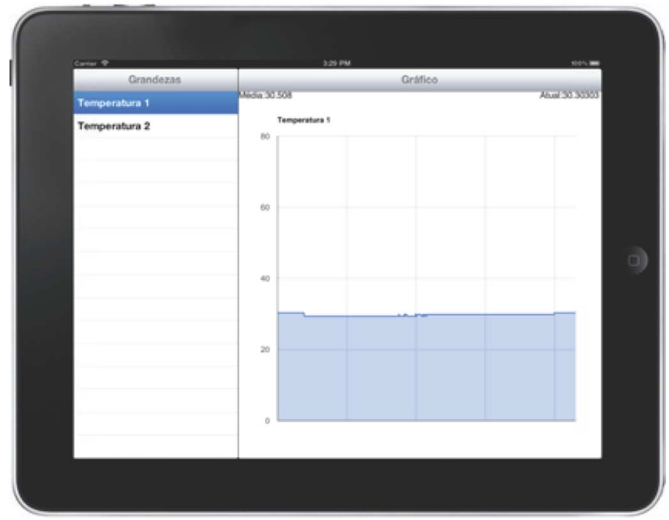

Fig. 13. Real time interface for iOS (e.g., iPad™).

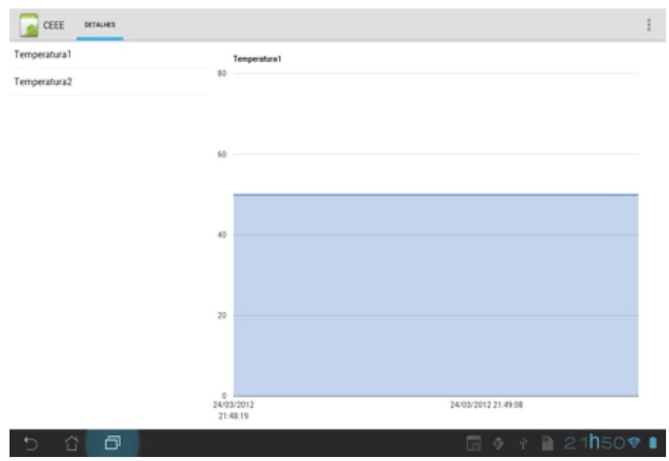

Fig. 14. Real time interface for Android™.

Recent developments in communication technologies have enabled cost-effective remote control systems, which have the capability of monitoring the real time operating conditions and performances of electric power systems. Each communication technology has its own advantages and disadvantages that must be evaluated to determine the best communication technology for automation system. In order to avoid possible disruptions in power systems due to unexpected failures, a highly reliable, scalable, secure, robust, and cost-effective hybrid communication network between system under analysis and a remote control center is paramount. This high performance hybrid communication network should also guarantee very strict quality of service (QoS) requirements to prevent possible power disturbances and outages.

A. RS232

The serial interface is employed when the RDAU is nearby the SCS. In this way, communication between the two modules takes places without the need of any other communication module. The serial communication is based on MODBUS. This protocol has two transmission modes: ASCII and binary. The binary mode (RTU) is the one used in our system. The end of

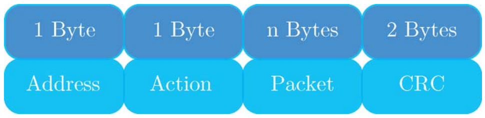

Fig. 15. MODBUS RTU framing.

a message is identified after there is no transmission for a minimum period of 1.5 times a data word transmission. The packet structure (Fig. 15) includes:

- network address;
- packet type;
- packet data;
- error detection mechanism.

The communication follows a master-slave approach, where only one device (the master) can query the other devices (slaves). The slaves reply back sending the data required by the master. The master can address one slave at a time or all the network devices through diffusion messages.

B. *Radio Frequency (RF)*

In a second scenario, where the monitored data is distant and there is not wired communication infrastructure, data gathered from the monitoring devices can be transmitted via a wireless interface, which is easy to implement and a way cheaper compared to standard wire communication (e.g., via optical fiber).

