Self-Powered Wireless Sensor for Air Temperature and Velocity Measurements With Energy Harvesting Capability

Emilio Sardini, *Member, IEEE*, and Mauro Serpelloni

***Abstract*—Air temperature and velocity measurements are important parameters in many applications. A self-powered sensor placed in a duct and powered by an electromechanical generator scavenging energy from the airflow has been designed and tested. It periodically transmits the measured air temperature and velocity to a receiving unit. The system basically consists of two macroblocks, respectively: the self-power wireless sensor and the receiving unit. The self-powered sensor has a section devoted to the energy harvesting, exploiting the movement of an airscrew shaft keyed to a dc motor. The self-powered sensor adopts integrated devices in low-power technology, including a microcontroller, an integrated temperature sensor, and a radio-frequency transmitter at 433 MHz. The data transmission is realized in Manchester encoding, with amplitude-shift-keying modulation at 433 MHz, allowing covering a distance between the sensor and the reader on the order of 4–5 m, depending on the power supplied in transmission. The air velocity is measured through the rotor frequency of the electromechanical generator, whereas, for the temperature, a commercial low-power sensor is used. An experimental system has been designed and fabricated, demonstrating that the airflow harvester can power the self-powered wireless sensor permitting air temperature and velocity measurements. The system can be used for real-time monitoring of temperature and velocity. The sensor module placed into the duct does not require any batteries.**

***Index Terms*—Airflow measurement, autonomous sensor, contactless system, energy scavenging, power harvesting, self-powered sensor, telemetry, wind energy.**

I. Introduction

AIRFLOW measurements contribute to determine the indoor air quality and to provide healthy environments for the occupants of the buildings [1]. The commercial airflow measurement system commonly requires a battery, but, recently, in the literature, alternative systems supplied by power-harvesting modules are proposed [2]. However, there are many reasons to eliminate the battery adoption: the size and weight of the devices and the unwanted maintenance burdens of replacement. Moreover, the disposal of the increasing number of batteries is creating an important environmental impact as they contain toxic chemicals. This paper outlines a self-powered sensor that, without any battery, autonomously performs the measuring functions and transmits data to an external receiving unit. The proposed sensor is powered by a harvesting system that exploits the mechanical energy coming from the velocity of airflow. Since particular power supply is not required, the self-powered sensor can easily be installed at any point of a building. In the literature, airflow harvesters are evaluated for their potential utilization in autonomous measurements. An airflow harvester can be a promising technological solution for producing electricity in different applications [3]–[6]. In general, it is necessary for the power consumption of the harvesting electronics to be less than the available power for harvest, which varies as a function of airflow velocity. In recent years, several groups have demonstrated small airflow harvesters based on the wind turbine principle. For this purpose, a properly sized small airflow turbine is required to exploit the available airflow potential for producing electrical energy. In [3], a wind energy system is evaluated for their potential utilization in urban areas. The techno-economic analysis of such energy systems is reported, as well as their life cycle assessment. In [7], this paper reports on the design, fabrication, and testing of small-scale piezoelectric windmill. The windmill was tested at an average wind speed of 4.47 m/s, and it provided 5 mW of continuous power. In [8], a 100-mm-diameter airscrew rotor is combined with a brushless dc motor operated as a generator that could deliver up to 28 mW at 5.1-m/s flow rate or 8 mW at 2.5 m/s. More recently, in [9], a smaller device with a 4.2-cm-diameter rotor is described. The device delivers powers of 2.4 and 130 mW at flow rates of 5.5 and 12 m/s, respectively. In [10], a small-scale airflow harvester is reported. This device was developed using MEMS technology and was aimed at higher flow-rate applications. It comprises a 12-mm-diameter axial-flow turbine integrated with an axial-flux electromagnetic generator. In [11], a self-powered autonomous sensor measures the air velocity and saves the data measured in nonvolatile memory of the microcontroller. The downloading of the measurement data is done at a later stage, the reading unit is positioned near the sensor module (a few inches away), and the magnetic field generated by the reading unit supplies the sensor module. The system presented in [11] does not require a battery; it can be used in areas where the power source is absent, such as open field, but does not allow real-time measurements since only postprocess monitoring is possible. In [12], an airflow measurement system for velocity higher than 4 m/s with power-harvesting capability is proposed for short-range application for monitoring purposes.

