Perpetual and low-cost power meter for monitoring residential and industrial appliances

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***Abstract*—The recent research efforts in smart grids and residential power management are oriented to monitor pervasively the power consumption of appliances in domestic and non-domestic buildings. Knowing the status of a residential grid is fundamental to keep high reliability levels while real time monitoring of electric appliances is important to minimize power waste in buildings and to lower the overall energy cost. Wireless Sensor Networks (WSNs) are a key enabling technology for this application field because they consist of low-power, non-invasive and cost-effective intelligent sensor devices. We present a wireless current sensor node (WCSN) for measuring the current drawn by single appliances. The node can self-sustain its operations by harvesting energy from the monitored current. Two AAA batteries are used only as secondary power supply to guarantee a fast start-up of the system. An active ORing subsystem selects automatically the suitable power source, minimizing power losses typical of the classic diode configuration. The node harvests energy when the power consumed by the device under measurement is in the range 10W÷10kW, which also corresponds to the range of current 50mA÷50A drawn directly from the main. Finally the node features a low-power, 32-bit microcontroller for data processing and a wireless transceiver to send data via the IEEE 802.15.4 standard protocol.**

***Index Terms*—Wireless sensor networks, smart metering, energy harvesting, active ORing, energy measuring.**

I. Introduction

In recent years the efforts of the scientific community in the field of electrical energy distribution and management have moved in two directions, namely Smart Grids and Smart Metering. The driving factor is the constantly increasing demand for energy from industrial, commercial and domestic customers while the available energy resources are going to exhaustion. Moreover, an irresponsible usage of the electrical energy and the poor quality of the power supply transmission determine waste of energy and low reliability of distribution systems. All these reasons lead to envision a new, intelligent way to produce, to distribute and to use the energy. The term Smart Grid, coined by [1], refers to the usage of the Information Technology for the power grids of the future, which will integrate the existing power generation systems with large- and small-scale production of energy from renewable sources. Concurrently, innovations have been addressed also at the side of the consumers. Smart Metering is one of the most important to promote more accurate management of the resources and to grow new awareness about the cost of the energy. For example, measuring and profiling the power consumption of any single appliance helps to reduce waste of energy [2].

In such a context, wireless sensor networks (WSN) and energy harvesters play a key role. Indeed, both Smart Grids and Smart Metering applications require distributed and real-time monitoring facilities for the elements of a power grid and user's appliances [3]. In fact, next-generation measurement systems must feature a small form factor, must be non-invasive and easy to install, and must be cost-effective in terms of production and maintenance, because of the large number of expected measuring points. Since wireless sensor nodes and standalone embedded systems are usually battery powered, energy harvesting capability becomes a strict requirement to reduce costs of battery replacement. Energy Harvesting technologies have gained increasing interest over the last years and in particular powering embedded systems with energy converted from the surrounding environment [4]–[7].

In this paper we introduce an innovative wireless current sensor node (WCSN) with self-sustainable capability for smart metering applications. It embeds two clamp-on Current Transformers (CT): one is used for the measurement of the current consumption and the second one to harvest energy. The clamp-on transformers are non-invasive sensors because they wrap around the power cable and make the node very easy to install. The WCSN is designed to measure the current drawn by a wide set of appliances. It measures power consumption from 10W up to a maximum amount of 10kW. In other terms, it can acquires and convert current values in the range 50mA÷50A when appliances are plugged to the main AC. The key feature of the sensor node is the energy harvesting subsystem that scavenges energy from the whole range of measurable currents, making the sensor node fully autonomous. Two AAA batteries are provided as backup energy source to avoid shut-down when appliances are not powered and to guarantee the start-up operations. One of the two power sources is automatically selected by an active ORing system. This active configuration, based on MOSFETs with very low on-state resistance, reduce the voltage drop and the power losses with respect to the diode-passive topology. The data acquired from the current transformer are processed by a low-power, 32-bit microcontroller and transmitted using IEEE 802.15.4 wireless standard protocol.

