Consideration of array module design for energy harvesting of power-line magnetic noise

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Abstract. Energy harvesting is a key technology for small self-sufficient devices, which use environmental energy as a source. If these devices target a wireless sensor network, their required energy is only a few mW. In our previous report, we demonstrated the ability to harvest 6.32 mW from a magnetic field of 21.2 μT at 60 Hz. This paper considers an array module design for power line magnetic noise energy harvesting. The experimental results show that small distance in axial direction makes the harvesting energy small. In order to investigate this phenomenon, magnetic flux distributions around the modules are also measured. From the results, we concluded that the modules should be separated by one diameter distance of the coil.

Introduction

We can easily find the existence of light, vibration, and thermal energy in our living environment. To efficiently harvest this kind of energy, a number of energy harvesting modules have been considered in recent years [1-3]. An interesting summary is reported by Roundy's group [4]. According to their report, the typical power density of light energy is 15,000μW/cm^3 (outdoor, direct sun), 250 μW/cm^3 for vibration energy (Piezoelectric conversion), and 15 μW/cm^3 for thermal energy (at 10 °C gradient). Compared with batteries and fuel cells, these values are remarkable. For example, a non-rechargeable lithium battery is a promising energy storage device, however, its power density is only 45 μW/cm^3 for a one year lifetime, and 3.5 μW/cm^3 for a ten year lifetime.

Electromagnetic fields are used as an energy medium in energy harvesting modules with a vibration source and wireless power transmission. In contrast, a wireless power transfer method proposed by an MIT group (Magnetic resonant coupling type) [5] has attracted many engineers. Unfortunately, no research has yet been carried out on how to harvest the energy of a power line magnetic field. In other words, power lines and their noise were not regarded as an energy transmitter and artificial energy source in our living environment.

From the view point of an engineer concerned with weak and low-frequency magnetic field detection, magnetic fields are considered harmful noise. Noise always exists in our living environment, and perfect magnetic shielding is not practical. Because power lines are a life-line for our modern life, we are 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) [6]. Therefore, we focused on this magnetic field as an energy harvesting source. In our previous report [7], we demonstrated energy harvesting of 6.32 mW from a magnetic field of 21.2 μT at 60 Hz. If the usable magnetic flux density increases 10-fold, the harvested energy increases 100-fold. If the magnetic flux density of 200 μT at 60 Hz is an acceptable level in a public space, the harvesting power density becomes 130 μW/cm^3. This value is comparable to the value of an energy harvesting module of a light source during a cloudy day. Because this module uses the resonance phenomenon, it is disturbed near a magnetic flux distribution. If a second module is closely placed near the first, both of their energy harvested capabilities may be affected. This paper considers an array module design for harvesting the energy in power line magnetic noise.

Energy harvesting module

Fig.1 shows our prepared energy harvesting modules, and Table 1 shows their specifications. The values for the inductance L (H) and resistance R (Ω) were estimated as

$$L = P_0 a n^2 \text{ (H)}, \tag{1}$$
$$R = 2\pi a n \rho / s \ (\Omega). \tag{2}$$

Where, P_0=1.6994×10^{-6} (H/m) is the coil constant for a Brooks coil [8], a (m) is the mean radius, n is the number of windings, ρ (Ω•m) is the resistivity of copper at room temperature, and s (m^2) is the cross section area of the winding. The measured values were in good agreement with the estimated values to within ±3 % relative error. To provide a resonance frequency at 60 Hz, we chose the resonant capacitor C (F) from

$$f = 1/\ 2\pi(LC)^{1/2} \text{ (Hz)}. \tag{3}$$

From the maximum power transfer theorem, we chose a load R_L (Ω) to be the same as the coil resistance and used the voltage drop as the output voltage V_{out} (V) for calculating the harvesting energy W (W) with

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

Fig. 2 shows a model for an energy harvesting module for a circuit simulator (LTSpice, LinearTechnology Inc.). From Faraday's law of induction and Thévenin's theorem, the amplitude of the voltage source V_{in} (V) can be expressed by

$$V_{in} = 2\pi^2 f n a^2 B \text{ (V)}. \tag{5}$$

Where, f (Hz) is the frequency and B (T) is the mean flux density crossed with the mean cross section of the coil. Table 1 shows the specifications of the module. It consists of an air-core coil, a resonant capacitor and a load, and can harvest 1 mW from a magnetic field of 19.8 µT at 60 Hz.