Manuscript received June 18, 2010; revised September 22, 2010; accepted September 23, 2010. Date of publication November 11, 2010; date of current version April 6, 2011. The Associate Editor coordinating the review process for this paper was Dr. Subhas Mukhopadhyay.

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Digital Object Identifier 10.1109/TIM.2010.2089090

In this paper, a self-powered wireless sensor is proposed for online measurements of air temperature and velocity. Velocity and temperatures are important indicators of operational efficiency in the regulation of air conditioning or in industrial implants [13], [14]. The self-powered wireless sensor does not require any battery since it uses the power harvested from the mechanical energy of the air flow. The self-powered wireless sensor sends the measured data to an external receiving unit.

The sensor continuously operates for airflow greater than 3 m/s. For slower flows, the sensor is off, and the receiver assumes that the velocity of air is below the threshold. The measurement data are acquired every 2 s, but this time interval can be reduced. With respect to [12], the system has been improved, its functionality has been modified, and the air velocity sensor requires less power. The air velocity is measured through the rotor frequency of the electromechanical generator using a magnetoresistor coupled to a magnet. The transmission at 125 kHz has been substituted with another at 433 MHz, increasing the distance between sensor and reader up to 4–5 m. The receiving unit is always on and ready. The system allows real-time measurement. For internal flow, such as ventilation ducts, the air velocity can reach 12 m/s in large ducts, down to 1–2 m/s. For internal air duct applications, tiny windmills have significant advantages. Considering these aspects, the self-powered wireless sensor has been designed to be powered with low airflow velocity.

II. Description of the Self-Powered Wireless Sensor

In Fig. 1, a sketch of the self-powered wireless sensor is shown. A commercial airscrew is connected to an electromagnetic generator. The harvested power, using the air motion energy, supplies an electronic circuit for the measurements of air temperature and velocity. The microcontroller, which coordinates the operation of the self-powered wireless sensor, initially is in an idle state. Every 2 s, it wakes up and switches on the sensor modules to execute temperature and velocity measurements. Subsequently, the microcontroller turns on the transmitter module and sends the package; after the transmission, it returns to the idle state. On the other hand, when the transmission power consumption is high, the energy storage system is recharged during the interval in which the sensor module is off. The interval of 2 s was considered sufficient to allow proper operation of the system since the measured quantities (temperature and velocity) have a slow dynamic. Finally, the microcontroller switches off the transmitter and returns to the idle state. Since the self-powered sensor is a wireless device, it encounters the typical problems of a wireless network. In this application, a point-to-point communication has been implemented. Point-to-point communication avoids managing the complexity of a network protocol, saving power, and making the system compatible with the available low energy. For these reasons, the self-powered sensor implements a simple communication at 433 MHz; other wireless protocols such as Bluetooth or Wi-Fi are more expensive in terms of power consumption.

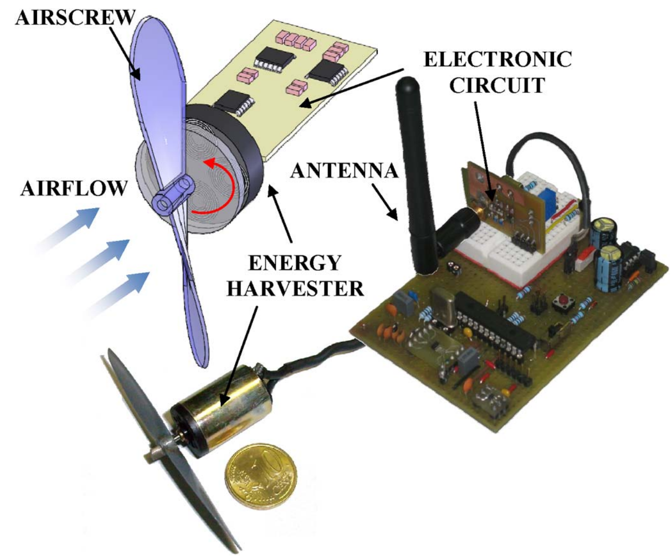

Fig. 1. Schematic diagram of the autonomous sensor.

