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POCO: 'Perpetual' operation of CO wireless sensor node with hybrid power supply

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ABSTRACT

Wireless sensor networks (WSNs) have recently been applied for the detection of a number of hazardous gases. Gas monitoring is of significance, for gas leakage and the resultant penetration of gases into the environment can lead to grave or sometimes fatal consequences. In this work, we propose a sensor node architecture for a wireless outdoor CO monitoring unit with an emphasis on the energy efficiency of measurements and optimal power supply mechanism. To guarantee the 'perpetual' operation, the sensor node is supported by a hybrid power supply, which takes advantage of both wind and solar ambient energy sources to power the node and to charge the high capacity super capacitors that act as energy buffers. Using an electrochemical CO sensor, we secure the low power consumption of the node without degrading the sensing capabilities. We demonstrate our experience of operating the developed wireless sensor node in real conditions. Our solution can be applied for CO monitoring in urban areas and outdoor industrial facilities.

1. Introduction

Wireless sensor networks (WSN) have been widely used in monitoring and control applications including gas detection [1]. This application is highly relevant to the smart cities and smart homes scenarios in the scope of the forthcoming era of Internet of Things [2]. In terms of cities, intense urbanization and the growing number of vehicles have resulted in the increase of carbon monoxide (CO) concentration. It is a colorless, odorless, and tasteless gas which is toxic to humans and animals in high concentrations. The natural sources of CO, apart those of vehicles origin, include volcanoes and forest fires. In industry, CO can be generated by operating stoves and combustion engines. The monitoring of CO, therefore, is of particular significance as this toxic gas is often present in industrial and living environments.

In the last decade, monitoring solutions have transitioned from wired to wireless, using the WSN paradigm, ensuring fast deployment and unmanned operation in difficult to access areas. The application of WSNs is, however, restricted by the limited onboard energy resources [1], requiring careful design and power management. It is highly important due to the fact that power consumption and accuracy, e.g., of measurements or synchronization, often go hand in hand [3]. The energy availability, in fact, affects both the lifetime of the node, as well as the accuracy and frequency with which measurements can be taken [4].

Indeed, the problem of power management in WSN has been tackled from different perspectives such as energy-aware synchronization [3], protocols [5], sensing [4,29] and analysis [6]. In terms of power consumption, the wireless transceiver is typically the most power hungry component onboard. The total energy consumption of sensor nodes could exceed hundreds of milliwatts, requiring the use of wires to provide electric power to the sensor node [7]. At the same time, the WSN paradigm involves not only the wireless data transmission, but also independence on power grid. As a matter of fact, the wired power supply limits the practical use of wireless sensor networks. The transition from electric power through wires to battery power requires a special focus on power consumption optimization [4,6] to ensure the WSN long lifetime. This problem has been addressed from different points of view so far. For example, the intelligent approaches presented in Refs. [8] and [2] adjust the operation of a gas sensor by changing its duty cycle depending on the context, e.g., people presence in a building. A similar intelligent approach developed in Ref. [9] is based on a sensor fusion compo-

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nent which detects the presence of chemical species and estimates their concentration. Analyzing the measured data, the node infers whether the situation can be potentially dangerous and whether the data must be forwarded to a network operator. The research conducted in Refs. [10] and [11] report on energy savings due to an optimized measurement procedure. In Ref. [10] the authors propose to change the duty cycle of the heating pulse of the sensor during the measurement by fast turning on and off the device. This approach may result in sensor damage. A more advanced “differential” heating profile is investigated in [11,12]: it is 65% more energy efficient while ensuring the sensor performance as in a typical measurement procedure. In contrast, designs shown in Refs. [13,14] demonstrate long lifetime of the sensor nodes by employing a light sensor in conjunction with a colorimetric chemical sensing film, but significantly suffer in performance in terms of long sensor response, which fails to meet safety requirements.

The lifetime of WSN can be increased by the application of energy harvesting technology [15–17]: different classes of generators can harvest and perform conversion to electricity from almost every form of ambient energy [30]. The sensor nodes can use the ambient energy directly or keep it in storage elements such as a battery or super capacitor. During the last decade there have been plenty of architectures and power management solutions [18] proposing and implementing the energy scavenging paradigm in the scope of WSN [31]. In the context of power hungry gas sensing, it should be noted that not all energy scavenging technologies generate sufficient amount of power [19,20]. Another crucial point is that some ambient energy sources are available only in particular weather conditions which do not guarantee the stable operation of wireless gas sensors.

Hybrid energy scavenging is considered as a technology which can potentially ensure the ‘perpetual’ operation of WSN and has become popular recently [23,24]. The prototypes have evolved from lab ones [25] to real deployments [26], e.g., for structural health monitoring. However, more research efforts are still required in this field to study hybrid structures in more detail, analyze their pros and cons, potential applications and real world deployments.

In this work, we present POCO (“poco” in Italian is “little”, “low”) a low power CO wireless sensor node with a hybrid power supply, which collects the ambient energy from sun and wind. In our approach, the dual harvester directly powers the sensor node at any time through the source with the most amount of available energy, while the remaining scavenged energy is stored in super capacitors or on a backup battery.

The novelty of this work is the following:

- The energy efficient design of the gas WSN platform with a particular focus on the hybrid power supply which includes the super capacitors, li-ion and two energy harvesting components: a solar panel and wind turbine. In particular, our solution helps to meet the standard requirements on the frequency of gases measurement [28] which affect the power consumption of the autonomous sensor node.
- We evaluate the performance in real conditions (except for wind). The proposed system ensures the required frequency of measurements and guarantees the sensor node ‘perpetual’ operation.

This paper is organized as follows: in Section 2 we describe the sensor node design focusing on the sensing and power management circuits. Section 3 presents the energy harvesting solution used in this work. We discuss the gas measurement procedure in Section 4. Experimental results are shown in Section 5. Finally, we provide concluding remarks and discuss our future work in Section 6.

