# Design, Development and Implementation of a Hybrid Network with Smart Sensors and Power Line Communication for Monitoring of Underground Electricity Substation

Paulo Sausen and Airam Sausen
Technology Department
Regional University of Northwest State
Ijuí, Brazil
{sausen,airam}@unijui.edu.br

Renê R. Emmel Jr.
State Company for Electric Power Distribution of Rio Grande do Sul – CEEE/RS
Porto Alegre, Brazil
ReneEJ@ceee.com.br

Mauricio de Campos and Camila S. Gehrke
Electrical Engineering Department
Federal University of Campina Grande
Campina Grande, Brazil
{decampos.mauricio,camila.gehrke}@gmail.com

Fabiano Salvadori
Electrical Engineering Department
Federal University of Paraiba
João Pessoa, Brazil
salvadori.fabiano@cear.ufpb.br

***Abstract*— The Smart Sensor Networks not only collect data, but also perform local processing, and may even operate in the system, and thereafter, if necessary, carry out the transmission. However, in some cases hybrid networks systems, that combine wireless with wired structures, may be more appropriate. The objective of this work is to develop a system that integrates a set of smart sensors and communication systems for use in an underground distribution power substation. The underground substation of the distribution system chosen belongs to the spot network located in Porto Alegre city, Brazil. Among all challenges of this work, establish the communication system installed inside the substation with the outside world, is without doubt the most complex, because, there are no commercial solutions for this problem. This paper presents the development of a hybrid smart system based on wireless sensor network combined with Power Line Communication. This system allows real time monitoring of the substation without the need to make any significant changes.**

***Keywords-Smart Sensors Networks; Monitoring Underground Power Substation; Hybrid Networks Systems.***

## I. INTRODUCTION

The need to manage the processes, combined with advances in electronics and wireless communication technologies have allowed the design of the Wireless Sensor Networks (WSN) [1]. The technology applied to these sensors, the data processing and communication networks, has allowed the evolution of these systems, which came to be called smart sensor networks. The sensors not only collect data, but also perform local processing and can act on the system and thereafter, when necessary, perform data transmission. These intelligent sensor networks enable a more effective monitoring and fault detection system, improving reliability and network maintenance [2].

Among the challenges of design, development and installation of smart sensor network can be pointed out environments where electromagnetic interference reduces performance and can also making it inoperable [3,9]. In these cases, hybrid networks that combine wireless systems with wired structures may be more appropriate [4]. These hybrid architectures still allow better power management of these systems, since in some cases the sensor node can be installed in difficult access areas. Thus, the physical connection can also be used as the redundant system of communication system.

The objective of this work is to develop a system, integrating smart sensors and communication systems, for use in a power electric underground distribution substation. The underground substation of the distribution system chosen belongs to the spot network located in Porto Alegre city, Brazil. The depth of this substation ranges 4-5 meters, under layers of asphalt and concrete. Therefore, another challenge of this work was to establish a communication system capable of communicating from the inside to the outside of the substation, since it is not possible by radio communication and there are not available physical communication installed for this purpose.

The rest of this paper is organized as follows. Section II presents the Underground Distribution Network. Section III presents a description of the monitoring system of substation. Section IV describes the partial results obtained from the monitoring system, and Section V concludes this work.

## II. UNDERGROUND DISTRIBUTION NETWORK

The underground distribution networks represent an advantageous alternative for applications in distribution systems in great urban centers, which are characterized by high concentrations of charge and require high levels of quality, continuity and reliability of electricity supplies.

There are two common ways of connecting underground distribution networks, the radial or network systems. The network system, also known as spot network system, is a low

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voltage distribution system, having a set of transformers connected in parallel, to supply electric energy to the load. This topology allows that the electricity supply is maintained even that one or more transformer get out the service as long as the total power of the remaining transformer is equal to, or greater than, the power consumed by the load. Moreover, it allows improving secondary voltage characteristics [5].

The spot network system is installed in Porto Alegre city, fed with 13.8 kV primary voltages, and 127/220V secondary voltages. It consists of 500kVA transformers, submersible, hosted in underground chambers.