Whereas the intent is to use the device indoors, in air ducts used for heating, ventilating, and air conditioning, the airflow, which is normally present, is used to drive a miniature electromagnetic airflow harvester to harvest the energy for the power supply. The adopted components for the airflow harvester are commercially available. An electromagnetic device was tested to be adopted in the harvester: a dc servomotor (1624T1,4G9 Faulhaber) with dimensions of 32 × 32 × 22 mm and a weight of 35.9 g. The servomotor has an electromagnetic force of about $K_e \approx 1.4$ mV/r/min with a tolerance of $\pm 1\%$ and load impedance $R_L > 8$ kΩ with a resistance between the terminals of about 75 Ω. The generator chosen is combined with two extremely light plastic blades (with 65-mm diameter). The number of blades of an airscrew is related to the efficiency at low velocity; geometry with a low number of blades ensures a higher efficiency at low velocity [3]. The available theoretical airflow power can be calculated with the kinetic energy, according to the following expression:

$$E = \frac{1}{2}mv^2 = \frac{1}{2}\rho A \Delta t v^3 \tag{1}$$

where ρ is the fluid density, A is the area normal to flux, v is the airflow velocity, Δt is the observation time, and m is the mass. The kinetic energy can be easily converted into the airflow power

$$P_w = \frac{1}{2}\rho A v^3. \tag{2}$$

This power is a function of area A, airflow velocity v, and air density ρ, which can be assumed to be of 1.2 kg/m^3 in civil and industrial contests. However, the theoretical maximum quantity of energy for a standard area of 55 cm^2 and an air velocity of 4.5 m/s is about 300 mW. A generator module cannot extract all of this power since the relatively high viscous drag on the blades, the bearing losses, and other factors. The formula is corrected with a power coefficient that is less than unity C_p. Large-scale airflow harvesters can be highly efficient, with power coefficients greater than 0.5; for small-scale airflow

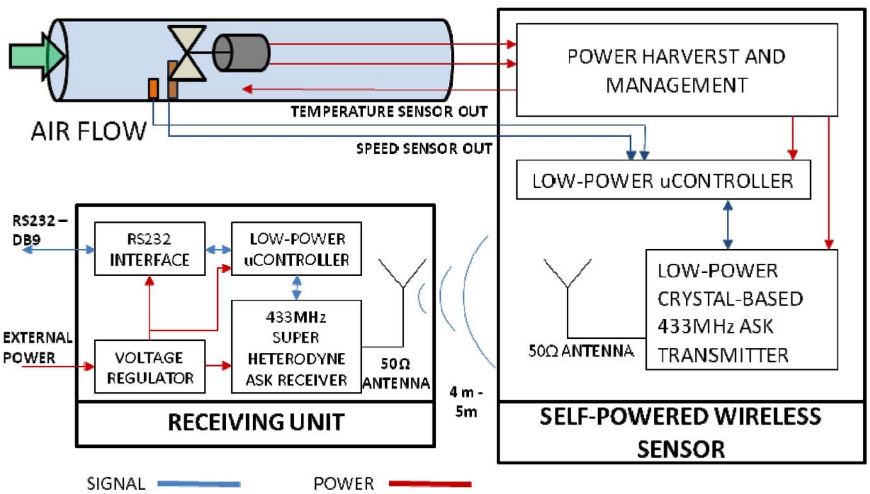

Fig. 2. Block diagram of the autonomous sensor and readout system.

harvesters, the performance is less good, i.e., about 0.1 [5]. This large variation in efficiency is caused by friction in the generator, internal electric resistance, and other nonidealities in the transduction between mechanical and electrical energy. The power extracted by a practical turbine is thus

$$P_m = \frac{1}{2} C_p \rho A v^3 = C_p P_w. \tag{3}$$

Assuming that the turbine is coupled to an energy transmission with efficiency η_m that drives a generator of efficiency η_g, the electrical power P_e available can be written as

$$P_e = \eta_m \eta_g C_p P_w. \tag{4}$$

The energy harvester efficiency is defined as the power extracted from the airflow over the kinetic power available for the area covered by the airscrew. In the next section, some experimental data on the generator efficiency are shown.