2. Sensor node design

2.1. System overview

An autonomous wireless sensor node for CO monitoring is shown in Fig. 1. The core element of the node is the processing unit, based on the ATXMTGA32A4 MCU, which manages the operations of the sensing and the wireless communication blocks. As for the CO sensor, we used an NAP-505 (Nemoto) gas sensor operating in amperometric mode for this work. The CO wireless gas sensor node uses the Zigbee technology and transmits data via the BACnet protocol. An ETRX3 Zigbee/IEEE802.15.4 modem was used for data transmission and the protocol was realized by the MCU program. This wireless technology is more energy efficient with respect to WiFi [32].

The ZigBee transceiver is operated by the AT commands, which are transmitted through the UART interface of the MCU. The node is supplied by a hybrid power supply via a DC/DC converter which outputs 2.8 V.

The wireless sensor is designed to operate in a wireless network in order to perform outdoor ecological monitoring of air in urban areas and industrial facilities. The data regarding the concentration of CO are sent to the network coordinator, which can be a computer with a Zigbee USB modem or device having a sound and light alarm. The range of data transmission depends on the antenna used and also the area in which the measurements are made. The range of transmission exceeds 300 m in open outdoor areas with an external antenna [21].

2.2. Sensing circuit

In order to increase the autonomous operation of the sensor node we implement a periodic CO gas measurement, i.e., there are three modes of operation which are data measurement, data transfer and sleep. We discuss them in this section.

The sensing circuit is built around a NAP-505 electrochemical sensor [22] with three electrodes (working, reference, counter) by Nemoto.

The sensing circuit of the node is shown in Fig. 2. It is a modified version of the sensing circuit recommended by Nemoto [22]. Our solution enables to carry out periodic measurements by switching the circuit on and off. When no measurement is conducted, the power supply is turned off by using MOSFET VT2 (IRLML6032). In order to connect the electrodes, we use an analogue switch DA2 (ADG801) instead of an FET transistor used in the Nemoto design. The idea behind this substitution lies in the operation of these devices in normal condition: if using an FET transistor in sleep mode the sensor electrodes are opened and if using an analogue switch the sensor electrodes are closed. Most of the time the sensor node is in sleep mode that makes the second option preferable. We discuss the sensor node operation in details in Section 4.

The measuring parameter (voltage) is at output 1 of amplifier DA3A (OPA 2369). This voltage is supplied to the MCU for detecting the concentration of the CO gas.

At normal conditions, a 1–2 min time interval is required for the stabilization of the output voltage of the CO gas sensor after coming out of sleep mode. Therefore, the duration of the measurements shall be no less than 2 min. However, if the working and reference electrodes are connected during the sleep mode, the stabilization period is reduced up to 10 s. It is a recommendation of the sensor manufacturer that was experimentally verified in this work. During the remaining time, the MCU switches the sensor to sleep mode due to power saving reasons for a specified period. The management of the operation mode of the sensor is performed by the analogue switch DA2 and MOSFET VT2. The MOSFET is connected to the MCU input–output line (SS line) and the transition between active and

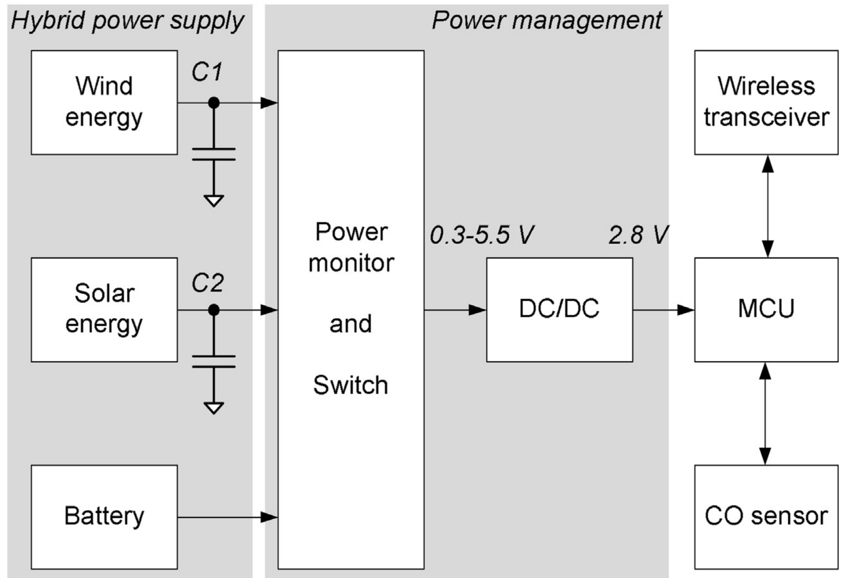

Fig. 1. The block diagram of the *CO* wireless gas sensor node with a hybrid power supply where *C1* and *C2* are super capacitors.

