# Design of magnetic field alarm powered by magnetic energy harvesting

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*Abstract*—**This paper presents a design of magnetic field alarm powered by magnetic energy harvesting. It consists of an energy harvesting module, Cockcroft-walton circuit and piezo buzzer. The energy harvesting module is composed of coil and magnetic flux concentration core. It can generate 200 µW from an environmental magnetic field of 200 µT at 60 Hz. The Cockcroft-walton circuit can converts the ac voltage to a suitable dc voltage for the piezo buzzer. This alarm can notice not only the magnetic field level defined by ICNIRP2010 but also the existence of magnetic field energy to be harvested. It is the first demonstration of a "self-generating component" powered by magnetic energy harvesting.**

***Keywords-magnetic field alarm; energy harvesting module; magnetic flux concentration core; CW circuit; self-generating component;***

## I. INTRODUCTION

Magnetic field is a reusable energy source to be used for both energy harvesting and wireless power transmission applications. Because electrical appliances are usually powered by electric wire, the well-known component of environmental magnetic fields is 50 or 60 Hz. In previous report, energy harvesting of 6.32 mW from a uniform magnetic field of 21.2 µT at 60 Hz, and activating a wireless sensor node have been demonstrated [1]. For energy management systems, some researcher's proposed a battery-free real-time current-waveform sensor powered by magnetic field around ac power line [2-3]. Because the output voltage of an energy harvesting module for environmental electromagnetic field is ac signal, rectifier and signal conditioning circuits should be installed for the energy source of wireless sensor nodes [4-6]. With a Cockcroft-walton circuit (CW circuit) [7-8] and storage capacitor [9], magnetic energy harvesting of 17 mJ from electrical appliances have been also demonstrated [10]. It may enough energy to activate a wireless sensor node, and "one-shot" signal. It was also mentioned the benefit of magnetic flux concentration core [11]. The theoretical design have revealed that the harvesting power is proportional to the fifth power of the outer diameter [12]. For example, air-cored Brooks coil of 280 mm in outer diameter demonstrated the energy harvesting of 562 mW from a magnetic field of 200 µT at 60 Hz. In contrast, the estimated power becomes 100 kW when the outer diameter is 3.6 m. It could be used for wireless power transmission application with a room-sized or building-sized coil system for producing a uniform magnetic field.

From the view point of the effect on humans, ICNIRP2010 provides a guideline for an acceptable electromagnetic field level [13]. At the power-line frequency of 50/60 Hz, an acceptable level in a public space is 200 µT. The motivation of this study is to notice and use this magnetic field. Compared with other reusable energy sources, such as light, thermal or vibration energy, human cannot notice the existence of magnetic field by own five senses.

This paper presents a design of magnetic field alarm which does not require an external battery, and the size is limited to 50 mm × 50 mm × 50 mm. Fig. 1 shows schematic diagram of the magnetic field alarm. It consists of an energy harvesting module, CW circuit, and piezo buzzer. It is an demonstration of "self-generating component" powered by magnetic energy harvesting. From the data sheets of the piezo buzzer sold in market, a special loud buzzer that functions at very low voltage was selected whose minimum operating voltage and current are as low as 0.7 Vdc and 0.3 mA (SC 0715 BL, Sonitron), respectively.

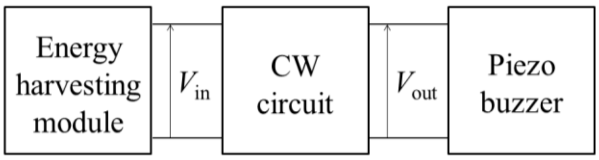


Figure 1. Schematic diagram of magnetic field alarm.