The greatest risks in this type of system are: inundation, overheating, fault in protection system, theft, and changes in system pressure [10]. Figure 1 shows the analog monitored quantities: (i) the current in the primary; (ii) the voltage and current on the secondary; and, (iii) temperature of the transformer frame and the environment temperature. The other quantities are digital type (on or off), e.g., the states of: pumps, fans and transformer operational lights. The system must also be able to monitor substation inundation and intruders.

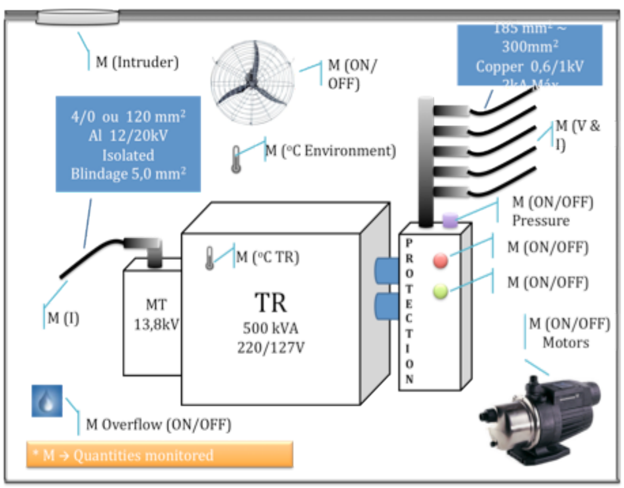


Figure 1. Monitored data by the system.

## III. DESIGNED SYSTEM ARCHITECTURE FOR MONITORING

The designed system (see Figure 2) is based upon the concept of intelligent sensors. The Intelligent Sensors Modules (ISMs) may acquire up to four magnitudes, i.e., two analogs 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 Gateway establishes the communication with the outside. As earlier mentioned, is not possible to carry out communication by radio or wired structure, since the characteristics of the substations does not allow the deployment of these systems. Thus, we used a Power Line Communication (PLC) system, allowing data transmission from the inside the substation. In the outside of the substation, a General Packet Radio Service (GPRS) transmits the data in 3rd Generation (3G) cellular communication system to a server.

The monitoring system has essentially the following subsystems (see Figure 2): a) Sub-system for data acquisition, b) Remote link, and c) Control subsystem.

### A. *Intelligent Sensor Module – ISM*

The ISMs are devices capable of performing data acquisition functions, data processing and transmitting/receiving data. Its architecture (Figure 3) consists of a power subsystem, a sensor subsystem and communication subsystem.

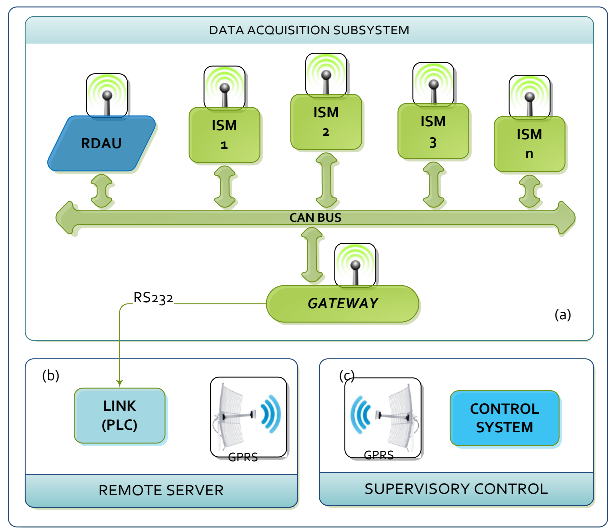


Figure 2. Complete monitoring system.

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 Analog-Digital Converter (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 900mAh capacity and 7.2 V.

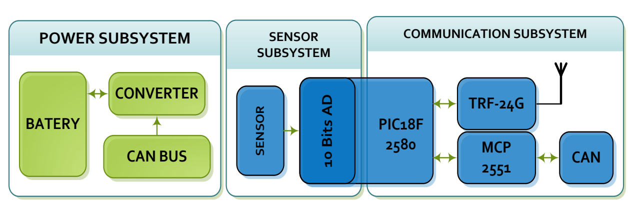


Figure 3. ISM architecture.