For generating a uniform magnetic field, we used our developed Simple-Cubic-3 coil system (SC3) [9]. SC3 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. In the area within a radius of 50 cm from the center, SC3 can generate a uniform magnetic field to within ± 1 % deviation [10]. Because the maximum diameter of the modules was 20 cm, we used this area to simulate power line magnetic noise. To evaluate frequency dependence, the output voltage was measured with an FFT analyzer. The frequency range was from 1 Hz to 1 kHz, and the amplitude was 1 $\mu T_{p\text{-}p}$ or 10 $\mu T_{p\text{-}p}$. To evaluate amplitude dependence, the harvesting energy was calculated from the measured output voltage. The frequency was 60 Hz, and the amplitude ranges were from 1 $\mu T_{p\text{-}p}$ to 10 $\mu T_{p\text{-}p}$ with a 1 $\mu T_{p\text{-}p}$ step and from 10 $\mu T_{p\text{-}p}$ to 60 $\mu T_{p\text{-}p}$ with a 10 $\mu T_{p\text{-}p}$ step. The maximum amplitude of the magnetic flux density of 60 $\mu T_{p\text{-}p}$ corresponds to 21.2 µT(rms). Fig. 3 shows examples of the frequency dependency of the modules. Compared with the simulated results for a magnetic field of 10 µT at 60 Hz, the relative error value was –40 %. Fig. 4 shows the amplitude dependency of the modules. Plots represent the measured results, and lines represent the simulated results. Compared with the simulated results, the average value of relative error was –67 %. In contrast, if the 60 Hz magnetic field was larger than 20 µT, the harvested energy was larger than 1 mW. Because there are no non-linear materials in the modules, the harvested energy is proportional to the square of the magnetic flux density [7]. If the magnetic flux density of 200 µT at 60 Hz is an acceptable level in a public space, the estimated harvesting power becomes larger than 0.1 W.

Array module

We prepared two energy harvesting modules which have the same specifications as summarized in Table 1, and placed both modules inside the SC3 coil system. We investigated the dependency of distance between the two modules on the total harvested energy. Here, we considered two parameters, distance in both the axial direction and in the radial direction. Fig. 5 shows the definition of two distance parameters. The harvested energy of one module was calculated from the measured voltage in the load with an FFT analyzer. The total harvested energy was calculated from the sum of both harvested energies. If there is no interference between the two coils, the total harvested energy should be 2 mW. Fig. 6 shows the measured total harvested energy as a function of the distance normalized by the outer diameter of the coil. The frequency and amplitude of the magnetic field generated by the SC3 coil system were 60 Hz and 21.2 μT, respectively. When both modules were placed at some distance in the axial direction, the total harvested energy was almost 2 mW. In contrast, it became 1/5 of this value when the distance in the axial direction was almost zero. This result pointed out that the modules should be placed at one normalized distance. For an explanation of this phenomenon, we measured the magnetic field in axial direction with a fluxgate magnetometer (μMag-01N, MEDA Inc.), around both modules. Fig. 7 shows the measured field when both modules were placed 10 cm apart in the radial direction. We did not measure the fields inside the modules. The fields around the modules were not uniform, and the values near the top and bottom surface were quite large. The maximum value was 75 μT, which was 3.5 times larger than the field generated by the SC3 coil system. Although there was no significant change in the fields near the radial surface, the field near another module side was slightly large as 36 μT. Fig. 8 shows the measured distribution when both modules were placed 10 cm apart in the axial direction. As a result, we can find a similar profile to that shown in Fig. 7. It should be noted that there was an unbalance in the amplitude of the fields near the top and bottom surfaces. The fields measured near another module's side were greater than those measured near the opposite side. The maximum values near another module side's and the opposite side were 85 μT and 65 μT, respectively.