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The paper is organized as follows: Section II and III presents an overview of the challenges in Smart Metering systems and the state of the art in designing fully autonomous sensor nodes for current metering. Section IV shows a detailed description of the implementation of the proposed sensor node. In Section V, we discuss the experimental results, while Section VI concludes the paper.

II. Smart Metering: background

A number of leading energy companies worldwide are spending enormous research effort to improve efficiency of the energy usage and into reducing energy consumption through smart meters for residential and commercial buildings [8]. One of the most important goals of smart metering in buildings is to suggest optimal schedules of electrical loads to meet established targets (e.g. to save energy, to equalize the demand, or for forecasting peaks of energy consumption).

Meter manufacturers are going on the market with a differentiated offer: both low-cost metering solutions suitable for large scale distributed monitoring of households, and high-end smart meter devices used for accurate and scientific measurements such as the quality of the energy provided. Moreover, manufacturers must account for the varying regulatory requirements of each region, as well as the different functionalities and services required for different markets. For example, as discussed in [9], automated meter reading regulations impose specific sampling rates and data transmission. Smart meters need to keep a small amount of data stored on-site because communications are not always reliable to meet billing requirements [10]. This increases the cost and the on-chip features necessary for smart meter ICs. As a result, the regulatory pressures of specific jurisdictions have a direct impact on the design of new smart meters down to the chip level. Usually these issues are addressed by using integrated System-on-Chip (SoC) solutions which are configurable and provide a rich feature sets for smart metering with minimum hardware components. SoC approach includes sensors, A/D conversion, microcontroller (MCU), communication interface and memory. Typically, MCU is used to perform the system management and multiple ADCs combined with signal analysis are used to handle the metrology functions [11].

Commercial ICs that perform energy measurement are surveyed in [12]. For example, Microchip MCP3905 supports real power measurement using two ADC channels optimized to perform both measurement of current and voltage. A fixed-function DSP block is on-chip for real power calculation. The output is a pulse sequence whose frequency is proportional to the power. Analog Devices ADE7953 measures line voltage and current, and calculates active, reactive, and apparent power, as well as instantaneous RMS voltage and current. It provides high accuracy electrical energy measurement IC intended for single phase applications. The device incorporates three ADCs with a high accuracy energy measurement core and provides access to on-chip meter registers through a variety of communication interfaces such as SPI, I2C, and UART. NXP EM773 energy metering IC is a 32-bit MCU solution designed specifically for electricity metering applications. In detail the EM773 is an ARM Cortex-M0 based, low-cost 32-bit energy metering IC, designed for 8/16-bit smart metering applications. Many MCU manufacturers develop highly-integrated ADCs for multi-phase applications. For example, the ADCs on AFE family, from Microchip, use hardware logic to perform synchronous sampling. The MCP3903 AFE provides six synchronously sampling ADCs for three-phase energy measurement. In a similar manner, Atmel 78M6631 energy measurement device contains all the hardware necessary (sampling and conversion elements) to implement a high-precision three-phase ADC.

Another fundamental feature is the communication technique to transmit data to the energy company or across a Home Area Network (HAN), which is usually the definition of the dedicated network connecting devices and appliances in a home [13]. The possibility of creating a in-home network of smart meters, or a network between households in the same neighbourhood, permits to monitor and control residential equipments both locally as well as aggregated. Depending on the number of smart meters in a HAN, the existing solutions for load power monitoring can be classified into two groups:

- The *distributed approach* requires that a smart meter is installed in any device of the HAN. Data is then transmitted to a central point. Commercially solutions typically are available as smart plug meters. They measure the power consumption of each appliance on-site and propagate the consumption values wirelessly to a central gateway.
- The *centralized approach* [14] is used to monitor an electrical circuit that contains a number of appliances by using only one metering instrument which estimates the number and type of the individual loads, their individual energy consumption and other relevant parameters such as time-of-day variations, through an on-site complex analysis of the current and voltage waveforms of the total consumption. Single smart meter systems are easier to deploy but often rely on expensive custom hardware and require either a priori knowledge about the household appliances and their electrical characteristics, or they require a complex training phase involving the users.