## II. ENERGY HARVESTING MODULE

Fig. 2 shows the equivalent circuit of the energy harvesting module. Based on the Faraday's law of induction and Thevenin's theorem, the amplitude of the voltage source $V_{in}$ (V) can be expressed by following equation.

$$V_{in} = 2\pi^2 f n a^2 \mu_{eff} \mu_0 H \text{ (V)} \quad (1)$$

Where $f$ (Hz) is the frequency of the magnetic field, $n$ (turn) is the number of coil windings, $a$ (m) is the mean radius of the coil, $\mu_{eff}$ is the effective permeability of magnetic flux

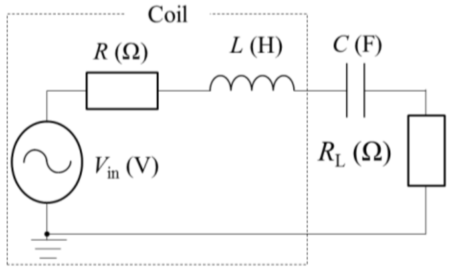


Figure 2. Equivalent circuit of the energy harvesting module.

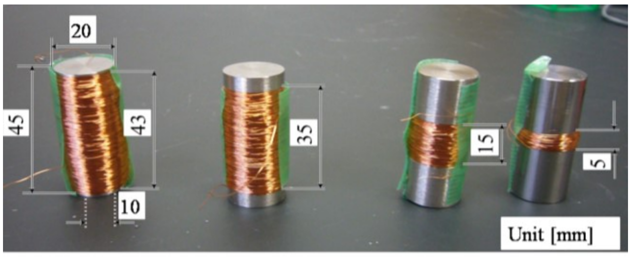


Figure 3. An example of energy harvesting modules as a function of the coil length. Magnetic flux concentration cores were made of PC permalloy.

concentration core, $\mu_0$ is the permeability of vacuum, and $\mu_0 \times \mu_{eff} \times H$ (T) is the mean flux density crossing with the mean cross section of the coil. The magnetic flange can concentrate the environmental magnetic field to the core, which improves the effective permeability. The effective permeability is defined by the following equation.

$$V_{in} = \mu_{eff} V_{air} \text{ (V)} \tag{2}$$

Where $V_{air}$ is the induced voltage of the coil without the core. The impedance of this circuit can be expressed by following equation.

$$Z = (R+R_L)+j(\omega L-(1/\omega C)) \ (\Omega) \tag{3}$$

When the imaginary part is negligible, the impedance becomes minimum. Using the maximum power transfer theorem, load $R_L$ should be the same as the coil resistance. The output voltage can be used for calculating the harvesting energy $W$ (W).

$$W = V_{out} / R = V_{in}^2 / 4R \text{ (W)} \tag{4}$$

If the diameter and total length of the core are fixed, the harvested energy is limited. Fig. 3 shows an example of energy harvesting modules as a function of the coil length. The magnetic flux concentration cores were made of PC permalloy. The total length is 45 mm, outer diameter is 20 mm, inner diameter is 10 mm, and the diameter of the coil is 0.2 mm. The values of number of coil windings are 500, 1500, 3500 and 4300 for 5, 15, 35 and 43mm in coil length, respectively. Fig. 4 shows the induced voltage as a function of coil length. The calculated results by FEM (JMAG-Designer Ver.12) are also plotted. When the coil length was larger than half of length of the core, the value of induced voltage converged. An increase in the coil length produces an increase in the number of coil windings and an decrease in the flange length. Although the

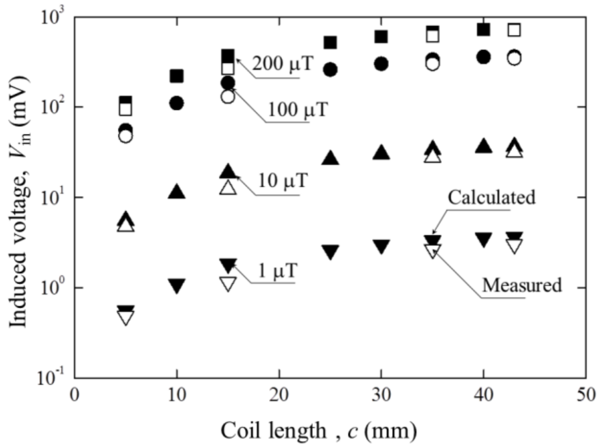


Figure 4. Induced voltage as a function of coil length, as a paremeter of magnetic field strength. The frequency of magnetic field was 60 Hz.