The TRF-2.4G transceiver developed by LAIPAC™ uses an nRF2401 component (NORDIC Semiconductors™). It uses GFSK modulation with a data transmission rate of up to 1 Mbps. The transceiver unit is includes an antenna, a frequency synthesizer, an amplifier, a crystal oscillator and a modulator/demodulator. The transmission power can be configured ranging from -20 dBm to 0 dBm, reaching distances up to 250 m (without obstacles).

The advantages of wireless communication include their commercial acceptance and their application in environments with physical barriers.

Some aspects affect the energy consumption of the radio, including type of modulation, data transfer rate, and transmission energy. A usual approach in the applications of wireless sensors is that their duty cycle is very short (i.e., around 1%). Nodes can schedule their events and remain in sleep mode, while there is no need to be active, saving battery power and extending the network lifetime.

Many microcontrollers have an asynchronous oscillator circuit, which remains running, while the core and the peripherals are inactive. This capability makes it possible to return from a sleeping state in just a few microseconds.

The radio has four operation modes: Transmission (TX), Reception (RX), IDLE, and SLEEP. The choice among different transceivers was based on two aspects: the frequency clock and the energy consumption for the different operation modes.

The transceivers that operate in 2.4 GHz are easily available and are less prone to noise. Due to their high data rate the energy consumption for a single bit transmission is very low. However, the same speed is also required from the microcontroller. This problem is addressed in the nRF2401 transceiver through the application of a data buffer that adapts a low performance microcontroller (e.g., 10 kbps) with the data rate transmission of the radio (i.e., 1 Mbps) [7]. The main characteristics of the transceivers analyzed in our research are presented in Table I.

TABLE I
A COMPARATIVE BOARD OF ENERGY CONSUMPTION FOR SOME COMMERCIAL TRANSCEIVERS

Model	A	B	C	D	E	F
NordicVLSI/nRF2401	1000	2400	1	0.5	15	6.5
Conexant/CX72303	1000	2400	1	0.02	24	11
Conexant/RF109	1200	2400	5	25	89	31
Ericsson/PBA31301	1000	2400	65	21	40	32
Ericsson/PBA31305	1000	2400	70	35	50	60

A Tx rate (kbps); B Frequency (MHz); C Sleep (uA); D Idle (mA); E Rx (mA); and F Tx (mA).

C. *Ethernet (TCP/IP)*

Third scenario, where the monitored data are distant from the SC and a wired infrastructure is available. Between all the advantages of Ethernet communication two useful situations can be described: places where wired networks has already been installed; or places where wireless communication is hard (e.g., due to interferences and difficulties to install antennas).

In this scenario the DE311™ from B&B Electronics™ module is being used. This module provides a data communication solution for connecting Windows™ and Unix/Linux hosts to asynchronous serial devices over a TCP/IP based Ethernet. As the input data is from asynchronous serial, and RDAU provides RS232, the communication between DE311 to RDAU is directly.

The protocol is based on sockets interface. Such technology, improved by the University of California, in Berkeley, made possible a UNIX implementation of the sockets package to TCP/IP protocols. Nowadays, it is the most usable method to access a TCP/IP network and Internet.

Originally the sockets were developed as the BSD (Berkeley Software Distribution) UNIX Operational System intrinsic parts. As a consequence, they use lots of concepts found in other Kernel routines. Particularly, sockets are integrated to the I/O routines.

This integrated system main advantage lies in its flexibility: can be written a unique applicative that transfers data to an arbitrary localization. A socket is, primarily, a transparent data connection between two computers linked on a net. It is identified by the computers network address as well as by a door localized in each computer.

Socket represents a TCP/IP network connection point. When two computers want to maintain a conversation, each one of them uses one socket. In this procedure a computer named server opens a socket, here specifically the supervisory controller, and makes a connection check. The RDAU sends a signal to the server socket aiming to start a connection. In order to establish a connection just the destiny address and the port number are necessary. In the TCP/IP specific door numbers are reserved to specific protocols, for instance, 25 to SMTP (Simple Mail Transmission Protocol) and 80 to HTTP (Hyper Text Transfer Protocol).