Discussion

It was found that a small distance in the axial direction makes the harvesting energy small. Because the modules use the resonance phenomenon, the magnetic fields around the module are disturbed. It was found that fields near the module surface became a few times greater than the value of the original field. If there was no significant interference in the harvested energy between two of the modules, the fields near the top or bottom surface had the same value. However the fields had an imbalance if they interfered. Let us consider the mutual inductance of two equal Brooks coil, $M = kL$. The coupling coefficient, k, has been well investigated with the parameter of the ratio of c / d [8]. Where d represents distance in the axial direction, and c represents coil width. At the conditions shown in Fig. 8, the corresponding value of c / d is 0.5. At that time, the coupling coefficient was 0.08807. In contrast, the coupling coefficient is less than 0.00299 when the value of c / d is smaller than 0.1. This means that the mutual inductance between the modules is negligible. If the distance and the outer diameter of the coil were the same value then $c / d = 0.25$ and we could not find the interference. In this case, the mutual inductance is a few % of the self inductance (e.g. $k = 0.01630$ for $c / d = 0.2$, and $k = 0.03770$ for $d / c = 0.3$). From these considerations, we concluded that the distance in axial direction should be larger than the coil's outer diameter.

Conclusion

We investigated the effect of distance between two modules on energy harvesting ability. It was found that a small distance in the axial direction makes the harvesting energy small. For an explanation of this phenomenon, we measured magnetic field in the axial direction, around both modules. From the results, we concluded that the modules should be separated by one diameter distance of the coil. It should be also noted that the magnetic fields near the surface of the module are large because the modules use resonance phenomenon.

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TABLE I

SPECIFICATIONS OF ENERGY HARVESTING MODULE

Parameter	Value
Coil width, c (mm)	50.0
Inner diameter, $2c$ (mm)	100
Outer diameter, $4c$ (mm)	200
Volume, $4\pi c^3$ (10^3 mm^3 or cm^3)	1570
Spacing factor, β	0.850
Number of windings, n	8500
Inductance, L (H)	9.04
Resistance, R (Ω)	345
Resonant capacitor, C (μF)	0.7
Load, R (Ω)	320
Resonance frequency, f_0 (Hz)	62.7
Quality factor, $Q= 2\pi f_0 L/(2R) = \pi f_0 L/R$	5.25
Half band width, f_0 / Q (Hz)	11.9

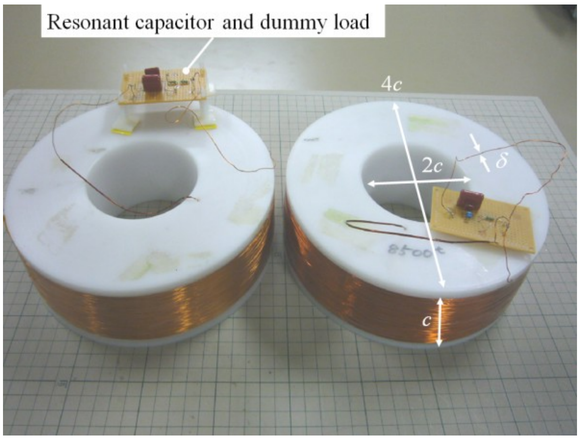

Fig. 1 Our developed energy harvesting modules.