 

The ISM is equipped with four sensing inputs, two digital and two analogs. The analog inputs designed to operate with signals in the range of 0 to 5V or 4 to 20mA, 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 uses the communication subsystem to 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. The device used to radio frequency (RF) communication is the TRF-24G module, which employs the nRF2401A transceiver. This device uses modulation GFSK (Gaussian Frequency Shift Keying) [12] for transmitting up to 1 Mbps. It features integrated antenna and the transmission power can be set from -20 dBm to 0, allowing a range of 250 meters (without obstacles).

The physical bus addresses the standard ISO11898-2, designed to international standard CAN communication [6, 7]. 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. Amongst 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 TM.

ISM prototype (see Figure 4) was developed to experimental validation. Each ISM has an address assigned by the Gateway when installing the network, organizing themselves autonomously (plug and play).

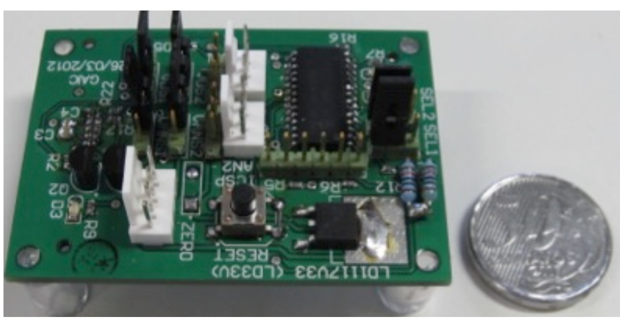

Figure 4. Intelligent Sensor Module (ISM).

## B. Remote Data Acquisition Unit - RDAU

Figure 5 shows the diagram of the Remote Data Acquisition Unit (RDAU), it can be seen that the RDAU is divided into three blocks: Communication Subsystem responsible for communication device; Sensor Subsystem responsible for acquisition of the voltage and current; and Power Subsystem that provides power to the system.

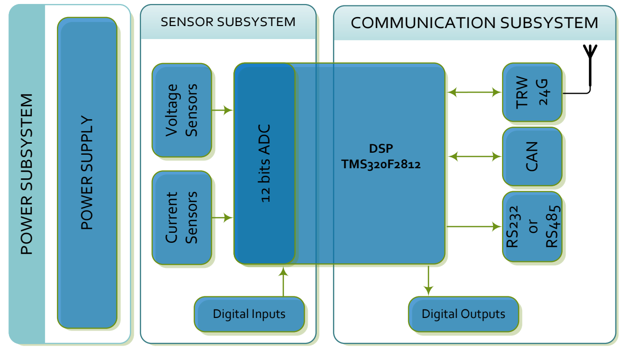


Figure 5. Remote Data Acquisition Unit (RDAU) Diagram.

The RDAU (see Figure 6) can communicate with the Remote Server (RS) via RS 232, RS 485, CAN bus or RF. If using the RS 485, CAN or RF, is it possible to connect multiple RDAUs to each Link Remote. Is controlled by a Digital Signal Processor (DSP) family TMS320F2812. The ADC is 12 bit and is programmed to 240 samples/cycle acquisition. Figure 5 shows the block diagram of RDAUs.

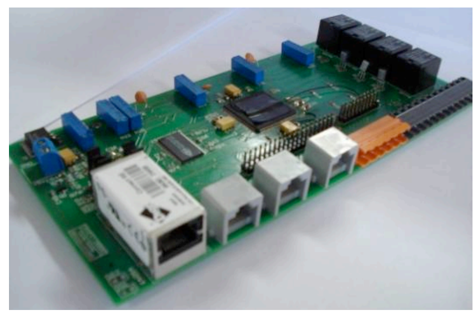

Figure 6. Remote Data Acquisition Unit (RDAU).

The RDAUs are connected by CAN bus for communication with the RS, but also has an RF communication module (model TRF-2.4G) used to perform communication with the Gateway and ISM devices.

## C. Gateway

It has been also developed a Gateway, which is responsible for interconnecting the set of sensors (ISMs + RDAU) and the PLC transmission system. The essential difference from the Gateway to the ISM itself is that there is an additional RS232 serial communications port used to perform the interconnection with PLC. The Gateway physical appearance can be seen in Figure 7.

