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Theoretical Design of Energy Harvesting Module or Wireless Power Transmission Receiver Using Magnetic Field of 0.2 mT at 60 Hz

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Abstract: This paper presents a theoretical design method for a magnetic energy harvesting module. This module consists of an air-core coil and resonant capacitor. With a simple RLC circuit model, it can derive an equation of harvesting energy as a function of coil size. In order to demonstrate the magnetic field, a uniform magnetic field is generated by the developed coil system. From the experimented results, it is successfully demonstrated 100 mW of energy harvesting from a magnetic field of 0.09 mT at 60 Hz. This value is in good agreement with the estimated results. Harvested energy is proportional to the square of the magnetic flux density. However, ICNIRP2010 provides a guideline that an acceptable level for human health in a public space is 0.2 mT at power-line frequency. This paper also discuss the possibilities of several applications related with both magnetic energy harvesting and wireless power transmission.

Key words: Magnetic energy harvesting, wireless power transmission, theoretical design, ICNIRP2010.

1. Introduction

Electromagnetic fields are usually used as an energy medium in energy transforming modules. In 2007, a wireless power transfer method proposed by an MIT group (magnetic resonant coupling type) [1] has attracted many engineers. The wireless power transfer methods could be categorized into three types [2]: magnetic induction, resonance, and microwave.

The magnetic induction method is the most conventional method. Because it focuses on the coupling factor between the transmitter and receiver coils, magnetic materials are usually used. It should be noted that the frequency range should be relatively low to reduce eddy current loss in the magnetic materials. Although the magnetic materials could limit undesirable magnetic leakage, power transfer efficiency strongly depends on the position between the transmitter and receiver coils. It is known that the typical transmission distance is less than 1 m. The resonance method uses the electric or magnetic resonance phenomena. An increase in the quality factor provides an increase in the power transfer efficiency, and the transmission distance could be a few meters. If inserting resonators between the transmitter and receiver coil, the transmission distance could be expanded. Because the typical frequency range used in this method is larger than 1 MHz, it should also take into account the energy losses in the power supply device and power conditioning circuits, such as rectifier circuit and DC-DC converter. While a magnetic material is not required to this method, the magnetic leakage around the resonance coil should be reduced. The microwave method uses the ability to hold a straight line. Solar Power Satellite/Station is a well known project where power is transmitted off the

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earth with microwaves. The receiver is usually called a "rectena" which consists of an antenna and a rectifier. Because the typical frequency to be used in this method is 2.45 GHz or 5.8 GHz, one can use a low cost magnetron used in a conventional micro oven for the transmitter. Although the system can be built at low-cost, the power transmission efficiency is not high compared with the other methods.

To realize a wireless power transfer device, it must confirm several rules. For example, from a human effects perspective, ICNIRP2010 provides a guideline for an acceptable electromagnetic field level [3]. In the case of the microwave method, the acceptable level is 10 W/m^2. Because typical power density of direct sun is 1,000 W/m^2 [4], one can easily understand that this is one of barriers to practical application. In contrast, one can use the environmental magnetic field whose amplitude is up to the value defined by this guideline.

In previous report, it have proposed the energy harvesting of power-line magnetic field [5]. Because power-lines are necessary for a modern life, it is required to coexist with undesirable magnetic power-line noise. From the view point of the effect on humans, an acceptable level in a public space is 200 μT at power-line frequency (50 Hz or 60 Hz). The developed energy harvesting module has demonstrated energy harvesting of 6.32 mW from a magnetic field of 21.2 μT at 60 Hz, and activating a wireless sensor node. This paper presents a theoretical design method of magnetic energy harvesting module, and confirm its validity through experimentally harvesting up to 100 mW of energy. Assuming that the usable magnetic field of 60 Hz is 200 μT, it also reveals the relationship between the module size and harvesting energy.