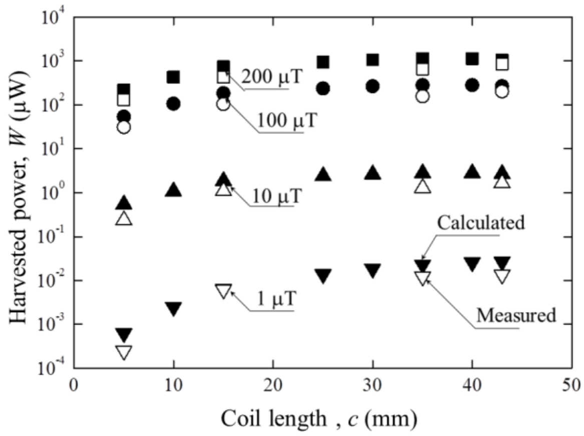


Figure 5. Harvested power as a function of coil length, as a paremeter of magnetic field strength. The frequency of magnetic field was 60 Hz.

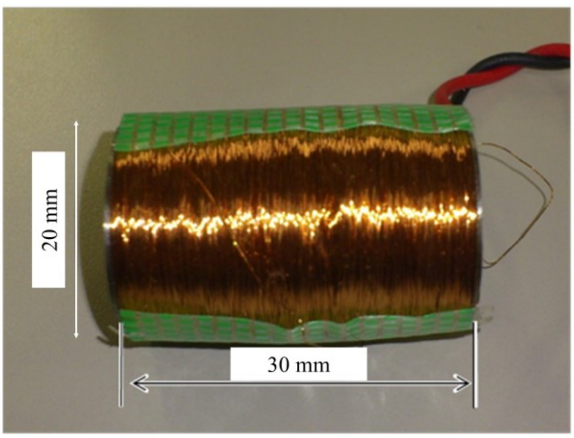


Figure 6. Energy harvesting module for magnetic field alarm. The magnetic flux concentration core was made of iron, whose flange length was 0.5 mm.

induced voltage is proportional to the number of coil windings, an decrease in the flange length limits the induced voltage because of an decrease in the effective permeability. Fig. 5 shows the harvested energy as a function of the coil length. When the coil length was larger than half of length of the core, the value of induced voltage converged.

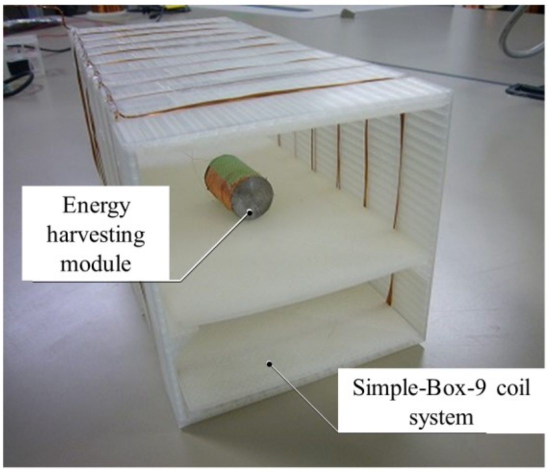


Figure 7. Experimental setup for evaluation of the energy harvesting module.