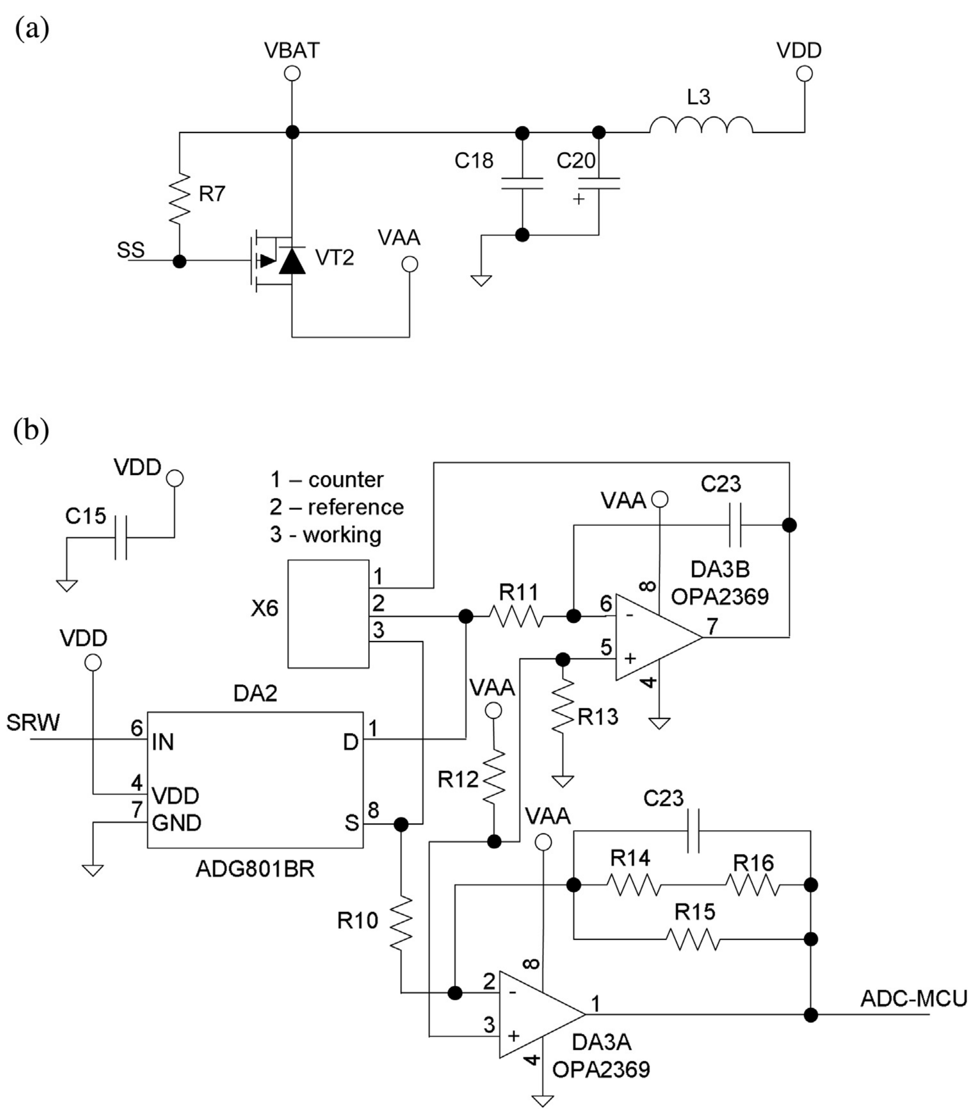

Fig. 2. Analog sensing circuit: (a) sensing circuit switch and (b) sensing circuit where *X6* is the *CO* sensor.

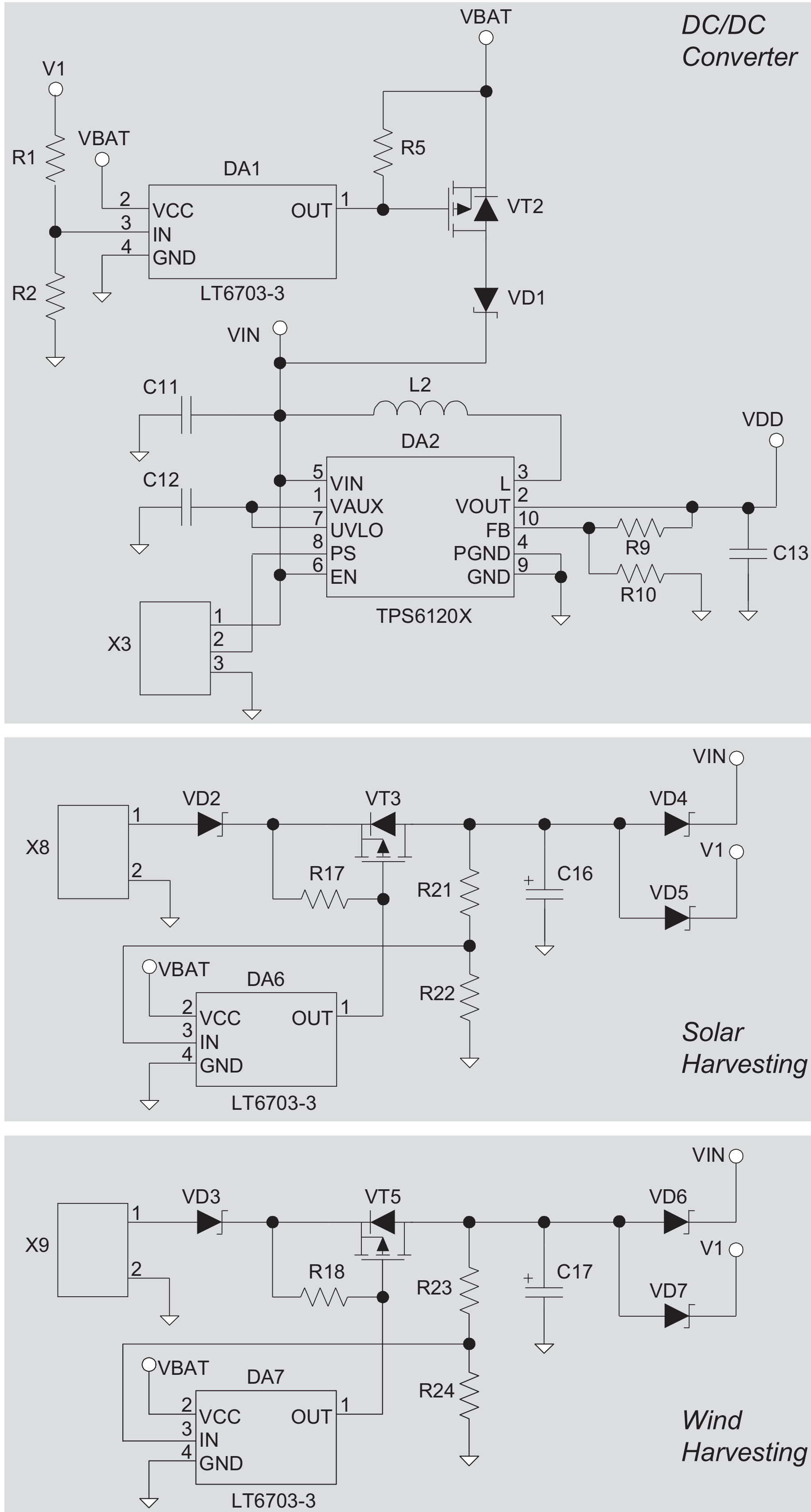

Fig. 3. Power management circuit.

sleep modes of the measuring circuit is provided. In sleep mode, this MOSFET is closed and there is no VAA voltage. In this case, the voltage at output ADC–MCU is also zero.