In Fig. 2, the block diagram of the self-powered wireless sensor and the receiving unit are reported. The electronic circuit of the self-powered wireless sensor consists of different modules. The power block provides the voltage and the necessary power to the circuit to ensure proper operations. The integrated circuit adopted for this purpose is MAX666 (Maxim). It is a voltage regulator that is suitable for micropower applications, ensuring low-power consumption during idle state of only 40 μA, a wide range of input voltage, and programmable output current limit. The transmitter (MAX1472) is commercialized by Maxim, and its working frequency is 433 MHz. This device modulates, according to on–off keying modulation, the magnetic field by a damping stage to transmit data. Two pins of the device are used to provide a clock signal for the synchronization of data transfer. The wireless sensor antenna and the readout antenna are both built by copper wire for communication at 433 MHz with a length of about 55 mm and a diameter of about 14 mm. The choice of frequency at 433 MHz has allowed reducing the size of the antenna than that in the case of transmission at 125 kHz [11], [12]. The low-power microcontroller chosen is the PIC18F26K20 commercialized from Microchip, which offers a 10-bit analog-to-digital converter and a timer unit for frequency analysis. The microcontroller has a low-power configuration: all the unused peripherals are switched off. To maintain the power consumption low, the clock of the microcontroller is 4 MHz during measurement and transmission activities, whereas the clock is 31 kHz during stop mode.

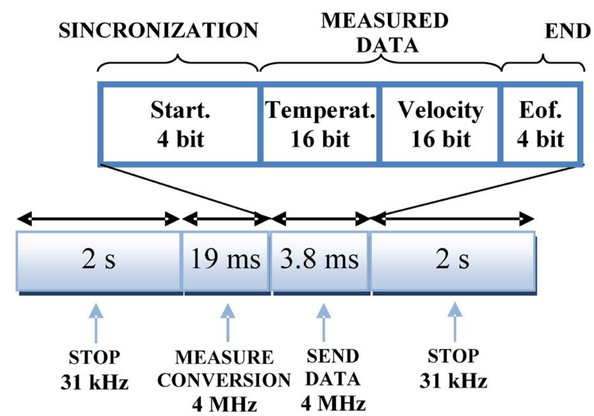

Fig. 3. Typical self-powered wireless sensor activities.

In Fig. 3, the time interval of each activity is given; the stop mode is 2 s long: in this state, all the peripherals are switched off, and the microprocessor clock is set to 31 kHz. Subsequently, the system wakes up and measures the temperature and velocity in about 19 ms, sends these data to the receiving unit in 3.8 ms, and then switches off. The transmission packet consists of 40 bits: two nibble for the start and end transmission synchronization and two measurement data, each of 16 bits.

The airflow velocity is measured by the rotor frequency of the electromechanical generator using a commercial low-power magnetoresistor as sensing element. The operating principle of the sensor and its use is extremely simple; the permanent magnet, with semicircular section, is mounted on the head of the airscrew shaft, whereas the magnetoresistor is placed over it through a suspended structure. The change in the magnetic field density correlated to the angular variation between the magnet and the magnetoresistor is taken out as a resistance change. The magnetoresistor (a Sn-doped single crystal film InSb) is fabricated in thin-film technology on alumina substrate [Ashai Kasei Corporation (Japan)]. Commercially, the company grouped this sensor, which is available in different shapes, with magnetic sensors having a semiconductor magnetoresistive element, encoded MW. The magnetoresistor is coupled with the permanent magnet located at the front face of the magnetoresistor. The permanent magnet is made of Sm2Co17 (samarium–cobalt magnet) with a diameter of 4 mm and a length of 3 mm. The resistance variation is used to correlate the rotation of the airscrew through a simple rectifier circuit composed of an operational amplifier (TLV2765). The rectified signal is then used as input to the microcontroller, which measures the period.