Two types of networking techniques are usually exploited in a Home Area Network [15]. One is designed to directly transmit data over power lines by using the numerous electrical outlets in a home. The other networking alternative is to use wireless transmission to send and receive data, but at a much lower data rate than typical WLAN.

Power Line communication (PLC)

PLC [16] uses existing electrical installation by overlapping the radio frequency band of 3kHz - 30MHz over the 50Hz power frequency to communicate digital information. PLC is used in smart buildings to locally or remotely control electrical appliances without needing to install new structures. The speed of these networks is 14-45 Mbps for indoor environments and can reach 224 Mbps for outdoor communication. The mainstream protocols in PLC technology are X-10, LonWorks or KNX that support different kind of physical layer and, finally INSTEON, HomePlug and PLC-BUS. INSTEON and PLC-BUS are proprietary standards that delays their adoption to some extent. INSTEON and PLC-BUS are proprietary standards that delays their adoption to some extent. The main problems related to PLC are signal attenuation and signal distortion caused by the interference from the network and the connected electrical devices thus introducing lack of reliability in data transmission in security.

Wireless Protocols

Due to the complexity and cost of re-wiring and potential retrofit in a house, a variety of short-distance wireless technologies are emerging to provide flexible networking patterns convenient to residents without the considerations of physical wiring and deployment. These technologies, including Bluetooth, ZigBee and Z-Wave, mostly work in the Industrial Scientific Medical Bands (ISM Bands), especially the 2.4GHz frequency range. As a proprietary protocol, Z-Wave suffers from the same problem as INSTEON and PLC-BUS. In terms of the control network in a smart home, the commonalities of wireless technologies are associated with low speed, low power consumption, high cost effectiveness, flexibility in networking and deployment as well as the coverage of the building.

By leveraging the flexible SoC features and the communication protocols available to the designers, manufacturers have a wide design space to effectively address the range of metering options: from low-cost solutions to top meters which offer wider memory, higher configurability, reliable network protocol and higher accuracy of the measure. As the research and the market for smart meters evolve, this flexibility will permit energy companies to tailor to the needs of customers and the dictates of regulatory authorities, and still optimizing operational efficiency and profitability.

III. Energy Harvesting for Smart Metering

Monitoring active and apparent power in smart metering applications is certainly the most important task to promote effective energy polices; therefore recent research efforts are directed to the current sensor nodes and transducers design. Cai *et al.* in [17] present a prototype of self-sustainable wireless current and voltage meter to monitor the load on the distribution line in Smart Grids. The current sensor is an air coil tested to sense up to 200A of current. The power consumption is high due to the presence of a GPS receiver for time-stamp, starting from 400mW in idle state, it raises to 1300mW during transmission. To achieve autonomous operations, they use two energy harvesters based on cubic shape coil which can deliver an output power of 744mW with an input current of 170A.

The stick-on wireless sensor node presented in [18] combines current and temperature sensors and is intended to monitor a variety of utility assets. This prototype is a battery-less device equipped with a ZigBee module and a 1F super-capacitor used as backup source to perform critical operations during power outage. The system exploits an application-tailored flux concentrator for reading and harvesting tasks. A novel boost converter is used to convert and step-up the low AC output voltage of the flux concentrator. The node consumes few tens of microampere in idle state and about 30mA in transmission. It cannot work with primary currents lower than 60A, while operating with a duty cycle of 60s with a primary current below 100A.

In [19], authors have designed and prototyped a very accurate autonomous voltage and current measurement unit which can sense AC voltage in the range 100V$\div$1000V and AC current in the range 1A$\div$1000A with an error less than 1% full scale. The supply system consists in two circuits operated in parallel which can harvest energy respectively from measured voltage and current. The operating range of the harvester spans from 5A to much more 350A, nevertheless the most considerable drawback of this solution is the lack of wireless communication.

