Wireless Sensor Network For Power Quality Monitoring According To IEC 61000-4-30

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Abstract **–** The paper proposes a distributed sensor network based on a wireless BlueTooth communication system or Power Quality (PQ) assessment in power systems. The architecture of the sensor node is described and characterized, together with the analysis of the measurement and communication procedure able to perform the PQ indices evaluation according the IEC 61000-4-30 norm.

I. Introduction

The necessity of online monitoring quantities spread on a wide geographical area have required the realization of intelligent measurement systems able to analyze and interpret large amounts of data into meaningful conclusions. The main element of these systems is a great quantity of low-cost, low-power, multifunctional micro-sensor devices able to measure quantities spread on a wide geographical area. The connection among these devices is usually called sensor network, while each element is called sensor node [1]. This sensor network (Figure 1) creates a smart environment with sensor node inter-communicating technologies that allows collecting, processing, analyzing and disseminating measurement data, permitting to access the information anytime and anywhere without a dedicate infrastructure and human supervision [2]. Networked microsensors technology is a key technology for the present and the future. In September 1999 [3], Business Week heralded it as one of the 21 most important technologies for the 21st century. Moreover, the improvement in the communication technologies has made possible the realization of wireless data networks. Cheap, smart devices with multiple onboard sensors, networked through wireless links or Internet, deployed in large numbers, provide unprecedented opportunities for instrumenting and controlling the environment [4]. Smart disposable microsensors can be deployed on the ground, in the air, under water, on bodies, in vehicles, and inside buildings. Usually each sensor node inserted in a sensing network is able to supervise different quantities and has embedded processing capability. Also onboard is the data storage, the wireless links to neighboring nodes and to the host and post-processing device. Current and potential applications of sensor networks include: military sensing, physical security, air traffic control, traffic surveillance, video surveillance, industrial and manufacturing automation, distributed robotics, environment monitoring, and building and structures monitoring. A possible interesting application of these sensor networks is the characterization of electrical distribution systems for the Power Quality (PQ) assessment. The interest about PQ is increasing all around the world, not only in consequence of the well known disturbance proliferation, but also in relation with the deep interconnection of electric networks, the less tolerance of equipments to voltage disturbances and, finally, the increased awareness of the detrimental effects of poor quality also from the economical point-of-view. The latter aspect is more evident in deregulated electric markets, where the new structure is characterised by a plurality of actors, interacting among them with contrasting or competing interests [5,6]. To this aim, the monitoring of the electrical system is needed. Moreover, monitoring electrical quantities acting on components is

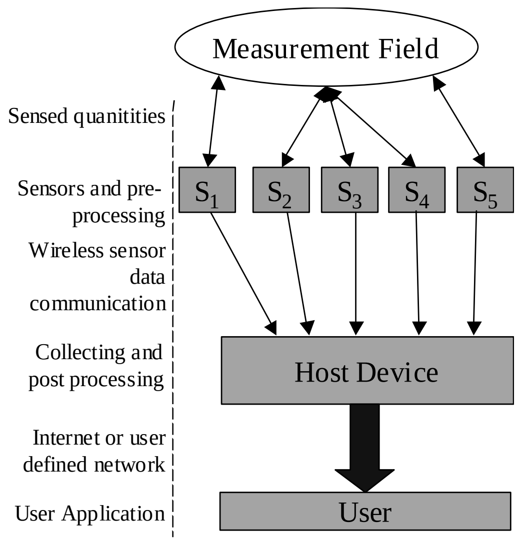


Figure 1. Example of a Sensor Network hierarchy.

the base of diagnostic systems that are becoming extremely valuable in the new liberalised energy market. In fact, utilities tend to leave managing criteria founded on the full redundancy and on the "time-based maintenance" rules for the adoption of the "condition-based maintenance" policy. In this approach, the component is substituted when it is reaching the actual end of useful life, strongly linked to both voltage and current disturbances [7,8], rather than in times predefined at design stage. In this scenario, a measurement system able to acquire variations and events evolving in an electrical system and to evaluate the PQ indices is strongly needed. To this aim, a suitable sensor network can be used. The authors, starting from their past experience on PQ assessment [8,9] and wireless measurement interface [10]-[12], propose a distributed measurement system based on a low-cost wireless sensor network able to implement measurement procedures for PQ indices evaluation according to IEC 61000-4-30 and IEC 61000-4-7 consequently [13-15]. Moreover, the measurement system is conceived to measure further quantities, not yet included in standards, but recognized as significant to assess PQ in a electrical system and to give indication for diagnostic purposes (e.g. duration, amplitude and frequency of voltage sags, voltage peak factor, and so on [16-18]). The measurement system can be used also inside an industrial environment, allowing a spatial characterization of PQ indices. The disturbances, in fact, propagate through the electrical network can assume different values in function of several parameters linked to the same disturbance nature and to the interaction with the supply system. The availability of a distributed measurement system can be then valuable for a twofold reason. From one hand, if susceptible devices are present in some nodes, these ones can be locally monitored to verify if the disturbance levels are still acceptable or not. From the other, if concentrated disturbing loads are present in some nodes, then their emission measurements can be helpful to properly avoid disturbance propagation in other nodes.