The low-power temperature sensor LM94022 is a precision analog-output CMOS integrated-circuit temperature sensor that operates at a supply voltage of as low as 1.5 V. The adjustable gain is set to obtain a good tradeoff between sensitivity and power consumption; in this application, the sensitivity is set to $-8.3\ \mathrm{mV}/^{\circ}\mathrm{C}$. The temperature sensor is installed inside a screen that protects it from forced ventilation. The screen cover is built to guarantee, however, the natural and constant ventilation of the sensing element.

The receiving unit consists of a receiver (MAX1473) commercialized by Maxim. The system is used to receive the information transmitted from the MAX1472, both produced by Maxim to work as a transmitter–receiver pair. This component was implemented in CMOS technology, allowing maintaining low-power consumption in a range between 3.3 and 5 V. Power is directly supplied from a PC connected to the receiver module (5 VDC at 500 mA). The MAX1473 integrates an internal amplitude-shift-keying superheterodyne receiver with a sensitivity of -114 dBm input $\div\ 0$ dBm and a carrier of 315–433 MHz. The receiver is connected to a microcontroller (PIC18F452) commercialized by Maxim. The operating voltage is 5 V, and the frequency of the bus clock is 7.38 MHz. A timer unit is used to decode the demodulated signal, and the data collected are transferred to the PC using a serial communication interface.

III. Experimental Testing System

An experimental system generates controlled velocity airflow in a plastic duct, where the sensor is placed. The schematic diagram of the experimental system is shown in Fig. 4.

The air tunnel was specially designed and developed in a laboratory for system calibration purposes. The air tunnel has a 20-cm-diameter section with a settling chamber at the entrance and a length of 1 m.

A commercial airflow generator is used as source for the controlled airflow along the duct, whereas the airflow velocity is monitored by the reference flowmeter (Lutron AM-4203) with ±2% accuracy. An airflow generator (24 V dc fan, Comair Rotron) whose rotational speed is controlled by the PC through a programmable power supply (Agilent E3646A) controls the flow velocity from 0- m/s up to 23-m/s values. A reference temperature sensor (Pt100) is placed inside the air tunnel centrally for the temperature measurements. A heater developed using power resistors (type SBC Meggitt Electronic Components) is powered by the power supply for the controlled air temperature. Full control on the air temperature is possible by programming the power supply and measuring the temperature by the reference temperature sensor (Pt100). A LabVIEW program controls the whole system.

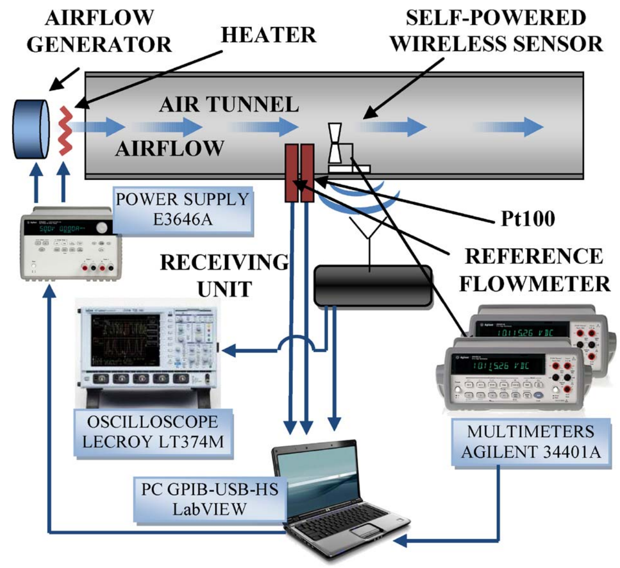

Fig. 4. Schematic diagram of the experimental system.

IV. Electromagnetic Generator Power

Two multimeters (Agilent 34401A) were used for measuring voltage and current generated by the harvester to analyze the performance of the power harvester. All tests were done at an ambient temperature of 20 °C and at the center of the tunnel. A set of tests on the airflow power harvester using different resistive loads and airflow velocities to demonstrate the energy conversion potential was conducted; voltages and currents have been measured for each airflow velocity.