2. Principle

Fig. 1 shows the equivalent circuit of the energy harvesting module. The values of inductance L (H) and resistance R (Ω) were estimated as:

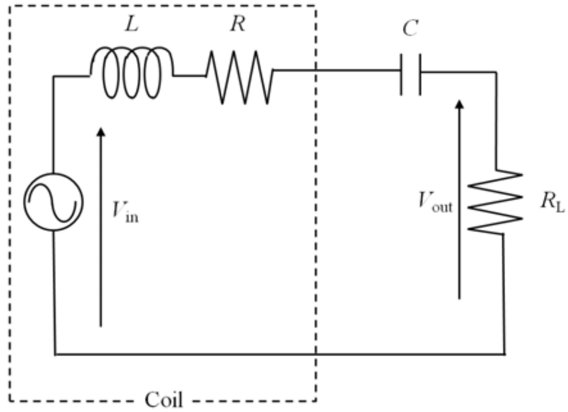

Fig. 1 Equivalent circuit of the harvesting module.

$$L = P_0 a n^2 \text{ (H)} \quad (1)$$

$$R = 2\pi a n \rho / s \text{ (Ω)} \quad (2)$$

where, a (m) is the mean radius, n is the number of turns, ρ (Ω·m) is the resistivity of copper at room temperature, and s (m^2) is the cross sectional area of the winding. P_0 (H/m) is the coil coefficient defined by the coil shape. For example, the value of P_0 for an ideal solenoid coil with finite length is determined by the product of the circular constant π, permeability of vacuum in H/m, length to diameter ratio of the coil, and the Nagaoka coefficient. If the ratio of coil length, inner diameter and outer diameter are constant, the value of P_0 becomes constant. A Brooks coil is a circular coil with a square cross section, and the ratio of the coil length, inner diameter, and outer diameter is 1:2:4 [6]. Because of the constraint shape, it is known that the value of P_0 is constant as 1.6994×10^{-8} H/m. This coil shape is suitable for development of a resonance circuit because it can achieve the maximum inductance for a given length of winding wire.

From Faraday's law of induction and Thévenin's theorem, the amplitude of the voltage source V_{in} (V) can be expressed by:

$$V_{in} = 2\pi^2 f n a^2 B \text{ (V)} \quad (3)$$

where, f (Hz) is the frequency and B (T) is the mean flux density crossed with the mean cross section of the coil. To provide a resonance frequency at 60 Hz, power-line frequency, the resonant capacitor C (F) can be chosen from:

$$f = 1 / 2\pi (LC)^{1/2} \text{ (Hz)} \quad (4)$$

Using the maximum power transfer theorem, load R_L (Ω) should be the same as the coil resistance. The output voltage V_{out} (V) can be used for calculating the harvesting energy W (W) with:

$$W = V_{out}^2 / R = V_{in}^2 / 4R \text{ (W)} \tag{5}$$

Substituting Eq. (3) gives:

$$W = (\pi^4 f^2 n^2 a^4 / R) \times B^2 \text{ (W)} \tag{6}$$

This means that the harvesting energy is proportional to the square of the magnetic flux density. If the coil has a magnetic core, the following equation can be obtained:

$$W = (\pi^4 f^2 n^2 a^4 / R) \times \mu_{eff}^2 \times (\mu_0 H)^2 \text{ (W)} \tag{7}$$

where, $\mu_0 H$ is the mean flux density when the coil does not exist and μ_{eff} is the effective permeability. Fortunately, the harvesting energy is proportional to the square of the effective permeability. However, the effective permeability is defined by the shape of the magnetic core due to the demagnetizing field. In other words, the effective permeability is finite value even if the magnetic material has infinity permeability.