II. The Proposed System

The realized distributed measurement system is constituted by a sensor network, composed by a number of wireless smart sensors placed on the measurement field, and a controller device, realized by a suitable elaboration unit that manage the entire network, collects the acquired data, post processes and transmits the analyzed data to the user. Using the BlueTooth technology, a star network topology was adopted (*Piconet*), with up to 256 wireless sensors node (the slave modules) connected to a PC-based controller device (the master). The master can connect up to 7 active sensor nodes contemporaneously, while the other sensors must be maintained in a quiescent state called *park mode*. Because all BT communications must be managed by the controller, each sensor node communicates only with the controller and inter-sensor data exchange is not allowed.
As far as the application is concerned, each sensor node is located in different sections of the electrical system, and is able to pre-process the acquired data as required from the IEC 61000-4-30 norm, to store the measurement information and, finally, to communicate these ones to the controller device.
In the following, both the realized smart sensor node and the controller device will be described.

A. The realized wireless sensor node

The hardware of the sensor node consists of five components: (i) processor, (ii) sensing element, (iii) memory, (iv) transceiver, and (v) power supply (see Figure 2). Each component has been developed taking into account three basic requirements: a) low cost, b) low power consumption, c) high immunity to electrical disturbances and wireless channel failures. In the following, a description of each components is given.
(i) Heart of the proposed sensor node is the micro-controller module; its main functions are the data acquisition from the sensing element, the processing of the acquired data, the store of the processed data in the memory, and the transmission of the saved data on the wireless channel. The processor module has been realized using a Microchip PIC18F452 low power micro-controller, which main characteristics are: a 40 MHz operating

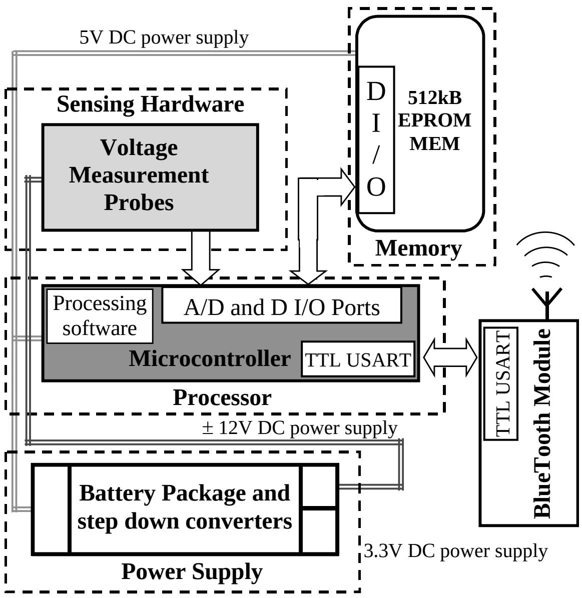
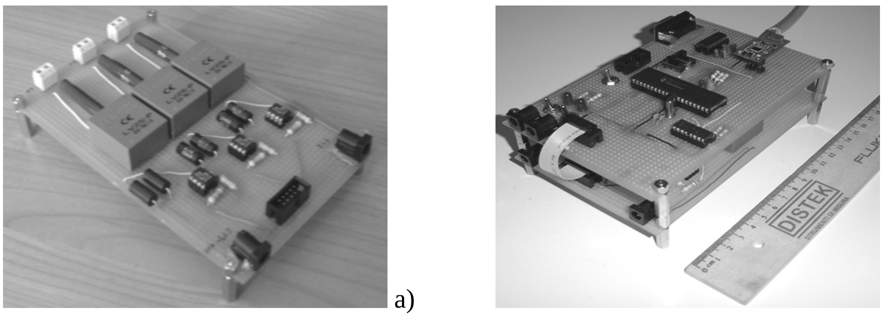