All the aforementioned works are suitable for grid-level monitoring in which currents are in the order of tens or hundreds of amperes. In contrast to such systems, the IEEE 802.15.4-compliant wireless smart meter presented in [20] features a device-level sensing granularity. In other words it allows to monitor the energy consumption of single appliances with a power consumption up more than 1kW and it can switch-off the appliance under control simply driving a solid-state relay. Even though the system is realized with low power components it does not perform energy harvesting but is powered by mains exploiting a small transformer. The total power consumption spans between the 140μW of the idle state and the 190mW of the radio transmission.

However, the trend is to reach perpetual operation of smart meters. In [21] a battery-free energy harvester is implemented on-chip by using 0.25-μm CMOS process. The harvester convert the AC signal coming from a Rogowski coil by means of an active rectifier and a set of boost converters. Such conversion technique, combined with a switched capacitor sampler, suppresses the total harmonic distortion and improves the power factor making this system good for power measurement. As the system is battery-free, a proper circuit is provided to guarantee the startup operations when the appliances are powered up. Nevertheless, it does not feature wireless communications or smart operations.

Finally, it is worth to mention that some products are already available on the market. To the best of our knowledge they can perform approximate analysis without any wireless capability and can generate only an alarm when the power consumption of a building rises above a certain threshold.

Table I summarizes the majority of the wireless sensor meters with energy harvesting capability presented in literature. They are designed to monitor power grids or electrical assets and thus the current under measurement is quite high. Indeed, nodes with lower sensing granularity and used to measure residential appliances are usually powered directly from the main.

TABLE I
SUMMARY OF MAIN ELECTRICAL FEATURES OF NODES CITED IN SEC. III

Reference work	Primary Current [A]	Harvested Power [mW]	Power Consumption [mW]
[17]	$\geq$100	$\geq$270	400 $\div$ 1300
[18]	$\geq$60	N.A.	0.4 $\div$ 100
[19]	5 $\div$ 350	N.A.	N.A.
[20]	$\leq$5	No Harvesting	0.14 $\div$ 190
[21]	N.A.	N.A.	N.A.

TABLE II
VALUES OF R_{MEAS}, POWER AND RESOLUTION

R_{MEAS}	Maximum Power	Resolution
560 Ω	1 kW	<1 W
270 Ω	2 kW	1 W
150 Ω	5 kW	2.5 W
80 Ω	10 kW	5 W

IV. SYSTEM DESCRIPTION

The wireless node for current measuring exploits two clamp-on current transformers and its architecture consists of four blocks: i) the current sensing section, ii) the energy harvester, iii) the active ORing system and finally iv) the MCU and wireless transceiver.

A. Current Sensing Section

The adopted current transformer features linear performance over a wide range of input currents and it is easy to install because it does not require any interruption or cutting of wires. Moreover it offers galvanic isolation since it decouples the digital circuit on the secondary side from the high voltage input. The main electrical characteristics of the selected sensor are the number of turns n=3000 and the maximum input current of 60A which corresponds to a maximum current of 20mA on the secondary side.

In Figure 1 we show the schematic of the measurement circuit. The current coming from the inductive coupling is converted to a proportional voltage by means of a precision resistor R_{MEAS} connected in parallel to the secondary side. The values of current that can be measured strictly depend on the value chosen for R_{MEAS}. The optimal values of the measure resistance are listed in Table II with the relative range of measurable power and resolution. The resistance values are calculated with the aim of maximize the span and optimize the accuracy of each power range.

The voltage obtained from the CT conversion is acquired and elaborated by the 32-bit microcontroller. As the 12-bit ADC is single-ended, we introduced a voltage divider formed by R_1 and R_2 which biases the voltage to positive values. The signal V_{REF} is generated by the DAC and it is possible to switch-off the bias and to save the power dissipated by the resistors during the sleep time.