Figure 7. Developed Gateway.

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The information exchange between Gateway and ISM is under MODBUS communication protocol. This is a master-slave protocol. Defines a structure of communication messages used to transfer analog and digital data between microprocessor devices, with detection and information of the transmission errors.

The MODBUS protocol is located at 7th level of the OSI Reference Model, which corresponds to the application layer that provides "client / server" communication between devices connected to different types of buses or network topologies [8]. The MODBUS also allows easy integration with SCADA systems [11], although these are not the main focus of this work.

The management and addressing the ISMs are performed by the Gateway, which in turn, updates and constantly checks the presence of new ISMs that for luck are connected to the bus.

### D. Modem PLC

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

- 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 is responsible for:

- 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 Kbytes to application memory and 2 kbytes 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 protocol. All these protocols are proprietary and are stored in ROM memory on the device. In Figure 8, the blocks diagram can be seen, with the constituent parts of a node based on PLC PL-3120.

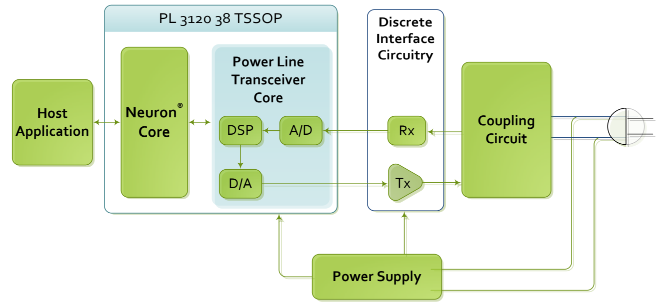


Figure 8 PLC node based on PL-3120.

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 (Figure 8), it is necessary for integration, between the PL-3120 and the circuit that couples the modulated carrier to the electric network, an interface circuit. 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 1A peak-to-peak. Figure 9 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.

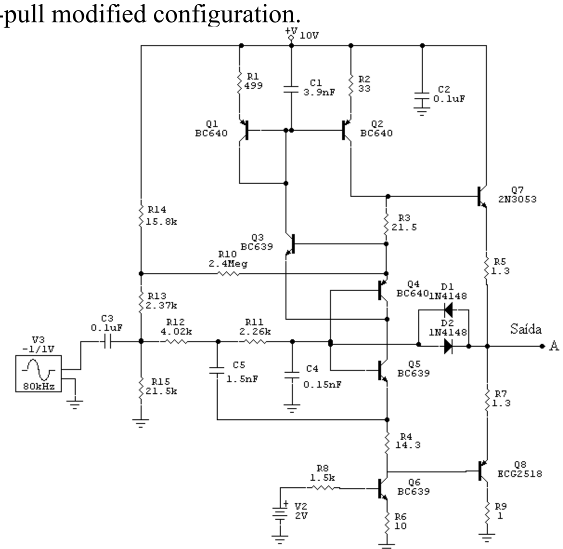


Figure 9. TX amplifier.

Figure 10 presents a frequency response analysis of the power amplifier for PLC transceiver. There is a practically flat response in the frequency range of 1kHz to 20kHz. In the frequency range corresponding of the band A, of the STANDARD CENELEC, there is a peak in the curve of the amplifier gain. The maximum peak occurs at 100kHz, falling abruptly after this frequency.

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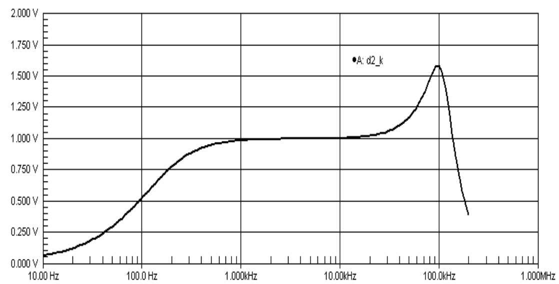


Figure 10. TX amplifier frequency response.