Figure 2. Schematic of the realized sensor node.

frequency, a multiplexed 8 channels analog-to-digital converter, a 32 kbytes program memory, a 1536 bytes RAM memory, one USART serial port and the I2C bus. A very important characteristics of the proposed micro-controller is the possibility to use some quote of the program memory with the RAM memory, allowing the storage of a large amount of program code and the right number of floating point variables required for evaluate PQ characteristic quantities reported in the IEC 61000-4-30 norm. A very useful feature of the used micro-controller is the possibility to operate in a low power consumption mode (*SLEEP mode*): during this phase the normal I/O processor activities are stopped and the maximum current required is less then 0.1 μA. The device can be waked-up from SLEEP mode in various way (an external reset, a watchdog timer wake-up, a change in the value of a particular I/O pin, at reception of data from the USART serial port). This features has been very important in order to realize the overall power saving procedures.
(ii) The sensing element is an ad hoc probe based on the LV-25P LEM voltage transducer (Figure 3a). This is a compensated closed loop voltage transducer using the Hall effect applicable to a RMS measuring voltage (Vpn) of 500V. This transducer is able to furnish a current signal proportional to the applied input voltage using a gain factor of 0.05mA/V, with a total accuracy of 0.9% and a linearity factor less than 0.2%. A response time of 40μS on the Vpn voltage allow about 4kHz bandwidth sufficient for the common PQ applications. Since the obtained bipolar output voltage range does not meet with the micro-controller 0-5 V A/D range, an ad hoc conversion circuit has been realized, using on a LT1006 single supply precision amplifier, 0.1% precision resistors and stable voltage regulators devices. Due to the presence of the ad hoc conversion circuit, in order to respect the IEC 61000-4-30 voltage transducer specifications, it was necessary to characterize the overall probe performance both for the amplitude gain accuracy and for the frequency bandwidth. The realized metrological characterization has been reported in the next section.
(iii) The memory module is constituted by two 512kbit Microchip 24FC512 serial EEPROMs, in order to obtain a total amount of available memory equal to 128kbyte. These devices communicate with the micro-controller via the I2C bus allowing a maximum clock rate of 1MHz. Also the memory module assures a low power consumption (27.5 mW and 2.2mW during the writing and reading operations respectively, and practically zero during the standby).
(iv) A BT module is used as the transceiver module. This is a 1.1 compliant class 1 Master/Slave module with an allowed maximum distance of 300m. A TTL compatible RS232 communication channel assures the communication with the TTL USART bus of the micro-controller module. The selected module allows a 3.3V power supply and has a power consumption of about 400mW during the connection phase.
(v) The battery package is composed by two high capacitance batteries sets providing the necessary +/-12V. The former, by the way of two high efficiency step-down circuits, supplies the micro-controller, the memory and transceiver modules, while the latter supplies the sensing hardware.
A photo of the whole realized sensor is reported in Figure 3b (the battery package is not reported). It can be noted the actual dimension of the realized sensor are very large due to unnecessary debugging circuitry. In its final version the sensor dimensions will be as low as a 10x10x5 cm parallelepiped. As far as the price of the sensor is concerned, it is possible to estimate a cost of about 50 Euro for an industrial production.

B. The controller device

As controller device, a PC-based system equipped with a master BT module was used. Suitable software modules have been developed to assure the administration of the entire network and the management of measurement data. In particular, the software implements all the functions necessary to the BT master module in realizing a “plug and play” wireless network where each device can be



a) b)

Figure 3. a) the realized sensing element; b) the realized sensor node.

automatically recognized and utilized whenever it goes into the sensor network or if polled by the user. Further, this software creates and continuously updates a database table that reports, for each sensor node, both all the acquired measurement information and the distinctive assigned logical address. The developed software performs the following steps:

i) at start up, all the powered-on sensor node are detected, recognized and classified;
ii) successively, for each sensor node (BT slave) an uniquely logical address is assigned;
iii) when the user wants to start a measurement procedure, two solution are implemented: (a) a single poll of a selected sensor node, (b) a global poll covering the whole network. If the (a) option is chosen, a single selected sensor is waked-up and its measurement session starts; in the case of (b) option, a broadcast command synchronizes the entire network and starts all the measurement routines on the sensor nodes. Details about will be given in the next section.
iv) at the end of the measurement session, all the sensor are placed in a low consumption state (park mode).