Many residential and industrial appliances are non linear loads and typically they have switching regulators just after a rectifier bridge and an input filter capacitor used as a peak detector. The current charges the capacitor only when the instantaneous AC voltage exceeds the voltage of the capacitor.

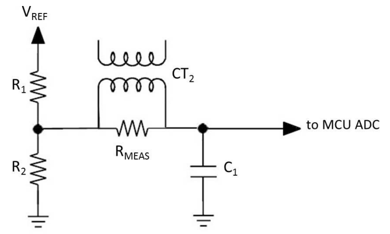

Fig. 1. Schematic of the current sensing circuit.

A single phase appliance draws actually the current during a time interval much smaller than the cycle driven by the 50-60Hz of the main, and this increments the RMS of the current and generates a harmonic content which is not considered by the simple phase lag φ.

The Power Factor (PF) value measures the contribution of both the phase lag φ and the high frequency content of the input current. This harmonic content, as well as the phase lag φ, is regulated by the European Standard EN 60555, which defines the limits and the constraints for appliances and mains.

To this purpose, the ADC samples with a frequency of 12.5kHz and the digital values are elaborated from the micro-controller. A raised Cosine Filter (RCF) is added to reduce the noise and the influence of frequencies which can be neglected in the assessment of the Power Factor. The filter is designed as a Finite Impulse Response (FIR) topology. While a Discrete Fourier Transform (DFT) has been implemented to assess the harmonic content which affect the PF. More precisely we evaluate the contribution of frequencies up to the 7^{th} harmonic component.

B. Energy Harvester

The energy harvesting circuit, shown in Figure 2, exploits an additional dedicated clamp-on (CT_1) current transformer as energy transducer. The transformer harvests a current of about 5mA when a primary current of 13A is consumed by the appliance, while a current of about 700μA is delivered with a primary current of 2A.

The AC to DC converter is a full-wave passive rectifier. It is realized by four Schottky diodes ($D_1 \div D_4$) with very low forward voltage to minimize power losses across the bridge. The energy buffer is a 0.47F electric double layer capacitor (C) with ultra-low internal resistance.

C. Active ORing

The power supply schematic in Figure 2 shows that the V_{CC} signal used to power the WCSN can be derived from two different sources: the energy harvester and two additional AAA batteries (B). These batteries are used as reservoir energy source to guarantee the system start-up. The switching between the energy harvester and the batteries must be automatic, fast and power efficient. For these reasons we implemented it by an active ORing system.Usually, the most simple ORing topology is built with a passive diode for each energy source and the resulting signal is given by the source showing the greatest voltage level decreased by the diode threshold. However, to

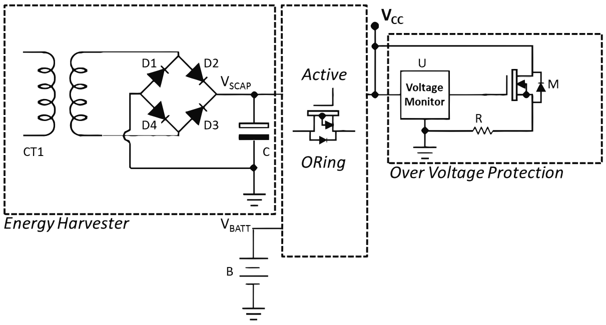

Fig. 2. Power supply schematic of the wireless current sensor node. A low-loss, low-power active ORing system generates V_{CC} by selecting the suitable source between the backup battery and the energy harvester. An over voltage protection is provided to avoid MCU and radio transceiver damages.