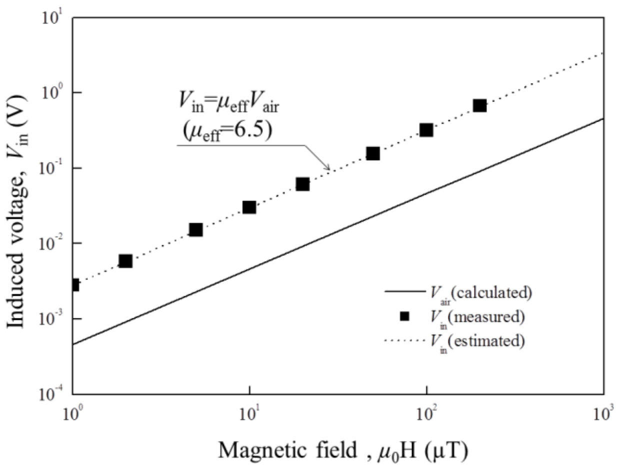


Figure 8. Induced voltage of the energy harvesting module as a function of magnetic field strength. The frequency of magnetic field was 60 Hz.

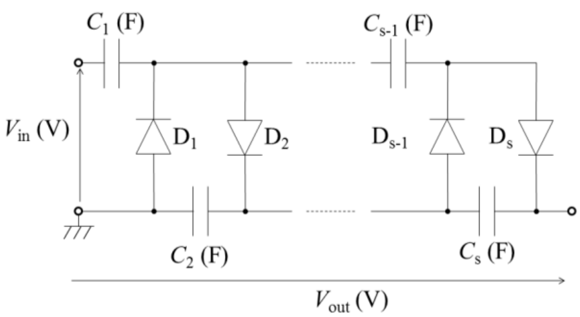


Figure 9. Schematic design of CW circuit.

Although an CW circuit can convert to a suitable DC output voltage, the input voltage should be larger than 0.1 V. From several considerations, final design of the energy harvesting module was defined. Fig. 6 shows the energy harvesting module for the magnetic field alarm. It consists of a coil and magnetic flux concentration core made of iron. The core has 10 mm in inner diameter, 20 mm in outer diameter, 0.5 mm in magnetic flange length, and 30 mm in coil length, respectively. The number of coil windings is 7000 with the wire of 0.12 mm in diameter. The measured resistance and inductance were 515 Ω and 2.04 H, respectively. From (1), the estimated value of induced voltage was 0.1 V when a magnetic field of 200 μT at 60 Hz crossed to the coil without the core.

Fig. 7 shows the experimental setup for evaluation of the energy harvesting module. The energy harvesting module was placed inside an Simple-Box-9 coil system (SB9). SB9 can generate uniform magnetic field. SB9 was composed of nine square coils connected in series, the ratio of the coil windings is 2:1:1:1:1:1:1:1:2 , and the distance was 1/4 side length of the coil. When the side length of the square coil is $d$ (m), it can generate 4.762/$d$ (μT/A) [14]. The fabricated SB9 has 0.1 m in the side length, which can generate 190.5 (μT/A) because the number of windings is 4 times as 8:4:4:4:4:4:4:4:8.

Fig. 8 shows the induced voltage of the energy harvesting module as a function of the magnetic field of 60 Hz. Solid line represents the estimated value of the induced voltage without the core, plots represent the experimental results, respectively. When the magnetic field was 200 μT, the induced voltage was 668 mV. From (3) and (4), the estimated effective permeability and harvesting energy of this module are 6.5 and 200 μW, respectively.

## III. CW CIRCUIT

In order to activate the piezo buzzer, the required output voltage should be larger than 1.5 V. To provide the suitable voltage, design of the CW circuit was considered. Fig. 9 shows the CW circuit. It consists of low-voltage-driving Schottky diodes (1N5818, ST Microelectronics corp.) and capacitors of 10 μF (1HEC-FS100M, Toushin Kougyou). The building block of the CW circuit consists of two diodes and two capacitors, and can provide twice value of dc output voltage. In an ideal CW circuit, the number of building block, or number of steps, can make the multiple the value of the dc output voltage. However, the losses in the CW circuit make the value low. The output voltage of the CW circuit can expressed by following equation.