Sockets present two main operation modes: the connection based mode and the without connection mode. The based connection modes work as a telephone; they have to establish a

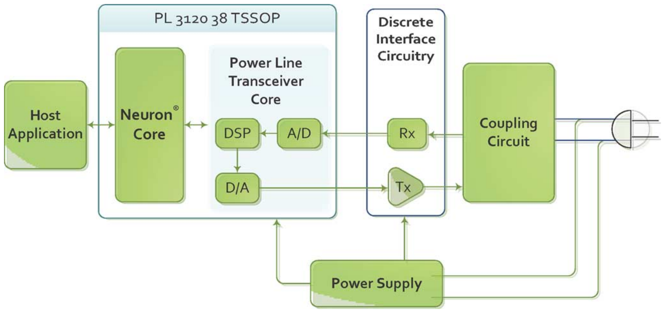

Fig. 16. PLC node based on PL-3120.

connection while interrupting the call. Everything that flows between these two events arrives in the same order as it was transmitted. On the other hand, the mode without connection does not guarantee the deliver, and the mail different items can arrive in a different order from that they were transmitted.

D. Modem PLC

The PLC system has been installed in Porto Alegre city, in the low voltage cabling of underground network. The PLC, transmitter/receiver pair, is developed by MODEM PLC PL-3120, ECHELON™. The MODEM PL-3120 is connected to a microcontroller, whose functions are:

- transmitter/receiver PLC installed in the transformer;
- data acquisition of the environment temperature and transformer frame;
- generation of data packet to send to the MODEM PL-3120 via the serial interface (UART);
- management control messages sent through the electric grid, supplied by MODEM PL-3120.

Transmitter/receiver PLC installed outside:

- receiving the data packets sent through the electric grid, supplied by MODEM PL-3120
- checking validity of data received;
- configuration of Modem GSM/GPRS;
- generation of data packet for sending for the GSM MODEM/GPRS via UART serial interface;
- control messages management sent via the cellular network, delivered by the GSM MODEM/GPRS.

The PLC MODEM PL-3120 NEURON™ incorporates a CPU, 4 kB to application memory and 2 kB of RAM. The NEURON™ processor executes routines for nodes protocols interconnection in a network PLC, Interoperable Self Installation (ISI), besides communication protocols, with the option to activate or not the CENELEC™ STANDARD. All these protocols are proprietary and stored in ROM memory on the device. In Fig. 16, can be seen the blocks diagram, with the constituent parts of a node based on PLC PL-3120.

The MODEM PL-3120 can operate in bands A and C defined in CENELEC™ STANDARD, which are selected from the crystal used to trigger the MODEM. The selection of the CENELEC™ band also defines the rate of data transmission on the network. By selecting the A band, the communication will occur at a rate of 3.6 kbps.

As presented in the block diagram Fig. 16 it is necessary for integration, between the PL-3120 and the circuit that couples the modulated carrier to the electric network, an interface circuit.