## IV. PRATICAL 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), box-manufacturing T-103-7A (code CEEE-D), which has the feeder 2RNE as energy supplies. 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 meters, Figure 11. There is no direct path between them.


Figure 11. PLC transmitter and receiver signals location.

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 seconds. 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. More details on this interface are presented in sequence of the paper.

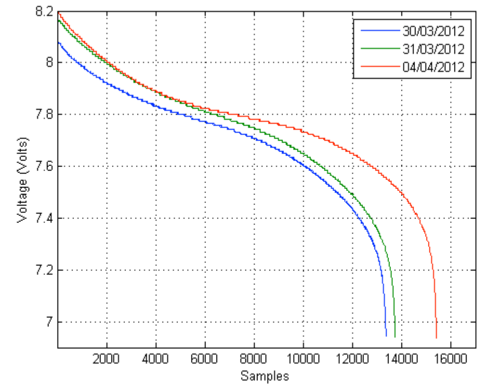


Figure 12. Backup system test (critical case).

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 57mA peak. Thus, we tested a set of batteries in extreme conditions of use, so that could be evaluated its durability. Figure 12 shows the results obtained in the discharge process. The sampling time is 1 second.

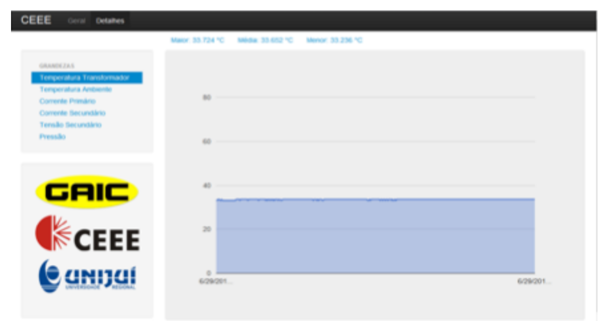


Figure 13. Real time interface for WEB.

Figure 13 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.

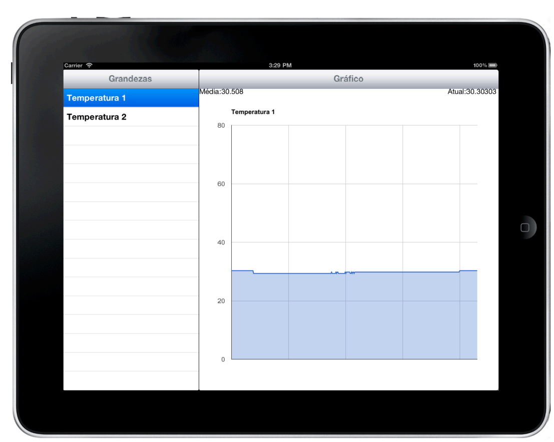


Figure 14. Real time interface for IOS (e.g.,IPAD).

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Figure 14 shows the application developed specifically to run on devices with IOS operating system (e.g, ipad and iphones). Finally, Figure 15 shows the application designed to run on devices with Android operating system.

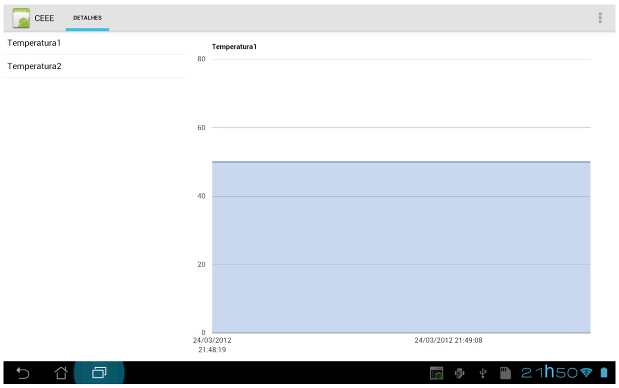


Figure 15. Real time interface for Android.

## V. CONCLUSIONS AND FUTURE WORK

This paper presented a monitoring system designed to monitor an underground substation power distribution. Advances in electronic communication systems and processing, and the high degree of integration, enabled the development of a high performance system for these applications.

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.

The system allows its application in intelligent systems and fault detection applications in underground spot network system. As future work we intend to investigate different modulation types for communication PLC in order to improve the transmission rate.

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