2.3. Power management

Since green sources of energy have an intermittent nature, a robust model is needed in order to provide a more stable operation of the sensor node. One of the ideas to address this issue is the application of a hybrid power source architecture which includes more than one energy source for the sensor.

As for the ambient energy sources, we use solar and wind energy harvesters due to their availability in most outdoor conditions and sufficient amount of power generated at their output. A wireless sensor node with energy scavenging technology requires a buffer to store the harvested energy. The energy buffer allows the system to be supplied even if the ambient source is unavailable at the moment when the system is in operation.

The hybrid power supply of the proposed sensor node consists of wind and solar harvesters each wired in parallel with a super capacitor and one 3.7 V, 3200 mAh li-ion battery. In this design, the battery is a backup storage: our experimental results demonstrate that the node can successfully rely on the ambient energy and the energy stored in the super capacitors. The logic behind the application of a hybrid power source is in ensuring stable 'perpetual' operation of the sensor node performing gas detection and controlling its concentration in the environment—an application that is often considered safety critical.

The power management block operates as follows: the voltage across the battery and super capacitors C16 and C17 (see Fig. 3) is controlled by the power monitor and relayed by the switch. The capacity of super capacitors is 400 F each. If the voltage across the super capacitors exceeds 0.9 V, the one with the most charged unit is selected for powering the node.

The reason for choosing 0.9 V is as follows. According to its data sheet, the DC–DC converter starts the operation at 0.3 V on its input. Our experimental results have shown that the power circuit does not work properly at 0.3 V (i.e., it does not provide 2.8 V at the output). This happens because the energy stored in a super capacitor at voltages lower than 0.9 V ($W = 0.45$ J) is not sufficient to produce power for the wireless sensor node. The stored energy is dissipated in the power circuit, particularly in the DC–DC converter. That is why we have adjusted the circuit operation for switching at 0.9 V.

It is interesting to note that the energy stored in the super capacitor when the voltage across its plates is 0.9 V is only 10% of the whole energy stored in the supercapacitor when the voltage across its plates is equal to 2.7 V. Therefore, it is practically useless to start DC–DC at 0.3 V: it does not result in a significant increase in battery lifetime for the wireless sensor node.

C17 is supplied by wind energy and C16 by solar energy. Energy harvesting of both ambient sources is implemented separately, i.e., each super capacitor can perform charging when its respective ambient source is available. The supplied voltage level is then converted to a stable 2.8 V by the DC/DC unit (TPS61200) DA2.

The voltage level on the super capacitors must not exceed the upper threshold, which is 2.7 V. To securely control the charging process and avoid the cells overcharging, we employ comparators DA6 and DA7 (see Fig. 3) for each charging channel. This circuit operates as follows: the voltage on the comparator input is compared to the reference voltage 0.9 V generated by the internal reference source. At the same time, the voltage of the super capacitors is divided by the resistive voltage dividers R21–R22 and R23–R24 for solar and wind circuits, respectively. This operation is to be performed in such a way that a 0.9 V value in the middle point of the divider corresponds to the maximum working voltage of the super capacitor.

The power management circuit of both ambient energy sources is connected using diodes VD4 and VD6. This allows the system to choose the most highly charged super capacitor for powering the node.

Both solar and wind power management circuits are joined using diodes VD5 and VD7 and connected to R1–R2. Its voltage is compared with the reference value 0.9 V and if it is higher than the reference one, the system switches from the battery to one of the super capacitors. Switching between the battery power supply to one of the super capacitors is performed by switch VT2.

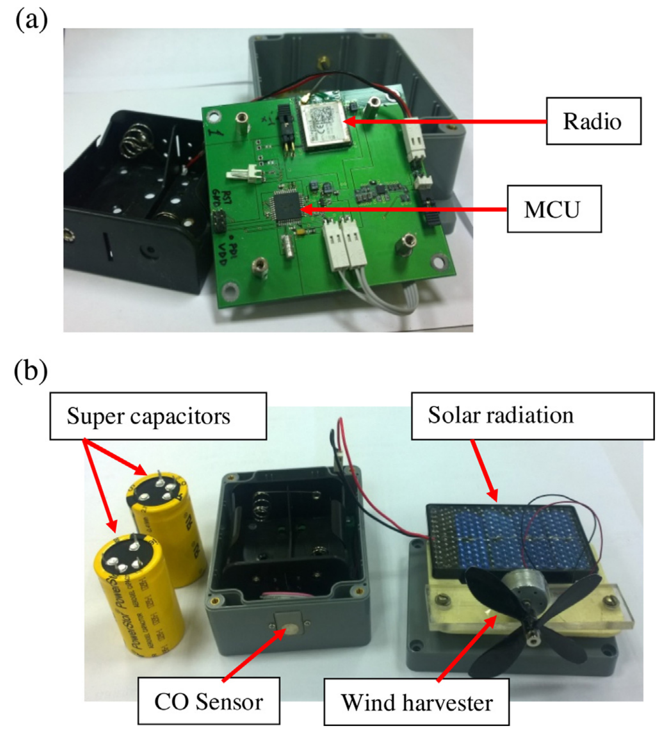

Fig. 4. Prototype of the wireless sensor node for *CO* monitoring: (a) a board with the MCU and wireless transceiver, (b) harvesters, super capacitors and *CO* sensor in packaging.

