A Wireless Sensors Suite for Smart Grid Applications

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Abstract. This paper presents a demonstrator of a Wireless Sensor and Actuator Network (WSAN) for Smart Grid applications, developed in the context of project WSAN4CIP. This WSAN is formed by WSAN nodes equipped with sensors and a wireless radio interface, which monitor key parameters of power grid equipments belonging to the Medium Voltage (MV) and Low Voltage (LV) segments. The measurements are reported to the SCADA system and constitute the basis of both safety and security services to improve the power grid distribution dependability. This paper describes the hardware of the sensor nodes and presents the respective performance results, attesting the feasibility of the proposed solutions.

Keywords: Smart Grid, WSAN, Sensor, Energy Harvesting

1 Introduction

The Smart Grid (SG) is an emerging concept where information technologies are used to provide embedded intelligence to the electrical grid, encompassing all of the latter's segments: power generation, electricity transmission, electricity distribution and consumption. According to this concept, the SG will have such capabilities as to integrate micro producers of energy (possibly coinciding with customers), to perform automatic fault detection and self-reconfiguration according to supply and demand patterns. In order to allow these advanced functionalities, the power grid must first be sensorized, i.e. fit with sensors that are able to collect and deliver relevant measurements to the processing systems, as well as electro-mechanical actuators that are used to change the configuration of the grid.

The SG is expected to gradually evolve from the legacy power grid. At the current stage, the deployment of extra technology can already improve the latter's dependability. For example, monitoring of power system parameters in the transmission and distribution segments, such as voltage, current and equipment temperature, as well as monitoring and control of substation devices is crucial for the efficient operation of the power grid, namely regarding early detection of fault conditions [1]. Wired com-

munication could be used, but wireless technologies usually constitute a less expensive option. The use of wireless sensors and actuators can also lead to a more powerful and efficient solution due to the deployment flexibility, besides avoiding the deployment of cables in already cluttered power grid facilities [2].

The FP7 project WSAN4CIP[1] has selected the power grid distribution segment as the specific target for one of its two demonstrators. This segment receives High Voltage (HV) lines from the transport segment of the grid, delivering Low Voltage (LV) and Medium Voltage (MV) lines to customer premises. It mainly consists of HV/MV substations, connected by MV power lines to industrial customers or secondary substations (where MV is converted to LV), as well as the LV power lines connected to LV customers. A SCADA system is used as a supervisory control and data acquisition system for this infrastructure.

This paper presents a demonstrator developed within the scope of the WSAN4CIP project, which addressed the protection of critical infrastructures through the use of Wireless Sensor and Actuator Networks (WSAN). The demonstrator includes sensor nodes developed within the project. This paper focuses the hardware of the sensor nodes and presents the respective performance results, attesting the feasibility of the proposed solutions. The detailed description of the WSAN architecture is presented in another paper [3].

The rest of this paper is organized as follows. Section 2 presents and overview of the WSAN demonstrator. The deployed sensor node hardware is described in detail in Section 3. The sensor performance results are presented in Section 4. Finally, Section 5 concludes the paper.

2   WSAN demonstrator overview

The WSAN4CIP project focused on improving the dependability of critical infrastructures. This demonstrator was intended to validate the research done for the specific case of the power grid distribution system.

A proof-of-concept demonstrator was deployed at EDP Distribuição[2] premises, more precisely at the São Sebastião primary substation, located in the neighborhood of the city of Setúbal, in the west of Portugal. The São Sebastião substation provides electric energy to the Setúbal region. Fig. 1 sketches the WSAN demonstrated in WSAN4CIP, where wireless sensor nodes and their links are also represented.