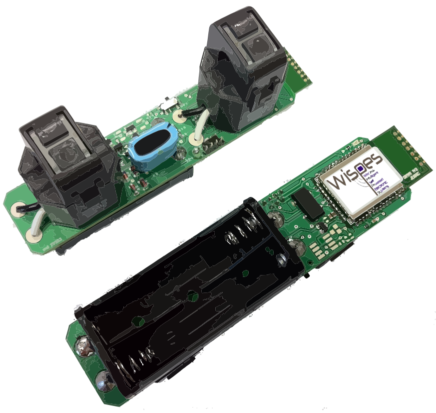

Fig. 3. Top and bottom view of the WCSN hardware prototype used in laboratory test.

remove the voltage drop introduced by the diode and to improve the efficiency, we implemented an Active ORing, at the cost of a more complex circuit.

D. MCU and Wireless Transceiver

A wide range of microcontrollers and radio transceivers are available on the market for a variety of metering applications. Our architecture is based on the JN5148 module from NXP, which provides an ultra-low power, high performance wireless microcontroller targeted to WSN applications, a 512kB serial flash memory and a real-time clock. The microcontroller features an enhanced 32-bit RISC processor, a 2.4GHz IEEE 802.15.4 compliant radio transceiver, 128kB ROM, 128kB RAM, and a complete set of analogue and digital peripherals such as a 12-bit ADC, a 12-bit DAC, a SPI interface etc. The key features of the JN5148 module are the very low sleep current, only 2.6μA and the low power consumption of the radio transceiver, namely at 3.0V it draws 15mA during transmission and 17.5mA when receiving.

V. Experimental Results

The performance evaluation is focused on the energy harvester and on the sensing circuit. We used a prototype shown in Fig. 3.

TABLE III

Energy harvester performance for different appliances

Appliance	P_{in} [W]	I_{in} [A]	I_{out} [mA]
Television	70	0.300	0.102
500W lamp	500	1.930	0.642
Oven	2000	8.600	2.856
Dishwasher	2500	10.840	3.610
Washing machine	3000	13.020	4.321

A. Energy harvester

The tests on proposed device started with the energy harvester performance evaluation. We emulated the power consumption (P_{in}) of real appliances by means of a variable power resistor, and then we measured the current in the primary circuit (I_{in}). Next we measure the current delivered by the harvester and charging the supercapacitor (I_{out}) by connecting the emulated appliances to the energy harvesting circuit. The results are listed in Table III.

The application firmware takes about 200ms for voltage sampling, data filtering and elaboration and radio transmission. Considering V_{CC}=3.0V, in this time interval the total power dissipated by the microcontroller and by the active peripherals including the radio transceiver is about 150mW, thus the energy demand is about 30mJ. When the node is inactive (sleep mode), most of the on-board components are switched-off and the WCSN consumes less than 30μW. Therefore, if the sleep time is properly calculated, the energy harvested during the sleep time balances the amount necessary for a measurement and a packet transmission; in other words a adjusted duty-cycle permits self-sustainable operations on the node. Clearly, shorter sleep intervals necessitate the intervention of the backup batteries to compensate the energy not scavenged by the CT. Moreover, appliances with higher power consumption permit the CT to deliver higher power, hence the sleep interval necessary to harvest enough energy for a measurement is shorter and the duty-cycle could increase. The graph plotted in Figure 4 shows the curve of the optimum sleep time as a function of the power dissipation of the appliances. The curve is obtained with experimental data and it shows that any appliance with a specific power consumption, is characterized by a specific duty-cycle which permits to obtain a perpetual measurement activity without the need of batteries.

B. Accuracy of the measurement circuit

Finally we evaluated the error in the current measurements. We firstly measured the current drawn by a set of appliances using a calibrated current meter, namely the Agilent U1193A. Then we performed the same measurement using our wireless current sensor node. Table IV shows that the maximum error of the WCSN is 1.6%. It is mainly due to the harmonic content of the measured current which contains a significant contribution at frequencies over to the 7^{th} harmonic component. The results and the accuracy achieved are however very good considering that the cost of the proposed system is much lower than equivalent battery operated measuring systems.