3. Energy harvesting

As specified earlier, in this work we employ two harvesting technologies: solar radiation and wind. The solar cell power is approximately 2 W at 1.5 A (short circuit current I_{sc} = 0.9 A and open-circuit voltage U_{oc} = 2.2 V). A small wind turbine provides a maximum open circuit voltage and short circuit current of 2.2 V and 27 mA at a wind speed of 4.3 m/s respectively.

The battery is used only as a backup energy storage. Changing from battery to energy harvesting sources takes place when the amount of voltage in the super capacitors is above 900 mV. The prototype of the sensor node with harvesters is shown in Fig. 4.

Since the main task designated for the gas sensor node is to monitor the CO concentration, it is necessary to provide a continuous operation of the sensor node even in cases when the amount of energy provided by the harvesting sources is not enough to power the sensor node. Therefore, the battery can be used as a complementary system for powering the sensor node. Each super capacitor stores energy independently as a result of which it will be possible to store and use the energy from each source with maximum efficiency.

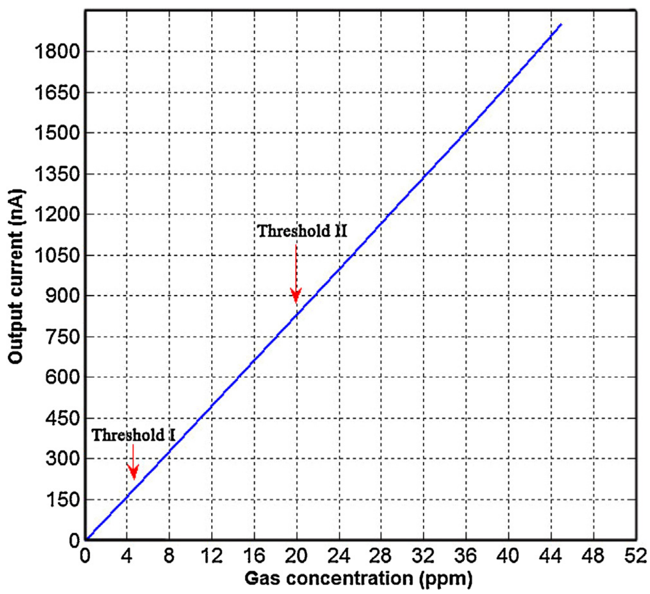

Fig. 5. Curve showing sensor response (output current) w.r.t. *CO* concentration.

The energy stored in the super capacitor for powering the node is given by the following equation:

$$W = \frac{C}{2} \times \left(V_{max}^2 - V_{min}^2\right) \quad (1)$$

where V_{max}, V_{min} are maximum (2.7 V) and minimum (0.9 V) voltage, respectively, and C is the capacity. The result is 1300 J or 0.36 Wh. Theoretically, fully charged capacitor stores 1430 J or 0.41 Wh.

4. Gas measurement procedure

In this section, we first overview the relevant standards on admissible CO concentration. The following standards regarding the maximum permissible concentration of CO gases for the residential areas as well as industrial complexes are accepted in Russia:

- For residential areas, the maximum permissible concentration of CO for a long term stay is 3 mg/m^3 (approximately 2.6 ppm at the temperature of 20 °C and pressure of 1 bar) and for a short duration of stay it corresponds to 5 mg/m^3 (approximately 4.3 ppm at the temperature of 20 °C and pressure of 1 bar).
- The maximum permissible value of the CO concentration at industrial complexes is 20 mg/m^3 (approximately 17 ppm at the temperature of 20 °C and pressure of 1 bar).

The operation principle of the sensor is based on applying a certain amount of potential difference corresponding to oxidation or reduction of the substance to be detected. The amount of current in the cell is proportional to the concentration of the substance.

In order to carry out precise amperometric measurements, three electrodes are used in the electrochemical sensor: working, counter and reference ones. The reference voltage is necessary to support a stable voltage between the working electrodes. The gas penetrates into a permeable membrane as well as a carbon filter, which removes all gases except carbon monoxide. The reaction takes place at the three phase boundary of electrolyte, gas and catalyst. As a result of the CO oxidation in the sensor, current flows. The results