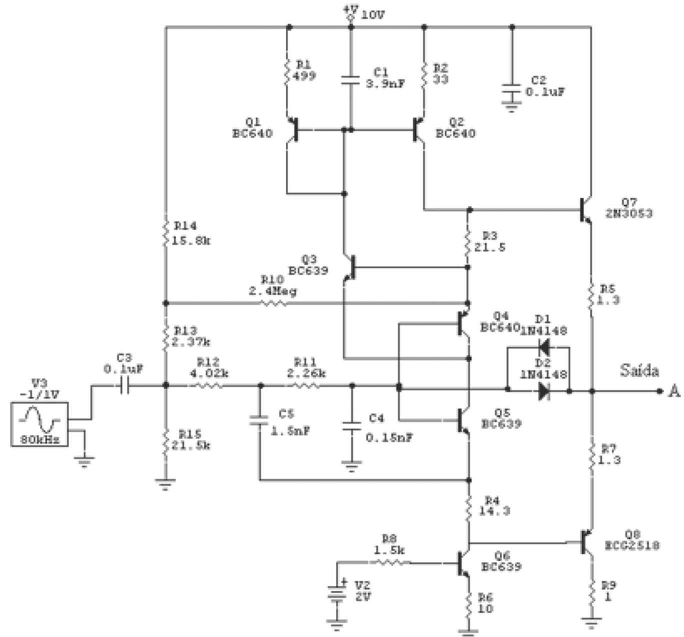

Fig. 17. TX amplifier.

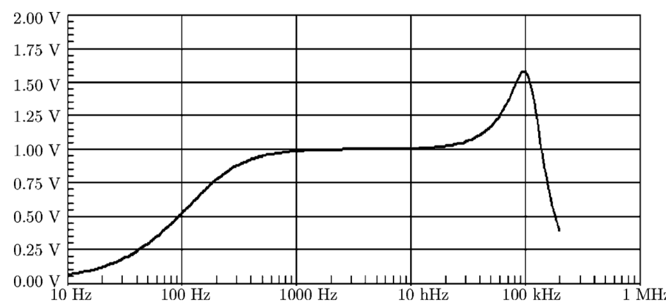

Fig. 18. TX amplifier frequency response.

The interface circuit is composed mainly of an amplifier that can be applied to an electric network signal at operation carrier frequency of the PL-3120, with up to 1 A peak-to-peak. Fig. 17 shows the circuit diagram of the amplifier output, which forms part of the interface circuit. It is a transistor discrete circuit in a push-pull modified configuration.

Fig. 18 presents a frequency response analysis of the power amplifier for PLC transceiver. There is a practically flat response in the frequency range of 1 kHz to 20 kHz. In the frequency range corresponding of the band A, of the CENELEC™ STANDARD, there is a peak in the curve of the amplifier gain. The maximum peak occurs at 100 kHz, falling abruptly after this frequency.

E. CAN

The physical bus addresses the standard ISO11898-2, designed to international standard CAN communication [19], [14]. It specifies patterns relating to the physical layer of the CAN protocol, one being the use of a transceiver device that makes the interface between the sensor and CAN bus node, making certain electrical conditions provided in the standard are met. Among these conditions include the protection against short circuits, voltage levels and others. Therefore, ISMs were connected to the bus via the CAN transceiver MCP2551, Microchip Technology™.

V. Experimental Results

To evaluate the system performance it was defined a set of experiments for analyzing:

- Remote data acquisition unit (RDAU) maximum practicable data acquisition and obstacles susceptibility;
- Intelligent sensor module (ISM)—maximum practicable data acquisition, obstacles susceptibility and maximum lifetime batteries;
- communication (Ethernet (TCP/IP) and wireless) transmission rate;
- power line communication (PLC)—Behaviorof the data transmission for differentdays and different days times;
- human-machine interface (HMI)—easy of understanding information and time response;

The RDAU/ISM systems were evaluated for different scenarios monitoring an underground electric distribution grid.

A. RDAU Maximum Practicable Data Acquisition

The RDAU improved the sampling rate, because it employs a DSP (TMS320F2812). In this case, the RDAU could achieve 264-samples/cycle, translating to 10920-samples/s. These results allow analyzing up to the 1282th harmonic. Considering that the RDAU is used for the signals acquisition with fundamental frequency of a 60 Hz, and as performs an ADC for each 130 μs, comes to a sampling frequency of 14 kHz, resulting in a maximum bandwidth, or the Nyquist frequency of 7 kHz. These values fully attend the technical standards for the monitoring of electrical power substations.

B. ISM Maximum Achievable Data Acquisition

The ISM are used only for the acquisition of signals with large constant times, and therefore it does not need a high processing capacity (e.g., temperature). The maximum capacity of acquisition of ISM was 12-samples/cycle.