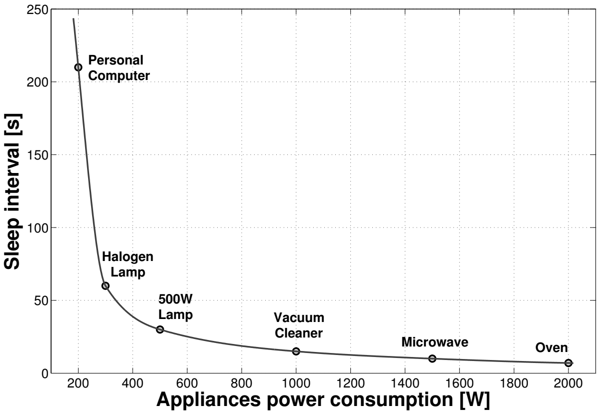

Fig. 4. Optimized sustainability curve. For a given appliance power consumption the curve returns the minimum sleep time interval to guarantee sustainable operations

TABLE IV
EVALUATION OF CURRENT MEASUREMENT ERROR

Appliance	U1193A [A]	WCSN [A]	Error [%]
Personal Computer	0.820	0.828	0.97
Halogen lamp	1.270	1.250	1.6
500W lamp	1.890	1.900	0.53
Vacuum cleaner	3.850	3.820	0.78
Microwave	4.690	4.765	1.6
Oven	7.650	7.580	0.92

VI. CONCLUSION

In this work a low-cost wireless current sensor node is proposed to monitor residential and industrial appliances. It is very easy to install because it exploits two clamp-on transformers and it can monitor AC loads in the range 10W÷10kW. The maximum measurable power and the resolution are programmable by changing the value of a proper resistor. The WCSN is powered by the appliance under test thanks to the efficient energy harvester featured and, in addition, backup batteries are provided to guarantee fast start-up operations.

Experimental results demonstrate that the WCSN can perpetually operate if a proper sleep time, which depends on the device under measurement, is set. The dependence on the batteries is minimal, since they are only necessary if the appliance is switched off for long intervals. Finally, the accuracy of node has been extensively characterized by measuring the current consumption of a set of appliances in the range 200W÷2kW and the maximum error, with respect to a calibrated instrument, is limited to 1.6% when the measured current contains a significant harmonic content.

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REFERENCES

[1] S. M. Amin and B. Wollenberg, "Toward a smart grid: power delivery for the 21st century," *IEEE Power and Energy Magazine, 2005*, vol. 3, pp. 34–41, Sept - Oct 2005.

[2] S. Ahmad, "Smart metering and home automation solutions for the next decade," in *Proc. of the international conference on Emerging Trends in Networks and Computer Communications, 2011 (ETNCC 2011)*, Apr 22-24 2011, pp. 200–204.

[3] V. Gungor, B. Lu, and G. Hancke, "Opportunities and challenges of wireless wensor networks in smart grid," *IEEE transaction on Industrial Electronics, 2010*, vol. 57, pp. 3557–3564, Oct 2010.

[4] D. Dondi, A. Bertacchini, L. Larcher, P. Pavan, D. Brunelli, and L. Benini, "A solar energy harvesting circuit for low power applications," in *Sustainable Energy Technologies, 2008. ICSET 2008. IEEE International Conference on*, nov. 2008, pp. 945 –949.

[5] D. Carli, D. Brunelli, D. Bertozzi, and L. Benini, "A high-efficiency wind-flow energy harvester using micro turbine," in *Power Electronics Electrical Drives Automation and Motion (SPEEDAM), 2010 International Symposium on*, june 2010, pp. 778 –783.

[6] D. Brunelli, D. Dondi, A. Bertacchini, L. Larcher, P. Pavan, and L. Benini, "Photovoltaic scavenging systems: Modeling and optimization," *Microelectronics Journal*, vol. 40, no. 9, pp. 1337 – 1344, 2008.

[7] D. Porcarelli, D. Brunelli, M. Magno, and L. Benini, "A multi-harvester architecture with hybrid storage devices and smart capabilities for low power systems," in *Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), 2012 International Symposium on*, june 2012, pp. 946 –951.