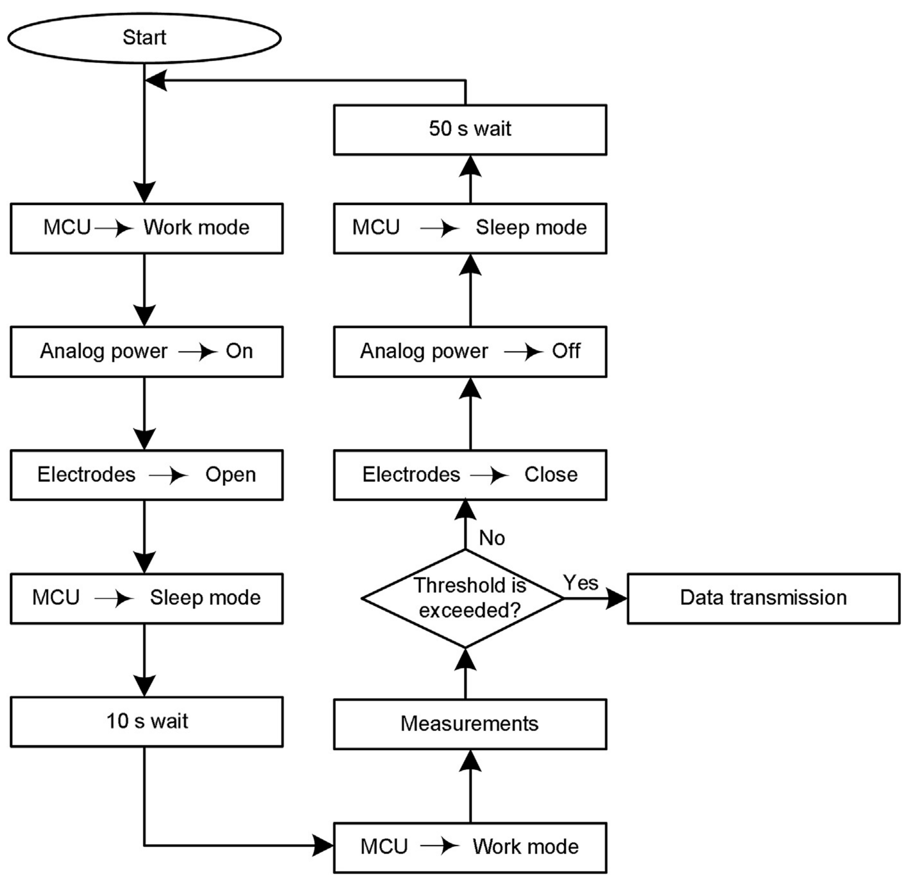

Fig. 6. Algorithm showing how the sensor node conducts gas measurement.

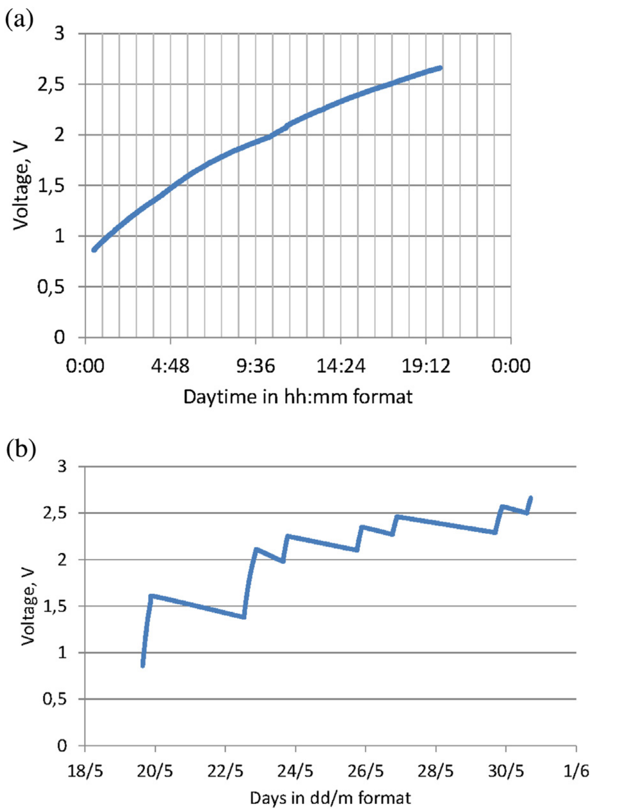

Fig. 7. Charging of the super capacitor from the wind generator: (a) continuous charging at wind speed of 4 m/s, (b) charging from the wind depending on its availability.

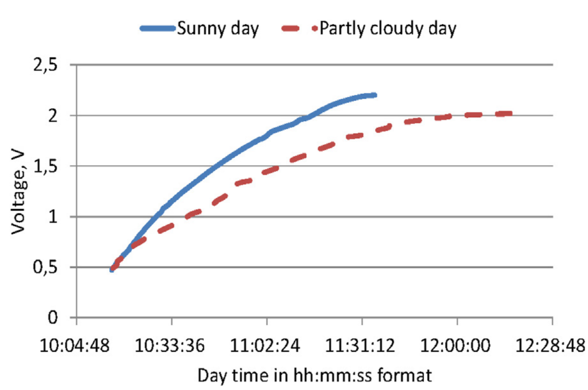

Fig. 8. Super capacitor charging through the solar panel.

of this experiment conducted under normal conditions are shown in Fig. 5. The CO gas was injected into a measuring chamber in which the sensor was located. The CO concentration was varied as can be seen in Fig. 5.

The sensor node is designed to detect CO using two thresholds (see Fig. 5), set to $T_1 = 5\,\mathrm{mg/m^3}$ and $T_2 = 20\,\mathrm{mg/m^3}$, respectively, and stored in the MCU memory. In fact, depending on the application needs, the user can manually program the thresholds. The mentioned thresholds can also be changed within the program. If the detected concentration is less than T_1—the sensor node goes to sleep mode; if the concentration is between T_1 and T_2—a local sound alarm announces the increased CO concentration; finally, if the concentration is higher than T_2—the node transmits an alarm message to an operator via the network coordinator. As a result, the operator can (de) activate an actuator, e.g., a gas valve, to avoid potentially dangerous situations.

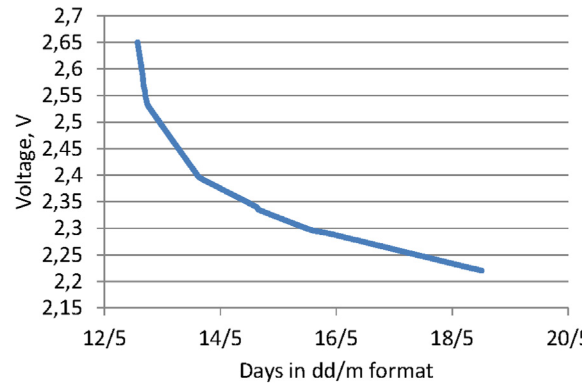

Fig. 9. Super capacitor self-discharge within 6 days.