Here, the limitation of harvesting energy defined by the coil size is considered. The air-core coil is Brooks coil having the spacing factor β:

$$ns = \beta c^2 \text{ (m}^2\text{)}. \tag{8}$$

where, c (m) is the length, $2c$ (m) is the inner diameter, $4c$ (m) is the outer diameter, c^2 (m^2) is the cross section and $3c/2 = x$ (m) is the mean radius of Brooks coil. Without considering a wire insulator, an ideal lamination factor corresponds to $\beta = 1$. Substituting Eqs. (2) and (8) into Eq. (7) gives:

$$W = c^5 \times (27\pi^3 \beta f^2 / 16\rho) \times \mu_{eff}^2 \times (\mu_0 H)^2 \text{ (W)} \tag{9}$$

It can be seen that the harvesting energy does not depend on the number of windings. In contrast, the harvesting energy is proportional to the fifth power of c. This means that the harvesting energy has strongly depended on the coil size.

3. Experiment

Fig. 2 shows the magnetic energy harvesting module, and Table 1 shows the specifications. It consists of an air-core coil, a resonant capacitor, and a dummy load. The measured values of the resistance and inductance were in good agreement with the estimated values to within ±3% relative error.

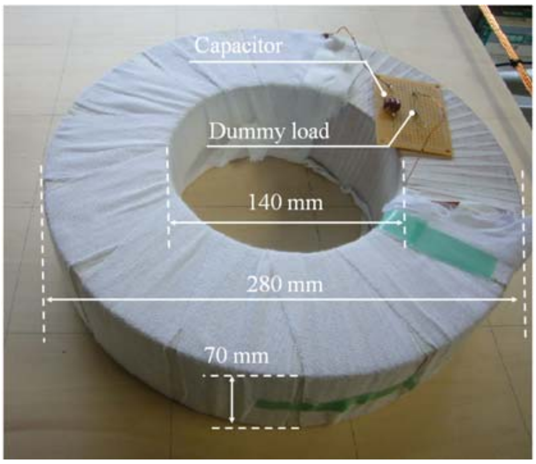

Fig. 2 Magnetic energy harvesting module.

Table 1 Specifications of the harvesting module.

Property	Value
Coil width, c (m)	0.07
Inner diameter, $2c$ (m)	0.14
Outer diameter, $4c$ (m)	0.28
Mean radius, $a = (3/2)\, c$ (m)	0.105
Diameter of the windings, δ (m)	0.5×10^{-3}
Cross section of the windings, $s = (\pi/4)\delta^2$ (m^2)	1.96×10^{-7}
Number of windings, n	18,395
Spacing factor, $\beta = ns / c^2$	0.737
Estimated resistivity, ρ (Ω·m)	1.78×10^{-8}
Coil constant for Brooks coil, P_0 (H/m)	1.6994×10^{-6}
Inductance, L (H)	
Measured	60.6
Estimated (= $P_0 a n^2$)	60.4
Resistance, R (Ω)	
Measured	1,060
Estimated (= $2\pi a n \rho / s$)	1,100
Resonant capacitor, C (F)	0.1×10^{-6}
Dummy load, R_L (Ω)	1,000
Frequency of the magnetic field, f (Hz)	60
Effective permeability, μ_{eff}	1
Estimated harvesting power, $W = (\pi^4 f^2 n^2 a^4 / R) \times \mu_{eff}^2 \times (\mu_0 H)^2$ (W)	$1.31 \times 10^7 \times (\mu_0 H)^2$

According to the theoretical estimation, the harvesting energy is 106 mW from the magnetic field of 90 μT. This energy is enough power to operate low-power consumption devices, such as MP3 player or PALM device [7]. Fig. 3 shows the experimental setup. To demonstrate environmental magnetic field, Simple-Cubic-3 coil system (SC3) [8] was used. SC3

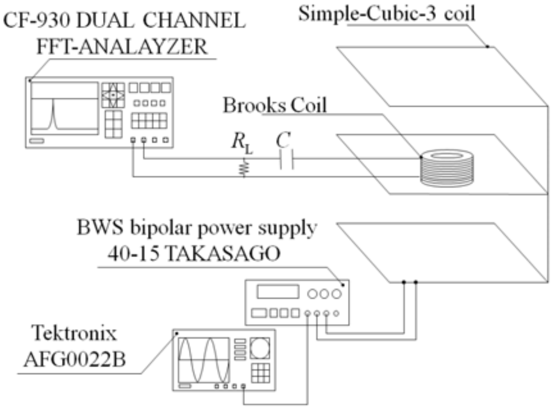

Fig. 3 Experimental setup.