III. Metrological Characterization And Performance Analysis

A first metrological characterization has been done in order to evaluate both the sensor node performance and reliability. For the first aspect, the voltage probe accuracy, the sensor node measurement software and the wireless channel throughput have been examined. In order to the reliability analysis, is noted that the weakly point of the overall realized sensor is the BT transmission system, compared to the other relevant sensor parts (the voltage transducers, the micro-controller and the memory). In particular, causes of the BT transmission failure are the presence of noise, fading, interferences and obstacles on the wireless channel. For these reasons, the sensor reliability has been assessed analyzing the number of failures in different wireless communication situations.

A. The metrological characterization of the realized voltage probe

As described in the previous section, the performance of the realized voltage probe (see Figure 3.a) has been characterized. A suitable measurement station was build up (Figure 4). Two precision 6.5 digit Agilent 34401 digital multimeters and a Tektronics 520D digital scope were used to measure the input/output sensor signals; as the signal generation device, a precision high power arbitrary function generator (SIMULBUS) is used. The main characteristics of the SIMULBUS are: 5 kVA max output power, 2.5kHz bandwidth, 470 VRMS maximum output with 0.4% voltage accuracy, ± 5 ppm frequency stability, with the possibility to create arbitrary waveforms using all the frequencies multiple than the 16÷66 Hz fundamental harmonic.
A first experimental test was done in order to evaluate the gain accuracy. In this test, a 50 Hz sine wave with RMS values going from 200 to 460 V in 27 steps was used as reference signal. The measurement results have shown that the output characteristic of the realized voltage transducer can be assumed as linear, with a correlation coefficient of 0,99998, together with a gain factor of 3,6681 [mV/V] and an offset factor of 2,5223 [V] with standard deviations equals to 0,0030 [mV/V] and 0,0014 [V] respectively.
A second experimental test was done in order to evaluate only the realized level translator bandwidth. To this aim, an Agilent 33220A signal generator was used instead of the SIMULBUS generator, and the LEM module was shorted. The realized test has shown a –3dB bandwidth of 60 kHz; in the DC-4kHz range, a maximum ripple output is 0,00341 dB_V and a standard deviation of 0,00012 dB_V assure the goodness of the realized sensor probe in the common PQ applications.

B. The realized measurement procedure and software metrological characterization

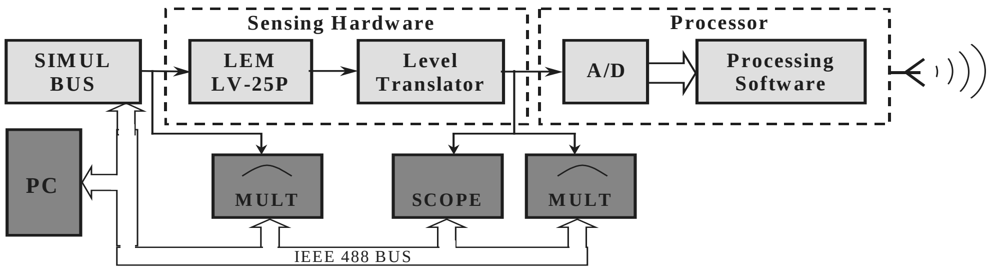


Figure 4. Measurement station for the voltage probe characterization.

The sensor node software was developed to respect the class A measurement methods defined in the IEC 61000-4-30 Standard for power supply systems. In particular, the realized sensor node is able to detect and analyse the following PQ phenomena: harmonic and interharmonic distortion, voltage dips and swells, and interruption. Regarding the first PQ phenomenon, in its actual state, the realized device is able to implements only the 3s time aggregation of the harmonic and interharmonic subgroups. This measurement is performed according to the IEC 61000-4-7:2002 standard, as recommended in the 61000-4-30 norm, so that the harmonic subgroups is computed as:

$$G_{sg,n}^2 = \sum_{k=-1}^{1} C_{10n+k}^2$$

where $G_{sg,n}$ is the n order harmonic subgroup, and C_{10n+k} is the RMS value of the voltage spectral line of order 10n+k obtained applying DFT algorithm on ten continues and gapless cycles of 20 ms. The interharmonic centred subgroups are computed as:

$$G_{ig,n}^2 = \sum_{k=2}^{8} C_{10n+k}^2$$

where $G_{ig,n}$ is the interharmonic centred subgroup of order n. To respect the requirements of Class A, the IEC 61000-4-30 flagging procedure is also applied for detecting dips, swells and interruptions. These events are identified using preassigned thresholds defined in percent of the declared voltage. If any of these events takes place, their number is stored. Proper event indices could also be computed, like for instance duration and depth of the dip; this first version of the device *does not cover also this evaluation.* It is worth noting that separated measurements of harmonics and interharmonic distortion can be effected by means of harmonic and interharmonic groups [13-15]. Here they are not presented since this last procedure is less time and computation consuming.