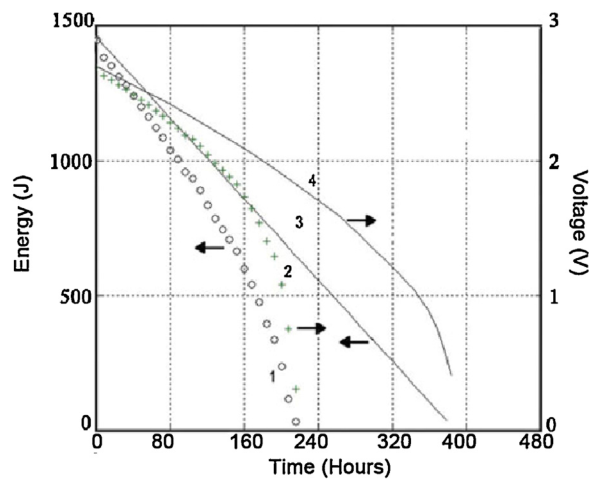

Fig. 10. Theoretical (solid curve) and experimental dependences (dots curve) for the supercapacitor energy (curve '1' and '3') and voltage (curve '2' and '4') during wireless sensor gas node operation.

The CO measurements are performed periodically according to the following algorithm (see Fig. 6). Most of the time, the sensor is in sleep mode, during which no measurements occur. During this time, the working and reference electrodes are connected. When a measurement is required, the MCU comes out of sleep mode and powers the sensor. At the same time, the working and reference electrodes are disconnected ("Electrodes → Open" state in Fig. 6), and transient signals can be observed at the output. In this case, as specified earlier, the stabilization of the output voltage is carried out within 10 s after the power is on. In order to decrease energy consumption within this time, the MCU goes again into sleep mode. Then, the MCU wakes up and the measurements of the CO concentration are performed and, if thresholds are exceeded, the data is sent to the sensor network coordinator. The measurements of the CO concentration are performed every minute during which the microcontroller wakes up. In this process, the working and reference electrodes still remain disconnected. When the measurements are over, the MCU connects the working and reference electrodes and switches the sensor node to sleep mode. Actually, the MCU is in energy saving mode almost the entire time, except when the measurements are performed or during the transceiver activation. During the data transfer time, the main consumer of energy is the transceiver. It is necessary to note that if the concentration of the CO gas is less than the defined thresholds, there is no need to send data to the network coordinator and this in turn decreases the power consumption.

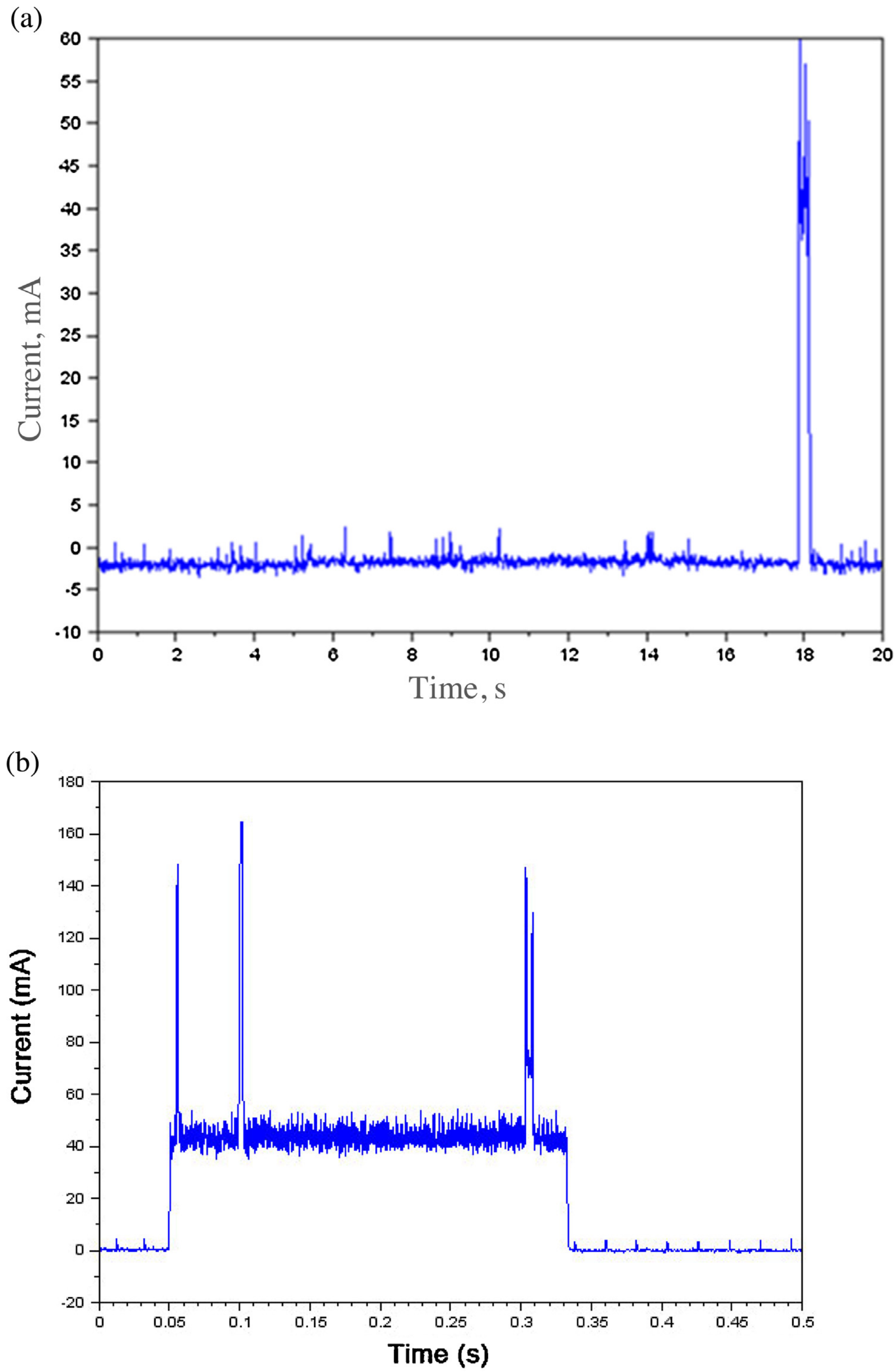

Fig. 11. Current consumption of sensor node: (a) in sensing mode and (b) average current consumption (sensing and data transmission) is 43.49 mA within 0.28 s.