The power grid distribution infrastructure mainly consists of a set of substations, MV power lines connecting substations to Medium Voltage/Low Voltage (MV/LV) power transformers residing in the secondary substations and LV power lines from the secondary substations to the customers. Some industrial customers may also get direct MV power lines. Associated to this infrastructure we consider also the SCADA system, which is a supervisory control and data acquisition system dedicated to the

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[1] Wireless Sensor and Actuator Networks for the Protection of Critical Infrastructures http://www.wsan4cip.eu/

[2] EDP Distribuição is the main company that carries out the function of electricity distribution operator in mainland Portugal.

infrastructure. Remote surveillance of the power grid is already done to some extent based on wired sensors. The use of wireless sensors can, however, lead to a more flexible and powerful protection scenario for the substations, power lines and power transformers. The deployment flexibility of WSAN allows capturing more status parameters than the currently deployed wired sensors and the wireless nature of the communication can contribute to avoid critical points of failure.
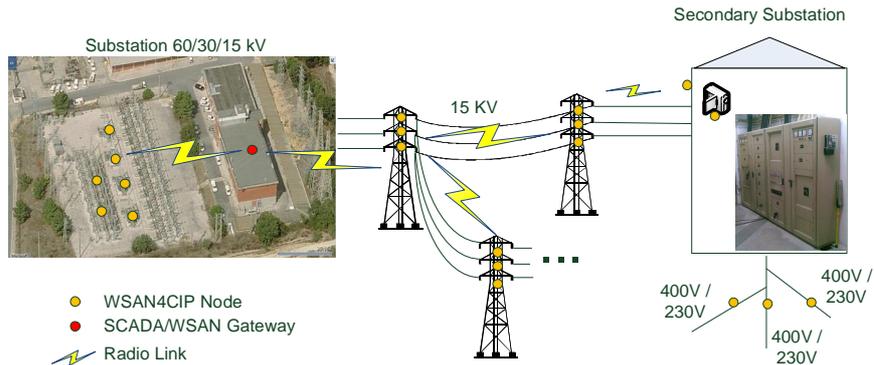

Fig. 1. WSAN for the electrical distribution segment of the power grid.

In the WSAN4CIP project we focused into improving the dependability of the substation components, MV and LV power lines, and MV/LV power transformers in the secondary substations. We have defined solutions for the remote active monitoring of: i) substation circuit breaker trip coil status; ii) temperature of the substation power transformer oil, substation neutral reactance oil and substation neutral resistor coil box; iii) MV and LV power line current activity; iv) MV/LV power transformer hotspot detection; v) human activity in the secondary substation through the use of movement detectors and video cameras. All the monitored parameters and images are visualized at the SCADA system, through a special-purpose graphical user interface.

The requirement for video transmission and the long distances between MV power line towers place additional requirements in terms of the communications and processing capabilities of the WSAN nodes, prompting the use of a broadband medium-range technology such as IEEE 802.11g for WSAN communications.

3   Wireless Sensor Nodes

Wireless sensor nodes include the sensor with the conditioning electronics, an IEEE 802.11g module, a DC-DC converter and an external power supply. WSAN4CIP has integrated two solutions: one based on a Silex SX-560 core[3] and a second solution based on a Beagleboard[4]. While video compression at the secondary substation requires a more powerful processing node such as the Beagle, scalar sensor

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[3] http://www.silexeurope.com/en/home/products/wireless-modules/sx-560.html
[4] http://beagleboard.org/

nodes can be based on a less powerful board such as the Silex SX-560 that requires less energy to operate (an energy analysis of the SX-560 is presented in [4]). The Beagleboard is also able to support a secure operating system. The inclusion of two different solutions allows also the demonstration of a heterogeneous scenario.

Sensor node PCBs integrating the Silex SX-560 SOC were developed at INOV. The external power supply is either MV power-line energy harvesting or 230 V AC, depending on the node. Conditioning electronics depend on the sensor type. Next subsections describe the hardware of the sensors for current intensity measurement, temperature measurement, and circuit breaker status detection.

3.1 MV current sensing node with energy harvesting

The MV and LV power line scenarios aim to monitor the status of particular power line sections. It is therefore possible to know centrally the location of a power line failure. The chosen MV power line has a voltage of 15kV and feeds a set of MV/LV power transformers in secondary substations. The line topology is a tree shape with several leaves consisting of secondary substations (see Fig. 1). The physical measurement to be done is the electrical current flowing through the line; a current transformer is used to measure its value and to derive a parasitic power source for the wireless sensor, reducing the power constrains on the wireless protocols through this energy harvesting technique. The current sensor samples the current on the line every second. This section describes the MV sensor only. The LV sensor is similar, but sensor nodes are in this case attached to public lamps, being fed directly from the monitored AC power line.