C. RDAU/ISM—Transmission Rate

Both, the RDAU and the ISM, use the same transceiver for communication (TRF 2.4 G). Radio frequency (RF) communication is well suited for environments with physical barriers. However, it is prone to interference.

D. RDAU/ISM—Obstacles Susceptibility

The ISM/RDAU systems were evaluated for two different scenarios (with and without obstacles). Preliminary results for the first scenario show that the sensor node is able to transmit without any packet losses up to a distance of 80 m, regardless of the antenna orientation. At a distance of 90 m, and with the antennas directed at each other, it was notice around 10% packet losses. Distances larger than 100 m showed an unacceptable number of packet losses. As for the second scenario, it was also noticed that obstacles such as a 30 cm concrete wall allow transmitting to distances only up to 60 m without any significant packet losses.

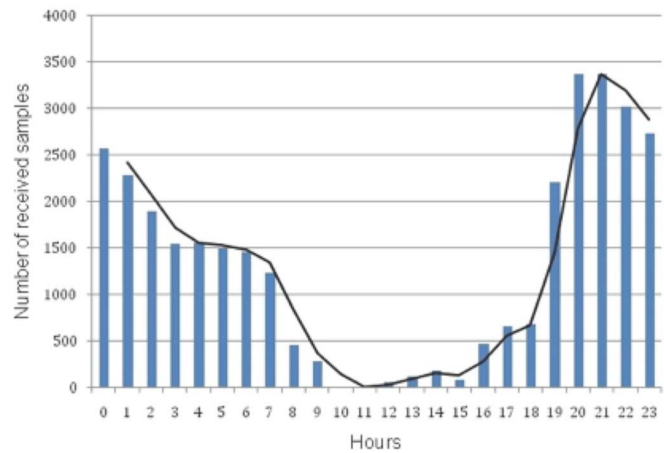

Fig. 19. Total data received by time of the day in the period August 29, 2011 to November 11, 2011.

E. RDAU/ISM—Maximum Lifetime Batteries

Considering that a WSN is energy constrained, it is paramount to reduce the consumption of energy due to modulation, filtering, and demodulation. The energy consumed by the radio depends on the type of modulation, data transfer rate, and transmission energy.

To extend the network lifetime, it was adopted the dynamic power management with scheduled switching mode (DPM-SSM) protocol for wireless sensor nodes [8].

DPM-SSM is a power management technique that schedules state transitions to a sleeping state based on the current nodes battery capacity. As the battery capacity degrades, upon reaching some predefined energy levels, the scheduling takes place more often to improve the battery capacity recovery.

When a node is switched to a sleep state, there is a huge reduction on the current drawn from the battery by that component. Hence, it allows to take advantage of the battery recovery effect. In a sensor node, the radio, in average, draws more energy from the battery. Thus, DPM-SSM adopts switching to the sleep state from a transmission state. By doing that, it is possible to take more advantage of the battery capacity recovery effect, because the gap between the current drawn from the battery between a transmission state and the sleep state is larger than considering the other state (i.e., between Rx and sleep).

Unlike the original DPM-SSM protocol that provides three operating modes, which are triggered depending on the current battery capacity, it was chosen just one operating mode that is activated starting from the very moment that the sensor node is activated. In this way, a node is always put to sleep after a transmission, regardless of the current battery capacity.

F. PLC—Data Transmission Behavior

The data transmission behavior can be verified by Fig. 19, which presents the sum total of data received by time of day in the period from 28/08/2011 to 11/11/2011. It can be seen, that the loss of data communication occurs in the period of greater load consumption, proving the influence of the power flow on the performance of the PLC modem.

