Battery-less wireless current sensor node utilizing the dependence of charging time of a capacitor on the current flowing through a power line

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Abstract: In this paper, we propose and demonstrate a new battery-less wireless current sensor node which transmits data using the power charged in a chip capacitor with a current transformer (CT). Since the charging time depends on the current flowing through a power line, the current value can be known by measuring the transmission interval if the node transmits data every time when the power is charged enough to the transmission. In this node, because analog to digital (AD) conversion is not needed, a simple circuit without a rechargeable battery can be realized.

Keywords: wireless sensor node, power monitoring, battery-less

Classification: Electron devices, circuits, and systems

References

1 Introduction

Sensor networks are expected to be utilized for health [1] and security applications [2] as well as environmental monitoring [3] and could enable real-time visualization of power consumption so that energy efficiency is improved. This is very attractive for the energy-management systems in a lot of facilities, such as offices, factories and homes.

Our research team has been developing an electrical power monitoring system with wireless current sensor nodes. The wireless current sensor with a current transformer (CT) and a button battery (LR44) [4] is a useful tool especially to install in existing facilities because the wiring work is not needed. This system has been installed in several thousands of convenience stores in Japan [5]. The nodes have been set at the power lines in the power distribution panels of the stores. Since each power line is connected to specific instruments, such as refrigerators, lighting, air conditioners, we can see the power consumption of these instruments and can decrease waste of the electricity by analyzing the obtained data. One of the respects to be improved of this system is the battery replacement. The life time of the wireless sensor node is about 1 year in the case that the transmission interval is 10 seconds. At present, about 16000 nodes are already installed in the convenience stores. The time and cost for the battery replacement is not negligible and the spread of this system could be prevented.

In this wireless sensor node, although the CT is used as current sensor, it must be able to accumulate energy from a power line for the operation of the wireless sensor node. Actually, Pedro Amaro et. al demonstrated that a Zigbee module can work using power generated by CT and charging circuit with a commercially available chip for power management [6]. Although they describe the basic battery-less platform that the power is generated with a CT, the method to measure the current flowing through a power line was not shown. In the case of using a CT for current measurement, a current value is generally measured by analog to digital (AD) conversion. However, this method needs a switch which changes the output line of the CT from the charging circuits to the measurement circuits. In addition, since the power for the AD conversion is also required, a bigger size capacitors or a rechargeable battery could be necessary.

This paper presents a battery-less wireless current sensor node using a simple charging circuit without an AD converter. This node transmits data using the power charged in a chip capacitor with a CT from a power line every time when the power is charged enough to the wireless transmission. In this system the time interval between the transmission is depend on the
current flowing through the power line. Therefore the current value can be known by measuring the transmission interval. In this node, because an AD conversion is not needed, a simple circuit can be realized.

2 Design

Fig. 1 shows the circuit realizing the proposed system. The power generated by the CT is rectified and step-up converted with Cockcroft-Walton circuit [7], then charged in the capacitor C₀. If the voltage generated by the CT is not enough to work integrated circuits (IC), the voltage have to be step-up converted. Usual step-up converter or charge pump circuits need switching signal and increase the DC voltage. Since the Cockcroft-Walton circuit directly step-up converts the AC output signal from the CT to DC signal, the efficiency is high. The R₀ is the shunt resistor. The V₀ is the voltage of C₀. The voltage V₁ divided V₀ by resistor R₀ and R₁ is monitored by the comparator U₀ with the band-gap reference voltage V_{ref} (≈1.242 V) generator (Burr-Brown TLV3012). The U₀, the power of which is supplied from the C₀, starts to work when the V₁ is 1.8 V. When the voltage V₁ exceeds the V_{ref}, the output signal of the U₀ changes to high level. Then, the capacitor C₁ is immediately charged through the diode D₀, for backflow prevention, simultaneously with increase of the voltage V₂ of the C₁. Then, the output signal of the comparator U₁ (Microchip MCP6441) changes to high level. Finally the analog switch U₂ (Analog Devices ADG849) becomes ON state, then the power is supplied to the micro controller unit (MCU) and radio frequency integrated circuit (RF-IC). At this time, since the power charged in the C₀ is supplied to the MCU and RF-IC, the V₀ decreases just after the analog switch became ON state. Then the output of U₀ immediately changes to low level. However, the output signal of the U₁ keeps high level until the V₂ decreases to V_{ref}. Since the speed of the decrease of V₂ is controlled by the resistor R₃ and C₁, enough time to finish the wireless transmission can be set. After the voltage V₂ drops down to V_{ref}, the analog switch becomes OFF state, and then the power in the C₀ starts to be charged.

Fig. 1. Schematic circuit of the developed wireless sensor node.
In this system, if the power consumption of the wireless transmission is the same every time, the transmission interval depends on the current flowing through a power line. For example, if the current is big, the interval between the transmissions is short because the $V_{1}$ increases up to $V_{\text{ref}}$ quickly. In this node, the operation of the MCU and RF-IC is only to transmit the ID of the node and the consumed power is the same every transmission. Thus, the current value can be known by measuring the transmission interval.