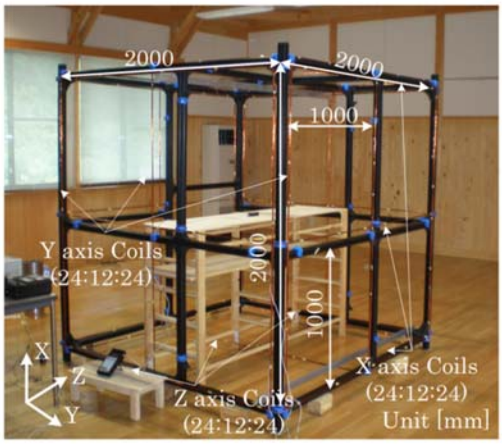

Fig. 4 Simple-cubic-3 coil system.

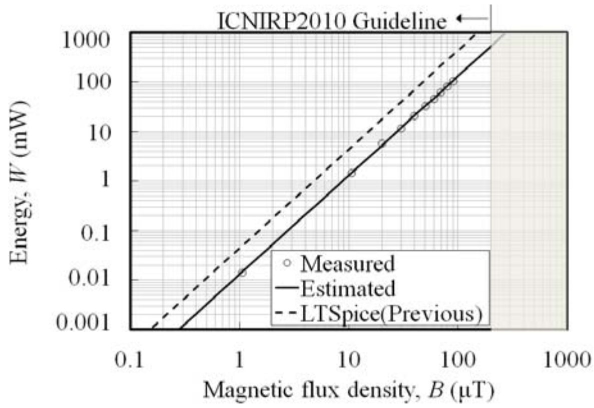

Fig. 5 Harvested power as a function of the magnetic field.

was composed of three square coils connected in series, and the distance was the half side length of the coil. The side length was 2 m, and the number of windings was 24:12:24. Fig. 4 shows a photograph of the SC3 system. Although this system can generate a magnetic field in an arbitrary direction with three set of SC3, it was generated a magnetic field in the X direction to be parallel to the coil axis of the harvesting module. In the area within a radius of 50 cm from the center, SC3 can generate a uniform magnetic field within ±1% deviation [9]. Because the maximum diameter of the modules was 28 cm, this area was used to simulate power line magnetic noise.

The frequency was 60 Hz, and the amplitude ranges were from 1 μT to 10 μT with a 1μT step and from 10 μT to 90 μT with a 10 μT step. To evaluate harvested energy, the voltage drop in the dummy load was measured with an FFT analyzer.

Fig. 5 shows the harvested energy as a function of the amplitude of magnetic flux density. The plot and line represent the measured and estimated value, respectively. The measured value is good in agreement with the estimated value. In a previous report, although the simulated result with a circuit simulator was about the same as the measured result, the relative error was -68% [5]. At that time, the eddy current loss in the coil was doubted. In contrast, the relative error of the estimated value here is +0.96%, because the measured value is 104 mW from a magnetic field of 90 μT at 60 Hz. From this result, it was confirmed the validity and usefulness of the theoretical estimation. It should be noted that the no significant eddy current loss was found even if the magnetic flux density is as high as 90 μT. This fact is an important merit of energy harvesting from a low-frequency magnetic field.

4. Discussion

It have successfully demonstrated the energy harvesting of 100 mW from a magnetic field of 90 μT at 60 Hz. Because the harvesting energy is proportional to the square of the magnetic field, it could be used for both an energy source and magnetic sensor. Incorporating this module into a wireless sensor network, one can build a crisis management system such as environmental magnetic field monitoring and power line soundness management. If the objective area is near a long-distance transmission line which is carrying constant power, numerous applications with several sensors could be considered such as disaster prevention and agricultural monitoring.