In Fig. 5, the diagrams obtained for the electromagnetic generator are shown. Using the dc servomotor, the maximum power extracted is about 45 mW for a load of 500 Ω at 9 m/s. In Fig. 6, the efficiency of the electromagnetic generator is reported for different airflow velocities and resistive loads connected. The efficiency is calculated as the ratio of the measured power P_e and the kinetic power P_w mathematically calculated with (2), considering an area of about 33 cm^2. While the mechanical efficiency for a good wind turbine can settle between 35% and 40%, the overall performance can easily descend to values between 13% and 15%. The overall efficiency is better than [12]. However, some considerations concerning the possible inefficiencies are shown here. First, the presence of the brushes in the airflow generator may be an inertial nonnegligible, particularly at low-engine velocities. Second, supporting the airflow turbine itself can be a constraint due to its size.

V. Self-Powered Wireless Sensor Experimental Results

The self-powered wireless sensor has been tested in the air tunnel. The unregulated voltage of the generator, the regulated voltage of the self-powered wireless sensor, the main system clock, and the data sent to the transmitter are reported in Fig. 7.

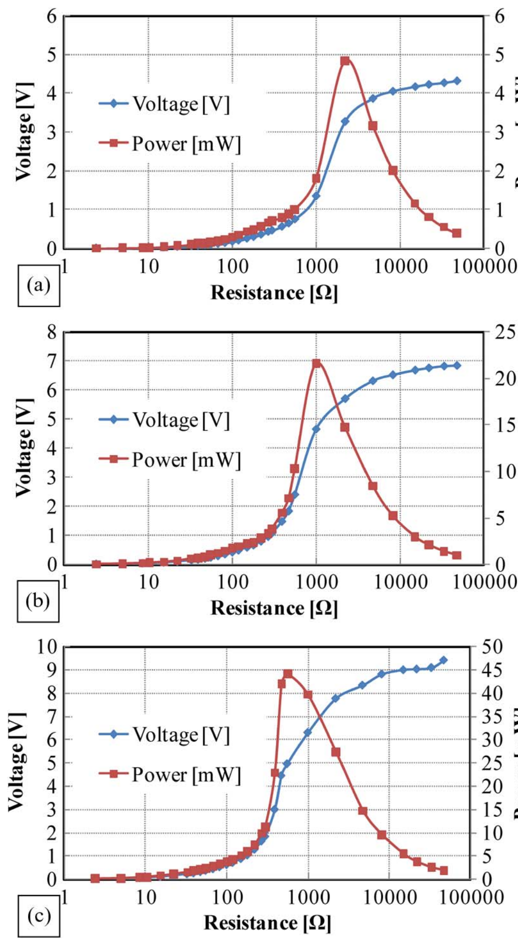

Fig. 5. Generated voltage and power by the dc servomotor at different airflow velocities. (a) 5 m/s. (b) 7 m/s. (c) 9 m/s.

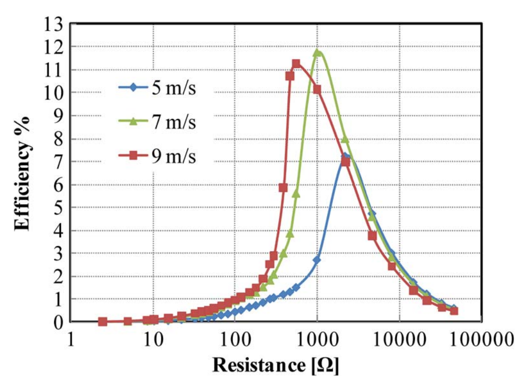

Fig. 6. Efficiency of the dc servomotor at different airflow velocities.