First, the power required for the wireless transmission was estimated so that the circuits realizing to supply the power to the MCU and RF-IC was designed. In this research, a C8051F930 (Silicon Laboratories) [8] and a nRF24L01 (Nordic Semiconductor) [9] were used. At the condition of wireless transmission described in Table I, the calculated operation time from the beginning of power supply to the MCU and RF-IC to the completion of the wireless transmission is $370\,\mu s$. Since the minimum operating voltage of these ICs is 1.8 V, the available charge ($Q$) is expressed as

$$Q = C_0 \times (V_{\text{st}} - 1.8) \quad (1)$$

Where $V_{\text{st}}$ is the threshold voltage for the $U_0$ and equals $V_{\text{ref}} \times (R_1 + R_2)/R_1$. In order to decrease the power consumption, the $R_1$ and $R_2$ should be high value. If both $R_1$ and $R_2$ are 10 MΩ, the $V_{\text{st}}$ is 2.48 V. In this case, $Q$ is $0.68 \times C_0$. Since the peak current of this operation is 11.3 mA at the wireless transmission [9], the maximum required charge is $4.18\,\mu A$. Therefore, the necessary $C_0$ is 6.15 $\mu F$. In this research, we used a 100 $\mu F$ of chip ceramic capacitor as the $C_0$.

<table>
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<th>Table I. Conditions of the wireless transmission.</th>
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<td>Frequency</td>
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<td>Packet structure</td>
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<td>Output power</td>
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If the forward voltage of $D_0$ is 0.3 V [10] and the output high voltage of $U_0$ is 1.8 V, the charge of the $C_1$ is $1.5 \times C_1$ when the output of $U_0$ is high level. Since the $U_1$ must keep the output high level for more than $370\,\mu s$, the $R_3$ and $C_1$ must meet following condition;

$$370 < -C_1R_3 \log(V_{\text{ref}}C_1/1.5C_1) \quad (2)$$

Eq. (2) is derived from the equation of discharge of a capacitor. According to Eq. (2), the value of $C_1 \times R_3$ should be more than $2.24 \times 10^{-3}$. In this node, 1 MΩ of $R_3$ and 100 nF of $C_1$ are used.

### 3 Experimental results

Fig. 2 shows the photograph of the developed wireless current sensor node. The dimensions of the substrate are 25 mm $\times$ 18 mm. In this node, the 4 times...
Fig. 2. Photograph of the developed node. (a) is front side of the substrate connected to the CT. (b) is the backside.

rectification circuit is used. Fig. 3 shows the relationship between the current flowing through a power line and transmission interval. In this measurement, a current calibrating apparatus (FLUKE 5080A), the maximum current of which is 20.5 A, was used. The power line connected to the apparatus was clamped by the CT of the node. Since the transmitted packet does not include the time at the wireless transmission, the transmission interval was measured by a receiver system that can save the receiving time. In the Fig. 3, the each point is the average of five measured intervals and the error bars are also shown. In this system, the maximum washable current is limited by the dispersion of the transmission interval and the dispersion is caused by the ripple. Although the maximum washable current of this node is about 20 A, it can be increased by means of installing some smoothing circuits. On the other hand, the minimum washable range is restricted by the maximum voltage of $V_0$ which is decided by the CT, shunt resistor $R_0$, step-up conversion circuit and the power consumption of the power control circuit. If the $V_0$ does not exceed the $V_{ref}$, the power charged in $C_0$ is not

Fig. 3. Relationship between current flowing through a power line and transmission interval.
supplied to the MCU and RF-IC. In the case that the CT is CTL-6-S32-SF-CL (U_RD), $R_0$ is 1 kΩ and the measured power consumption of the power control circuit of Fig. 2 is $3.6\, \mu A$ at $2.4\, \text{V}$ of $V_0$, the minimum measurable range is about 2 A.

Fig. 4 shows a measurement of a ceramic heater with a 400 W - 800 W selection switch. A commercially available clamp meter was used to compare the measured values and the current values at 400 W and 800 W were 3.9 A and 7.7 A, respectively. This result indicates that the measurement values are almost the same.

![Graph showing current measurement results](image)

**Fig. 4.** Demonstration result of measurement of a ceramic heater with a 400 W - 800 W selection switch.

### 4 Conclusion

We developed battery-less wireless current sensor which can realize by the simple circuit without a rechargeable battery and an AD conversion function. The power for the operation of this node is charged in 100 $\mu F$ of the chip capacitor and the wireless transmission is carried out every time when the power is charged enough to the transmission. We showed that the developed nodes can measure the current from 2 A to 20 A and the causes which contribute to the limit of the measurable current range. We also demonstrated the current measurement of a ceramic heater and indicated that the measurement values were almost identified with the values measured by a commercially available clamp meter.