According to the theoretical estimation, the harvesting energy of this module becomes 562 mW from a magnetic field of 200 μT at 60 Hz. This value is attractive enough to find applications related with both energy harvesting and wireless power transmission. From the technical view point of wireless power transmission, it is free from the problem in transmission distance. If the required area is already known, it should be designed a coil arrangement to generate a uniform magnetic field within the desired area. It can be also chosen a three dimensional field generator when the harvesting module is required to move about. In this case, three set of SC3 is one candidate because of the practical advantages in construction and usefulness.

Because the harvesting module has 28 cm in diameter, it is not suitable for a wearable use. According to the acceptable level defined by ICNIRP2010, it was revealed the relationship between the coil size and estimated energy. Fig. 6 shows the estimated energy as a function of the outer diameter of a Brooks coil. In this estimation, it was used Eq. (9) with similar constant values as the harvesting module; the spacing factor is 0.737, the resistivity is 1.78 × 10^{-8} Ω·m, and the frequency is 60 Hz. The line represents the air-core coil, and the dash and dotted line represent the coil with a magnetic core having an effective permeability of 10 and 100, respectively. From the results, one can easily understand that the estimated power is proportional to the square of the effective permeability. It is found that the required outer diameter of an air-core coil for harvesting 1 W is larger than 300 mm. If it can be designed the harvesting module with an effective permeability of 100, the required diameter becomes 50 mm. Unfortunately, the theoretical design revealed that the estimated power is negligible if the outer diameter is less than 1 mm. In contrast, if it can be prepared a relatively large air-core module, the estimated energy is enough in typical applications related with wireless power transfer. For example, the outer diameter of 1.6 m as a human size corresponds to 3.19 kW. In order to receive of 100 kW power, the required diameter is about 3.2 m. It should be noted that the outer diameter could be reduced incorporating a magnetic material.

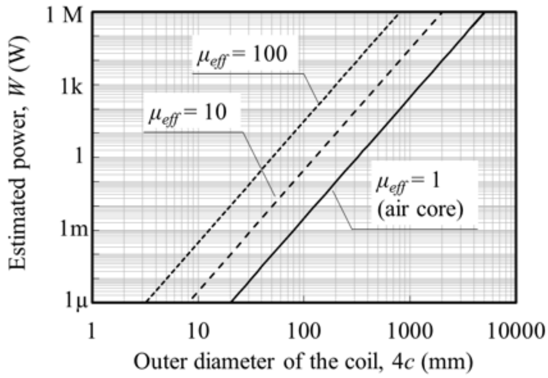

Fig. 6 Estimated power as a function of outer diameter of the module, as a parameter of the effective permeability (β = 0.737, ρ = 1.78 × 10^{-8} Ω·m, f = 60 Hz, $\mu_0 H$ = 200 μT).

From typical demand on batteries, one can discuss the practical applications of energy harvesting. An electrical watch and a calculator are good examples of the lowest power consumption devices whose required power is 1 μW order [7]. From this point of view, the smallest outer diameter of the air-cored harvesting module can be defined as 20 mm. Compared with button batteries, the lowest energy storage in several kinds of batteries, it is not a disappointing size.

5. Conclusions

This paper presented a theoretical design method for a magnetic energy harvesting module, and demonstrated the energy harvesting of 100 mW from a magnetic field of 90 μT at 60 Hz. The experimental results have not only showed the validity of design, but also provided numerous possibilities of attractive applications related with both energy harvesting and wireless power transmission. The theoretical design have revealed that the estimated power can be discussed as a parameter of the outer diameter. If the diameter of air-core Brooks coil is larger than a few centimeter, one can find several applications related with energy harvesting. It can be also found typical applications related with wireless power transfer, if that diameter is larger than a few meters. The use of a magnetic core is promising to reduce the module size because the estimated power is proportional to the square of the effective permeability. It should be noted that the uniform magnetic field to be harvested in this estimation is of an acceptable level as defined by ICNIRP2010.

Acknowledgments

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