In the time interval labeled as "Start-up power harvesting," the airflow generator is turned on, and the power-harvesting module begins to power the sensor. For the test reported in Fig. 7, the start-up time is about 1 s. From this moment, the system is powered, and it continuously works, as long as the airflow velocity is maintained. An analysis of the power consumption during the stop, measuring, and transmitting activities has been performed. The first three rows of Table I report the typical values, whereas the last two rows show also the power values of the temperature and velocity sensors and their conditioning circuits. The magnetoresistive sensor and conditioning consume very low power, i.e., about 100 μA. An operational amplifier (TLV2765) is used as a comparator and is switched on only during the measurement phase (19 ms) via a shutdown pin. The CMOS temperature sensor is of very low power since it consumes only 7.5 μA and does not require a conditioning circuit. In this situation, the microcontroller, the magnetoresistor, and the temperature sensor require a power of about 616 μW, as reported in Table I. The power required by

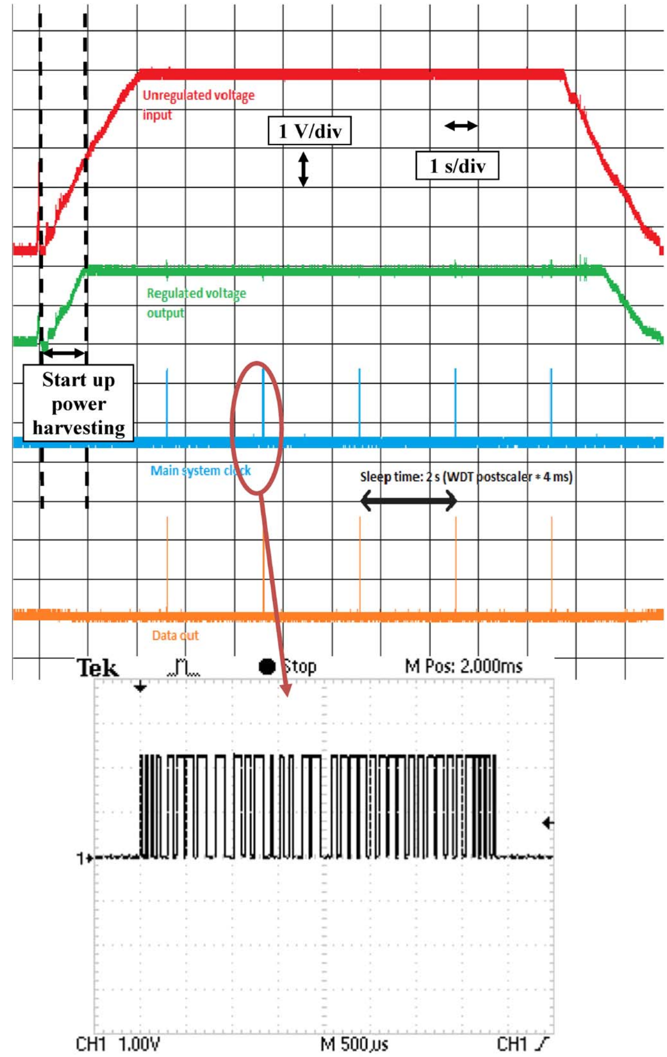

Fig. 7. Wake-up signals of the self-powered wireless sensor.

TABLE I
TYPICAL POWER CONSUMPTION

	Current consumption	Voltage level	Power supply
Measurement activity	280 µA	2.2 V	616 µW
RF transmission	13 mA	2.2 V	28 mW
Stop Mode	40 µA	2.2 V	88 µW
Temperature sensor	7.5 µA	2.2 V	16.5 µW
Velocity sensor & conditioning	100 µA	2.2 V	220 µW

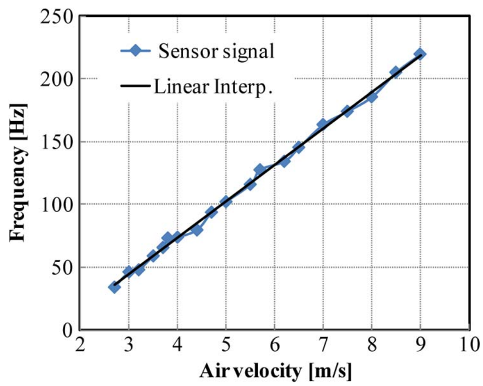

Fig. 8. Frequency values versus different airflow velocities.