The electrical current flowing through each line (phase) is sensed and measured, using a current transformer (CT). The current to charge the battery is also obtained from the MV line, using the same current CT. Therefore, two working modes are defined for this WSN node: current sensing and energy harvesting. In the current sensing mode, the current in the line is estimated based on the current passing in the secondary winding of the transformer. The harvesting mode uses the secondary current to charge the battery. Modes are controlled by the microcontroller of the wireless module.

Fig. 2 depicts the block diagram of the circuit that implements the conditioning electronics and the energy harvesting from the line.

A CT is an instrument transformer intended to have its primary winding connected in series with the conductor carrying the current to be measured or controlled. In a window type CT, the secondary winding is insulated from and permanently assembled on the core, but no primary winding exists as an integral part of the structure. Primary insulation is provided in the window, through which one turn of the line conductor can be passed to provide the primary winding. A large current in the primary winding is reduced to a lower level to be more easily measured. The number of secondary turns determines the amplitude of the output current.

The used CT is a split core CT that can be temporarily opened to be place around existing wires, without disconnecting the primary circuit. Other specifications are:

minimal current value in the line is 5A; maximal current value is 300 A; and accuracy in current measurements up to 10%.
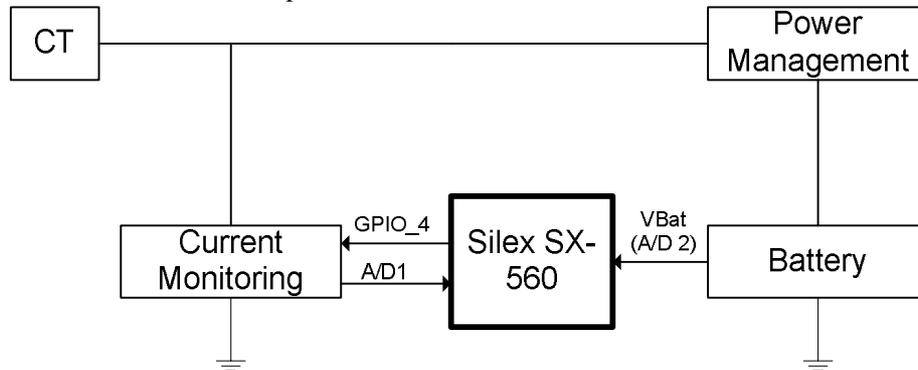

Fig. 2. Electronic circuit for current sensing and energy harvesting

The Hobut CTS80-1[5], with a ratio of 400/5 was selected. It supports a primary current up to 400A. This CT is suitable for three classes of accuracy: 0.5% up to 2.5 VA; 1% up to 6 VA; and 3% up to 10 VA, being adequate to the specifications for current measurement accuracy (10%).

The GPIO_4 signal (Fig. 2), from the microcontroller in the Silex SX-560 module, controls the energy harvesting and sensing modes. It switches on/off a NMOS transistor in the Current Monitoring module. When the transistor is switched on, the sensing mode is on and it avoids current to pass to the battery circuit. The voltage at A/D1 is converted by an ADC and sent to the microcontroller. It represents the secondary current, permitting to determine the current in the MV power line.

The transistor is switched off in the energy harvesting mode, when the current is allowed to flow to the battery. The battery charge can be monitored, reading VBat that is connected to an input port of the ADC.

The ADC (ADC122S021) is a two-channel 12-bit successive-approximation ADC converter, suitable for sensing applications, with a serial interface compatible with the Serial Peripheral Interface (SPI) of the SX-560.

The electronic circuit is enclosed in an aluminum alloy box with a cubic shape (Fig. 3). The aluminum box is completely covered with a Scotch™ 23 Electrical tape, a highly conformable Ethylene Propylene Rubber (EPR) based, high voltage splicing tape. It is a non-vulcanizing, shelf-stable tape with excellent electrical properties. Tape can be used as insulation for low-voltage applications as well as insulation for splices up to 69kV.

To guarantee high resistance to outdoor weather conditions, namely to humidity, rain and UV rays, the box is then painted with liquid silicon. This node was designed as to be suspended on a 15 kV aerial power line (Fig. 3).

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[5]   6.   http://www.hobut.co.uk/current-transformers/split-core-cts/series-80U

Fig. 3. MV power line current sensing wireless node.