[8] S. Depuru, L. Wang, V. Devabhaktuni, and N. Gudi, "Smart meters for power grid, challenges, issues, advantages and status," *Power Systems Conference and Exposition (PSCE), 2011 IEEE/PES*, march 2011.

[9] F. Benzi, N. Anglani, E. Bassi, and L. Frosini, "Electricity smart meters interfacing the households," *Industrial Electronics, IEEE Transactions on*, vol. 58, no. 10, pp. 4487 –4494, oct. 2011.

[10] A. Kiani and A. Annaswamy, "The effect of a smart meter on congestion and stability in a power market," *Decision and Control (CDC), 2010 49th IEEE Conference on*, dec. 2010.

[11] S. Bruno, S. Lamonaca, M. La Scala, G. Rotondo, and U. Stecchi, "Load control through smart-metering on distribution networks," *PowerTech, 2009 IEEE Bucharest*, pp. 1 –8, july 2009.

[12] X. Jiang, S. Dawson-Haggerty, P. Dutta, and D. Culler, "Design and implementation of a high-fidelity ac metering network," *Information Processing in Sensor Networks, 2009. IPSN 2009. International Conference on*, pp. 253 –264, april 2009.

[13] M. Huq and S. Islam, "Home area network technology assessment for demand response in smart grid environment," *Universities Power Engineering Conference (AUPEC), 2010 20th Australasian*, dec. 2010.

[14] M. Zeifman and K. Roth, "Nonintrusive appliance load monitoring: Review and outlook," *Consumer Electronics, IEEE Transactions on*, vol. 57, no. 1, pp. 76 –84, february 2011.

[15] N.-H. Nguyen, Q.-T. Tran, Leger, J.-M., and T.-P. Vuong, "A real-time control using wireless sensor network for intelligent energy management system in buildings," *(EESMS), 2010 IEEE Workshop on*, Sept 2010.

[16] C. Jin and K. T, "Smart home networking: Combining wireless and powerline networking," *Wireless Communications and Mobile Computing Conference (IWCMC), 2011*, pp. 1276 –1281, july 2011.

[17] F. Cai, E. Farantatos, R. Huang, A. S. Meliopoulos, and J. Papapolymerou, "Self-powered smart meter with synchronized data," in *Proc. of the IEEE Radio and Wireless Symposium (RWS 2012)*, Jan 15-18 2012, pp. 395–398.

[18] R. Moghe, Y. Yang, F. Lambert, and D. Divan, "Design of a low-cost self powered stick-on current and temperature wireless sensor for utility assets," in *Proc. of the IEEE Energy Conversion Congress and Exposition, 2010 (ECCE 2010)*, Sep 12-16 2010, pp. 4453–4460.

[19] Z. Kolodziejczyk, P. Michalski, and W.Kardi, "Novel autonomous voltage and current measurement unit for smart grids," in *Proc. of the Int. Symposium on Power Electronics, Electrical Drives, Automation and Motion, (SPEEDAM 2012)*, Jun 20-22 2012, pp. 780–784.

[20] A. Reinhardt, D. Burkhardt, P. Mogre, M. Zaheer, and R. Steinmetz, "Smartmeter.kom: A low-cost wireless sensor for distributed power metering," in *Proc. of the IEEE 36th Conference on Local Computer Networks, 2011 (LCN 2011)*, Oct 4-7 2011, pp. 1032–1039.

[21] T.-C. Huang, Y.-Y. Yang, Y.-H. Lee, M.-J. Du, S.-H. Cheng, and K.-H. Chen, "A battery-free energy harvesting system with the switch capacitor sampler (scs) technique for high power factor in smart meter applications," in *Proc. of the 19th IEEE/IFIP international conference on VLSI and System-on-Chip, 2011 (VLSI-SoC 2011)*, Oct 3-5 2011, pp. 359–362.