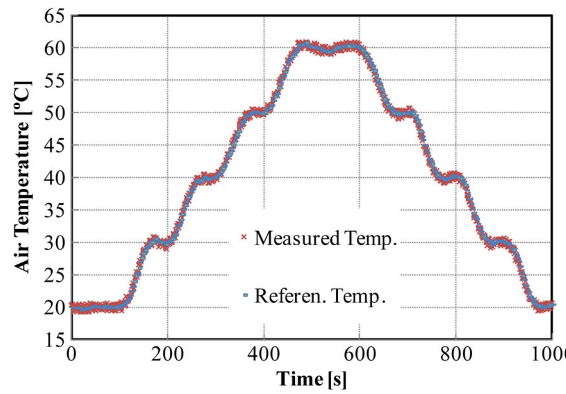

Fig. 9. Calculated values of air temperature, compared with the values obtained with the reference Pt100.

the self-powered wireless sensor in the activities is reported in Table I. As can be seen from the table, the power consumption during measurement activity and stop mode is low, whereas the RF transmission requests about 28 mW of power supply, with a current consumption of about 13 mA and a voltage level of about 2.2 V. The time interval for transmission is still very short, the energy required is greater than the instantaneous power produced by the harvester, and it is extracted from that stored into the capacitors. Furthermore, since the voltage level generated by the motor is variable and no more than 2.2 V is required by the electronic circuit, the choice of using a low-power linear regulator is the simplest.

Therefore, to test the transmission activity, the wireless sensor has been located in the tunnel and communicates with the receiving unit externally placed. The low-power microcontroller sends the digital signal to the transmitter for the transmission. The base station receives the transmitted signal and extracts the Manchester encoded information.

Preliminary tests have been carried out to assess the transmission capacity of the system. The transmission tests between sensor and receiver were made by placing the sensor in two different points of the tube: central (50 cm from the outlet) and at the outlet position. The outlet position placing is the most suitable for air-conditioning applications because it allows easy installation, even in existing systems. The plastic tube has a diameter of 20 cm. The system has achieved a distance of about 4–5 m in the open field.

Furthermore, several tests were executed to analyze the sensing performances. The airflow velocity data collected by the autonomous sensor have been compared to the reference flowmeter (Lutron AM-4203). In Fig. 8, the rotation frequency values are obtained using different airflow velocities. The black line represents the linear interpolation of the data obtained using the method of least squares. The linear interpolation allows calculating the function that correlates the rotation frequency of the generator with the air velocity in the duct. The calculated equation is

$$v = 0.034 \cdot f + 1.46 \tag{5}$$

where f is the frequency in hertz, and v is the air velocity in meters per second. The range of validity is considered to be 2.7–9 m/s. In this range, the trend is considered linear. In fact, from Fig. 8, it can be observed that, in the range considered, the nonlinearities can be neglected. Equation (5) has been implemented in the microcontroller to calculate the velocity. This has reduced the computational time of the microcontroller. The linearization involves a maximum deviation from the line of about 0.2 m/s, which represents about 2%, compared with full scale, which has been considered acceptable.

In Fig. 9, the calculated values of air temperature are compared with those obtained with the Pt100 placed in the tunnel centrally near the wireless sensor. The temperature was varied from the ambient temperature of about 20 °C to 60 °C; it is consistent with the possibility of the adopted heater. The measured temperature values match the reference ones; the maximum deviation is about 0.4 °C.

VI. Conclusion

A self-powered wireless sensor for air temperature and velocity measurements with energy harvesting capability has been proposed. The system has been designed for measuring the air temperature and velocity of an airflow and transmits the measured data, with a 433-MHz point-to-point communication, to a receiving unit with a time interval of 2 s. The sensor can work without any battery, using a power-harvesting module; this paper has demonstrated that airflow is a viable source of energy for powering autonomous devices. The results from testing the prototype have indicated that, with careful design of the airflow harvester and the electronic circuit, it has been possible to supply the electronic circuit of the sensor and to perform the measurement and transmission activities. The result is an efficient harvesting system that is capable of providing small amounts of power to supply the circuit and allow the measurement of air temperature and velocity. The preliminary experimental data have shown that the sensor can operate at velocities of as low as 3 m/s. The self-powered wireless sensor can be used in ducts for civil or industrial applications for the control of the health of the environment.

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