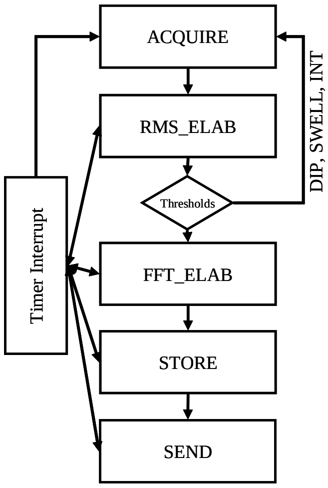


Figure 5. Block Diagram of the realized measurement procedure.

As far as the software aspect is concerned, the measurement procedure is based on several routines briefly schematized in Figure 5 and described in the following. The main routine is the ACQUIRE one. This is configured as a time interrupt based routine that grants the right acquisition time whatever is the actual device processing. This routine acquires one sample point of the input voltage signal, updates the calculated RMS value and stores the acquired data in the microcontroller RAM in the bit reversed sequence as required by DFT algorithm. At the end of the 20 ms acquisition time, the RMS_ELAB routine calculates the RMS value, and compares it with the above mentioned thresholds. If no dips, swells or interruptions are present, the measurement procedure continues; otherwise, the event is counted and the flagging procedure is applied. Once 10 cycles of 20 ms without events are collected, the acquired data are swapped in a processing array, and the FFT_ELAB routines is launched. This routine implements an in-place FFT algorithm on the 512 samples using a rectangular window. At the end of the harmonics and interharmonic subgroups measurement procedure, the STORE routine saves the processed data in the I2c EPROM memory, while the SEND routine transmits the data to the user. It is worth noting that the FFT_ELAB routine performs the required elaboration during the 200 ms acquisition phase (real-time elaboration), assuring the gapless data acquisition.

Table 1. The estimated sensor node performance

	Mean	**Std_dev**	**# of failures**
2 m distance closed			
$T_{INQUIRY}$	18191,4 ms	3,1 ms	0
$T_{CONNECTION}$	500 ms	64 ms	0
T_{SEND}	191 ms	11 ms	6
10 m distance closed area and wall obstacle			
$T_{INQUIRY}$	18176,5 ms	2,7 ms	0
$T_{CONNECTION}$	325 ms	26 ms	0
T_{SEND}	189,8 ms	6,8 ms	0
50 m distance open area			
$T_{INQUIRY}$	18173,4 ms	2,6 ms	2
$T_{CONNECTION}$	337 ms	13 ms	5
T_{SEND}	286 ms	20 ms	4

C. The sensor node throughput and reliability evaluation

The sensor node throughput can be defined as the amount of information that the sensor is able to dispatch in the time unit. As described in the previous section, each time the sensor node performs a valid 200ms (short term) analysis, it dispatch the

RMS and harmonic and inter-harmonic results to the network master module. In order to analyze the network throughput, the most important communication phases have been experimentally characterized by means of a suitable measurement station composed by a Tektronics TDS520d digital scope, a PC-based host station with a BT master module and one sensor node with a BT slave module. Three times defined as:

- $T_{inquiry}$, the time the sensor node require to respond to an inquiry command;
- $T_{connection}$, the time the master and the slave BT module need to perform a BT connection;
- T_{send}, the time required to transfer 1552 byte (the dimension of the obtained result);

have been estimated in 20 consecutive tests, executed at different distance between the master and the slave BT modules and different operative connection (open and closed areas). The obtained results are reported in Table I, which reports also the number of failures in each transmission operation.

V. Conclusion

The paper proposes a wireless sensor network able to perform the acquisition and elaboration of voltage signals in elecrical systems in order to evaluate the PQ indices according to the IEC 61000-4-30 norm. The wireless solution adopted, based on the BlueTooth thecnology, together with the performed choiche of the measurement and elaboration devices, makes the realized measurement system to be a good compromise between a good performance and a very low cost. This is important for an large scale adoption in all the situations (expecially when the sensor displacement is very difficult) that requires a punctual electric system analysis from a PQ characterization point-of-view without adopting specialized expensive instruments. The tests carried out on the sensor node prototype confirm the apparatus goodness also in terms of linearity, bandwidth and reliability.

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