3.2 Trip coil sensor and actuator

The trip coil is the component of the circuit breaker that permits to interrupt the electrical current flow, by applying 110 V at its terminals. After the activation of the circuit breaker, the coil can be damaged. A sensor and an actuator periodically evaluate the operating status of the circuit breaker. In order to verify the status of circuit breaker status, a 5 V DC voltage is applied every 60 minute by an actuator. If there is current flow, the coil is working properly.

To verify the existence of a current flow, a magnetic sensor is used. The selected sensor (KMZ10C) is a magnetic field sensor, employing the magneto-resistive effect of thin-film permalloy. Four sensors, connected in a Wheatstone bridge configuration, define the complete sensor. Conditioning electronics includes an instrumentation amplifier (MAX4208) with adjustable gain defined by two external resistors. The analog amplified voltage is converted to a digital value by an ADC that includes an internal sample and hold circuit. The digital signal is connected to the microcontroller of the Silex SX-560 Module by an SPI interface. As the 110 V DC voltage can be simultaneously applied to the coil terminals, a optocoupler is used to provide electrical isolation.

3.3 Temperature sensors

At the distribution substation, failures in power transformers affect a series of power lines and all the downstream secondary substations, resulting in problems for homes and businesses. Some failures can be detected just by monitoring the oil temperature of the 15 kV power transformers. The Neutral Reactance oil tank and Neutral Resistor coil box temperatures are also monitored as a means for failure detection. Their temperature can significantly rise during phase-earth failures during which these devices have to dissipate very high currents while the power line connectivity is not interrupted by the circuit breakers.

The selected sensor (LM70) is a silicon temperature sensor, detecting the voltage change across a *pn* junction. Temperature resolution is 0.25°C while operating over a temperature range of −55°C to +150°C. Depending on the temperature range, accuracy changes from ±2° up to +3.5/−2°C. The LM70 is an integrated circuit, including the temperature-sensing element, the signal conditioning electronics, an ADC con-

verter and the SPI serial data link. Therefore, it connects directly to the microcontroller of the Silex SX-560 module.

3.4 Video Surveillance, Intrusion and Hotspot Detector

This WSAN node is the result of mixing different technologies, all interconnected to a Beagleboard WSAN node:

- Video surveillance: Logitech's Quickcam Sphere AF Webcam connected through a USB interface. To ensure the goal in harsh illumination conditions, it was implemented a small device of illumination composed by a light-emitting diode (LED) device controlled through GPIO;
- Motion detection: passive infrared (PIR) sensor communicating through GPIO;
- Hotspot detector: IRISYS IRI 1011 Thermal Infrared Camera communicating through a RS232 serial data link. Due to unavailable RS-232 ports on the Beagleboard, the interface with the Thermal Camera was made with a RS-232 to USB adapter.

4 Tests and results

The current sensor was tested separately at special lab facilities before the WSAN integrated tests and trial deployment. This was due to the harsh electromagnetic conditions to which it would be subject during the trial, as well as the high costs of retrieval and redeployment. The other sensors were tested both in lab and *in situ*, i.e. already coupled with the monitored equipments. This section will cover the individual sensor performance tests. The integrated WSAN performance tests are described in another paper [1].

4.1 MV current sensing node

In order to find potential EMC (ElectroMagnetic Compatibility) problems, the wireless current sensor node was tested under exposure to the electromagnetic fields generated by the 15 kV power line. Fig. 4 presents the testing environment. Firstly, the node behavior was tested for voltages of 9kV, 13 kV and 20 kV. No problems were detected on the wireless communication or on the node functionality. Only for 20 kV, the corona effect [5] starts to be noticed.

Fig. 4. High Voltage Tests

Accuracy was also analyzed in the MV environment. Results are depicted in Fig. 5. Measured values present an offset to the theoretical values. Calibration was then done by software.
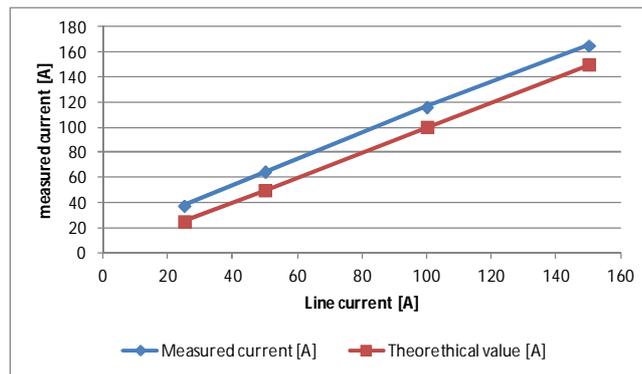

Fig. 5. Accuracy analysis for MV.