5. Experimental results

In this section we demonstrate experimental results aimed at the evaluation of super capacitors performance depending on the ambient energy sources conditions.

5.1. Evaluation of supercapacitor performance

Fig. 7 demonstrates the curves showing the super capacitor charging from a wind generator. As a wind source, we used a fan which was placed in front of the wind generator at a distance guaranteeing constant 4 m/s wind speed for the generator. The wind speed was controlled by a wind speed detector.

Fig. 7(a) shows the time required to charge the super capacitor till 2.7 V at 4 m/s wind speed. This speed is chosen as an average daily wind speed in May in Moscow. Fig. 7(b) shows the time required for super capacitor charging depending on wind availability in outdoor conditions. The curve contains the parts associated with the wind availability and increase of voltage level.

Some parts are associated with the wind absence or its low speed which results in the super capacitor self discharge or slow charging.

Fig. 8 presents the curves of super capacitor charging using a solar panel in outdoor conditions. One of the curves shows charging in sunny weather in May in Moscow and the second curve demonstrates the results of the same experiment in cloudy weather. We did not measure the intensity of solar radiation since the goal was to evaluate the charging process in average sunny and cloud conditions.

Fig. 9 shows the status of the super capacitor self-discharge (current leakage) within approximately one week. During the first day the super capacitor discharges pretty quickly. When it achieves the value of 2.3 V the discharge process becomes slower. We have not continued this experiment till the full discharge of the super capacitor since the weather conditions certainly change during one week and sun or wind are expected to appear.

Fig. 10 shows the theoretical and experimental dependences for the super capacitor energy and voltage during wireless gas sensor node operation, if a fully charged super capacitor (1300 J, 400 F, 2.7 V) is used. We can observe that the super capacitor discharges much more quickly (for 200 h) compared to the theoretical time of 360 h. This result is due to the actual energy losses occurring in the conversion of energy, in particular because of losses in the DC–DC converter and the super capacitor self-discharge. DC–DC converters have a high efficiency (more than 90%) in the case of a lower voltage, but relatively low efficiency in the case of the need to raise the voltage (that is in our case).

5.2. Power consumption and life time estimation

Fig. 11 illustrates the current consumption during the CO measurement and data transfer to the network coordinator. The peak of current consumption is observed when data is received or transmitted. The current peak associated with connecting or disconnecting working and reference electrodes is not visible at this time scale since the switching time takes place in milliseconds.

It can be seen from Fig. 11(b) that the main power consumption periods are caused by the operation of the modem. The average current consumption during the data transfer time is 43.49 mA within 0.28 s (Fig. 11). Therefore, one measurement and consequent data transmission within one cycle, i.e., 1 min, results in 0.2 mA of average current consumption. Using one 3.7 V 3200 mAh li-ion AA-type battery as a backup power supply, the node can operate 21 month. Based on our experiments and strong background in this area we could claim that the lifetime of the proposed solution is basically limited by degradation of the physical conditions of electronic components and CO sensor. For this reason we always put "perpetual" in quotes, to mean that real perpetual operation in not physically attainable.

According to the sensor specification its lifetime is 7 years [22]. Periodical calibration (one per year) is a must requirement if the sensor is embedded in a gas detection system which is supposed to function in a harsh environment such as a gas plant, for instance. In our case the system operation is defined by two low thresholds and supposed to be deployed in a living area where working environment is friendly. The sensor parameters do not degrade much and according to relevant standards do not require calibration throughout the sensor lifetime.

The sensor node for CO monitoring proposed in this work improves the power consumption of the state-of-the-art platforms [8,10,27] up to three times depending on the measurement procedure and the period of measurements.

6. Conclusion

In this work, we have presented a CO wireless gas sensor with a hybrid power supply which takes its energy from solar and wind ambient sources. The sensor node can be applied for outdoor monitoring in urban areas and industrial facilities. The combination of the alternative energy sources and a backup battery can significantly extend the sensor lifetime ensuring its 'perpetual' operation.

The CO wireless gas sensor node has two gas concentration thresholds, i.e., 5 and 20 mg/cm^3. The sensor is designed to operate in the IEEE 802.15.4 ZigBee networks. The electrical circuit of the CO wireless gas sensor node and the measurement algorithms are optimized so that efficient energy consumption can be achieved.

It is shown that the charging of the capacitor by the solar cell is much more effective than that of the wind turbine. Therefore, a wind generator cannot effectively provide the power for wireless gas sensor node. This is a reason why the hybrid power supply with at least two ambient sources is needed.

We have demonstrated that a fully charged super capacitor discharges much more quickly (200 h) compared to the theoretical time (360 h). This result is due to the actual energy losses occurring in the conversion of energy, in particular in the DC–DC converter. Besides, we have experimentally demonstrated that the super capacitor was self-discharging within approximately one week from 2.7 V to about 2.2 V. Therefore, the self-discharge does not drastically influence the operation time of the wireless gas sensor node.

Switching from battery to the alternative energy sources takes place when the amount of voltage at the super capacitors is 0.9 V; i.e., even when they are not fully charged. This mechanism saves more energy for the battery which acts as the energy buffer. The choice of using wind or solar energy is based on the amount of voltage available on the corresponding super capacitors, i.e., that alternative source powers the sensor node whose super capacitor has the highest voltage. Moreover, the circuit design makes it possible to charge the super capacitors and extract energy from them simultaneously.

We plan to apply the developed power supply circuit to other devices of the WSNs as well. These devices can be coordinators, actuators, relays and other gas sensors.

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