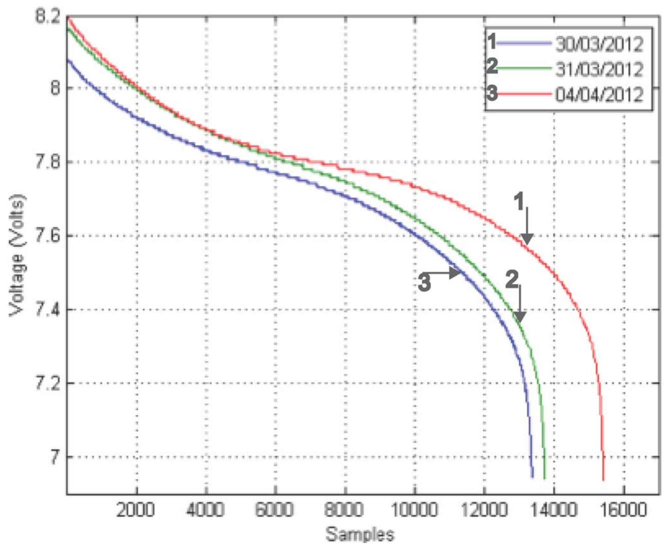

Fig. 20. Backup system test (critical case).

VI. Application Results

The tested system was installed in the spot network system of the CEEE-D (State Company for Electric Power Distribution) in Porto Alegre city.

The monitoring system (ISMs and RDAU) was installed in the northeast spot network system (RNE). The developed Gateway manages the receipt of the data system and is connected to the PLC signal transmitter, in the low voltage transformer output. The approximate distance from the transmitter to the receiver is about 250 m. There is no direct path between them. Due to the robustness provided by the adoption of hybrid structure for the ISMs and RDAU, packet losses in communication did not occur. The most critical data such as voltage and current, travel through CAN system when the data is not received properly by transceivers.

The proposed system was tested for 90 days collecting data at intervals of 10 s. In this period, more than 2 GB of information that is stored in a database were transmitted, the packet loss rate was less than 1%, which proves the robustness of the proposed system. A graphical interface able to access this database was developed, which can be executed from any desktop or mobile device.

The battery system of sensors nodes operates as backup in cases, which the redundancy occurs. In these cases, the worst possible condition occurs when the sensor node is continuously processing and transmitting data, where his current drawn reaches 57 mA peak. Thus, it has been tested a set of batteries in extreme conditions of use, so that could be evaluated its durability. Fig. 20 shows the results obtained in the discharge process. The sampling time is 1 s.

VII. Conclusion

The system provides flexibility, fault tolerance, high sensing fidelity, low cost, rapid response, and interoperability, making the system an ideal platform for power usage evaluation and condition monitoring altogether, and allowing the construction of high level intelligent power management system in smart grids.

Several scenarios were analyzed considering different communication types. The tests aimed to analyze the behavior of the three subsystems that make up the automation system for an underground electric distribution grid.

For data acquisition subsystem the tests were conducted aiming to verify the signals bandwidth acquired by RDAU. This analysis was performed from the Nyquist Theorem and Fourier Series. Simultaneously use of these methods has the capability to analyze harmonics.

The analysis of the RDAU bandwidth presented results consistent with the established standards [13], [19]. Where RDAU bandwidth was 7 kHz. It was found that the RDAU to identify until the 128th harmonic.

The ISM tests were performed in this case: the distance that the module is capable of transmitting and the number of packets sent during a time. Preliminary results show that the sensor node is able to transmit without any packet losses up to a distance of 80 m. At a distance of 90 m, and with the antennas directed at each other, it was around 10% packet losses. Distances larger than 100 m showed an unacceptable number of packet losses. With obstacles such as a 30 cm concrete wall allows transmitting to distances only up to 60 m without any significant packet losses.

The use of PLC technology has proved to be an interesting alternative considering that the electrical grid is available for use not requiring new wired structure. But showed problems in moments of greater power flow.

The application in the underground, among the challenges of this application may be highlighted the communication between indoor and the outdoor of the monitored substation. Furthermore, considering the difficulty of access to the system, determined the use of a hybrid system eliminating the necessity of regular maintenance of the batteries.

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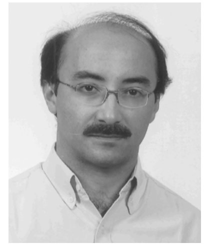

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