4.2   *In Situ* Accuracy Tests

For the current measurement tests, extra current was externally injected in the LV lines by the EDP technicians and the sensor reports were confronted against the known current injection values.

For the trip-coil, on-demand tests were performed while the trip-coil was operational. Then, the 110 V terminal was disconnected from the trip-coil to check whether the malfunction was automatically detected. The on-demand test was also repeated under this condition.

For the intrusion and hotspot detection tests, the respective situations were simulated by the EDP and INOV team. The tests entailed the transmission of images from the LV/MV power transformer to the primary substation. The corresponding SCADA screen is shown in Fig. 6. For the hotspot detection, a soldering iron was placed in

front of the camera, while for intrusion detection, a member of the EDP team simulated intrusions in a secondary substation.

The measurement precision test results are listed in Table 1 and Table 2. It should be noted that these results already have sensor calibration into account. Regarding the temperature measurements, the precision is high, with an average error of 1% and maximum of 3%. For the power line current measurements, the average error was 4.58% with peaks of 10.83%. This precision is enough to detect breakdown spots in the power-lines as well as to provide coarse reports about the distribution of current consumption within the EDP network. The remaining components feature a high precision.
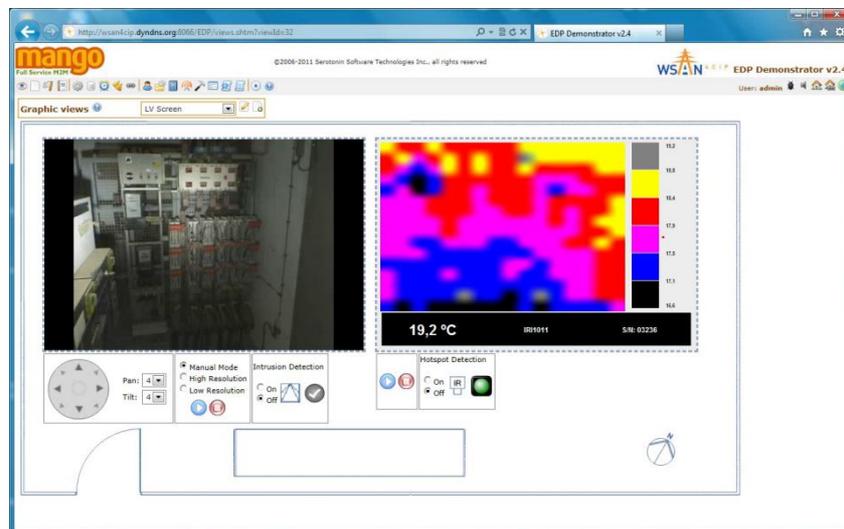

Fig. 6. SCADA screen.

5   Conclusions

This paper has presented the sensor node hardware that was developed and deployed in the demonstrator of FP7 project WSAN4CIP. Besides standalone tests, the sensors were also tested as nodes of the WSAN, both in-lab and in the deployed pilot system. Results of performed tests show that sensors performance is adequate. The energy harvesting mechanism implemented to recharge the WSAN node batteries demonstrated to be effective in powering sensors to measure MV power line activity.

Table 1. Temperature and Current Precision Evaluation.

Application	Number of Trials	Average Error	Maximum Error	Standard Deviation
Power Transformer Oil Temperature[6]	10	1.0%	3.0%	0.4%
Power Line Current	20	4.6%	10.9%	3.1%

Table 2. Event Precision Evaluation.

Application	Number of Trials	Measurement Errors	Success Rate
Trip Coil	24	0	100%
Intrusion Detection	11	0	100 %
Hotspot Detection	10	0	100 %

6 Acknowledgement

7 References

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[6] Temperature precision measurements were similar for the Neutral Reactance and Neutral Resistance components, since the sensor node is the same.