$$V_{out} = \alpha \times s \times \sqrt{2}\ V_{in}\ (\mathrm{V}) \qquad (5)$$

Where $\sqrt{2}V_{in}$ is the peak value of the input voltage, $s$ is the number of steps and $\alpha$ is the ratio compared with the ideal value. When there are no losses in the circuit, the value of $\alpha$ is 1. Fig. 10 shows the schematic design of the experimental setup for evaluation of the CW circuit. The output voltage was measured with a TRUE RMS MULTIMETER (Digital tester 187, FLUKE.).

Fig. 11 shows the measured output voltage as a function of the magnetic field, as a parameter of the number of steps. It was found that all CW circuit provided the amplified dc output voltage when the magnetic field was larger than 10 μT. If the magnetic field was larger than 100 μT, the output voltage was larger than 1.5 V when the number of steps was larger than 4. Fig. 12 shows the ratios, $V_{out}/V_{in}$ and $\alpha$, as a function of the number of steps. The magnetic field was 200 μT at 60 Hz. From (5), ideal step-up ratios, $V_{out}/V_{in}$, are 2.83, 5.66, 8.49, 11.3 and 14.1, respectively. However, the measured step-up ratios are 2.47, 5.08, 7.5, 9.76 and 11.9, respectively. Although an increase in the number of steps produces an increase in the output voltage, it also produces an increase in the energy loss at the circuit. When the number of steps was 4, the maximum value of $\alpha$ was obtained. From the consideration mentioned above, the number of step was designed as 4 for the magnetic field alarm.

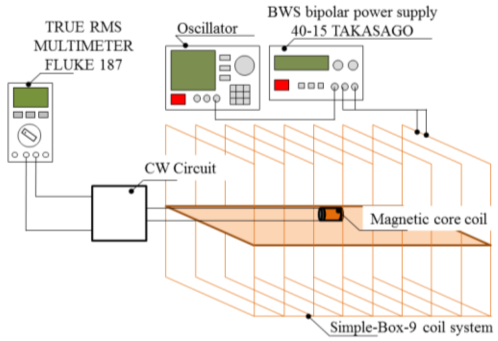


Figure 10. Experimental setup for evaluation of the CW circuit.

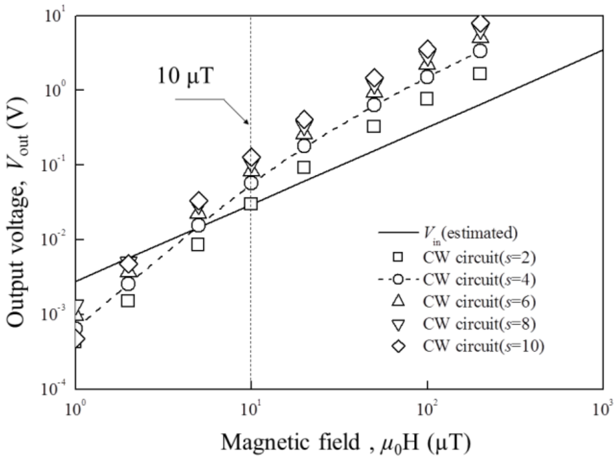


Figure 11. Output voltage of the CW circuit as a function of magnetic field strength. The frequency of magnetic field was 60 Hz.

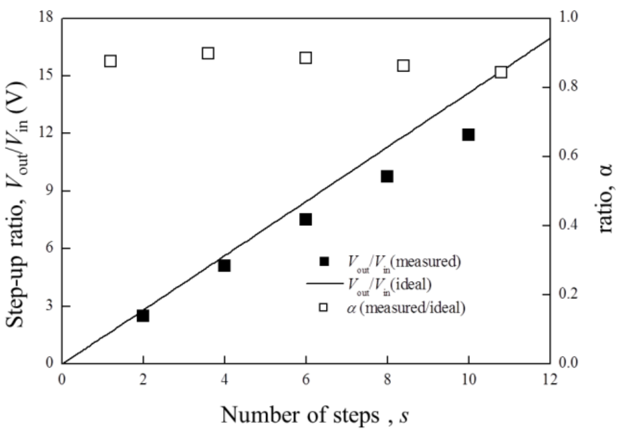


Figure 12. Measured ratios, $V_{out}/V_{in}$ and α, as a function of the number of steps in the CW circuit. Magnetic field was 200 μT at 60 Hz.

## IV. MAGNETIC FIELD ALARM

Fig. 13 shows the magnetic field alarm. All of the parts were contained inside a cubic case made by an 3D printer (MakerBot replicator 2), and the size of the alarm is 50 mm × 50 mm × 50 mm. In order to check the operation, it was placed inside the SB9. When the magnetic field of 60 Hz was larger than 100 μT, the alarm started to sound a buzzer. Fig. 14 shows the measured output voltage as a function of magnetic field. When the alarm sounded a buzzer, the voltage drop at the buzzer was about 0.5 V. This alarm can notice the existence of environmental magnetic field without any external battery.

## V. CONCLUSION

This paper presented a design of magnetic field alarm. It

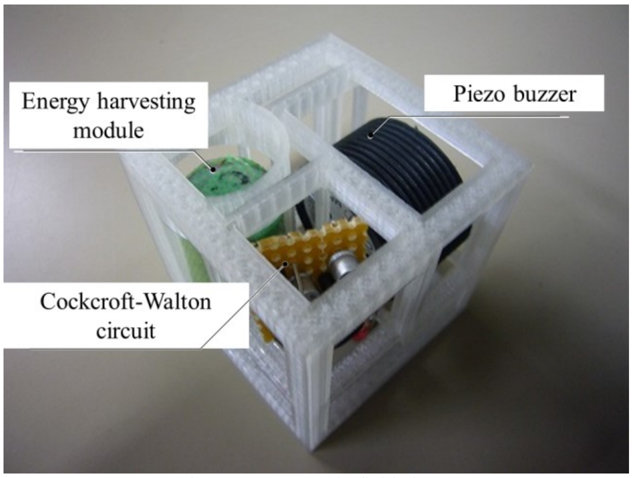


Figure 13. Magnetic field alarm.

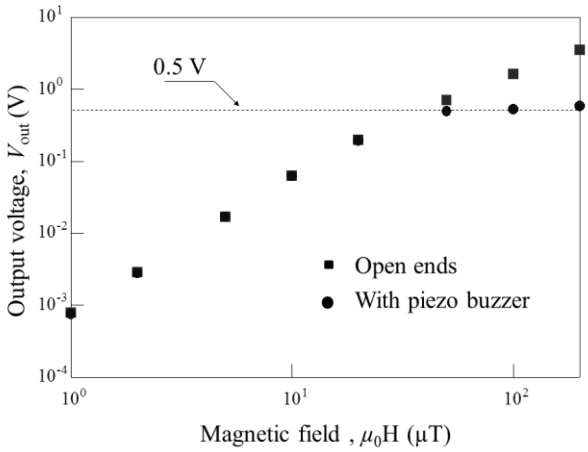


Figure 14. Measured output voltage as a function of magnetic field strength. The frequency of magnetic field was 60 Hz.

consists of the energy harvesting module, CW circuit and piezo buzzer. The energy harvesting module has a magnetic flux concentration core whose effective permeability was 6.5, and it can provide 200 μW from environmental magnetic field of 200 μT at 60 Hz. With the help of CW circuit, a suitable dc voltage can provide to a load. This alarm can notice not only the magnetic field level defined by ICNIRP2010 but also the existence of magnetic field energy to be harvested. It was the first demonstration of a "self-generating component" powered by magnetic energy harvesting.

## ACKNOWLEDGMENT

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