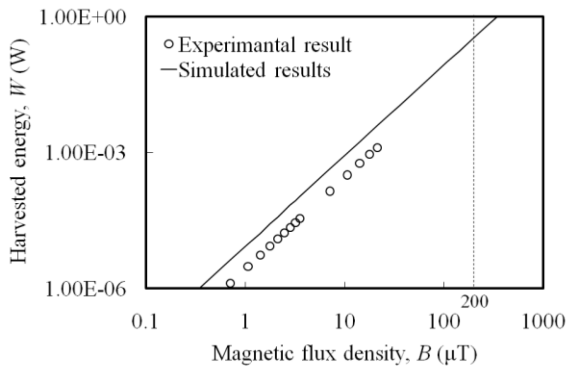

Fig. 4 Amplitude dependency of the modules. Plots represent measured results, and lines represent simulated results.

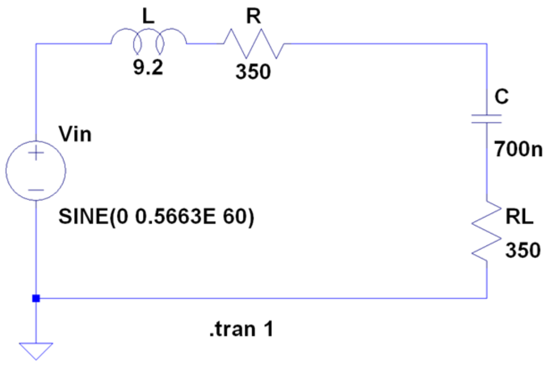

Fig. 2 A model of an energy harvesting module for a circuit simulator.

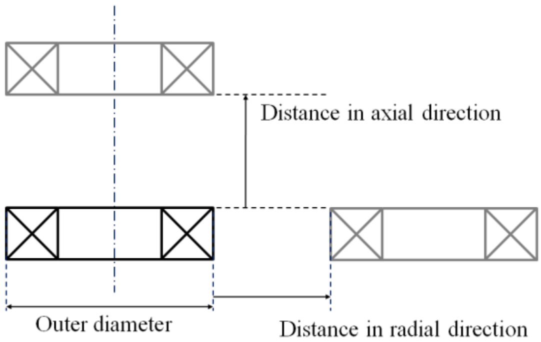

Fig. 5 Definition of the two distance parameters.

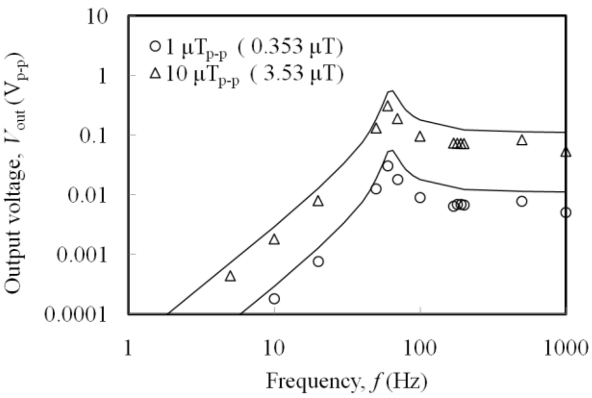

Fig. 3 Frequency dependency of the module. Plots represent measured results, and lines represent simulated results.

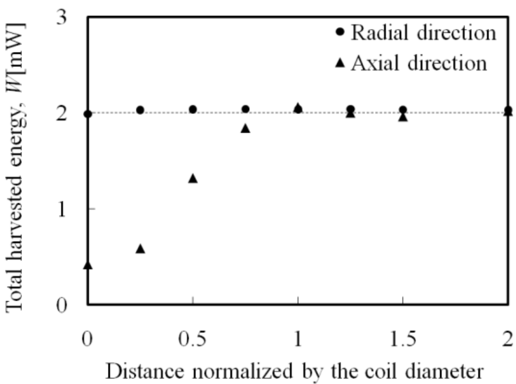

Fig. 6 Measured total harvested energy as a function of the distance normalized by the outer diameter of the coil.

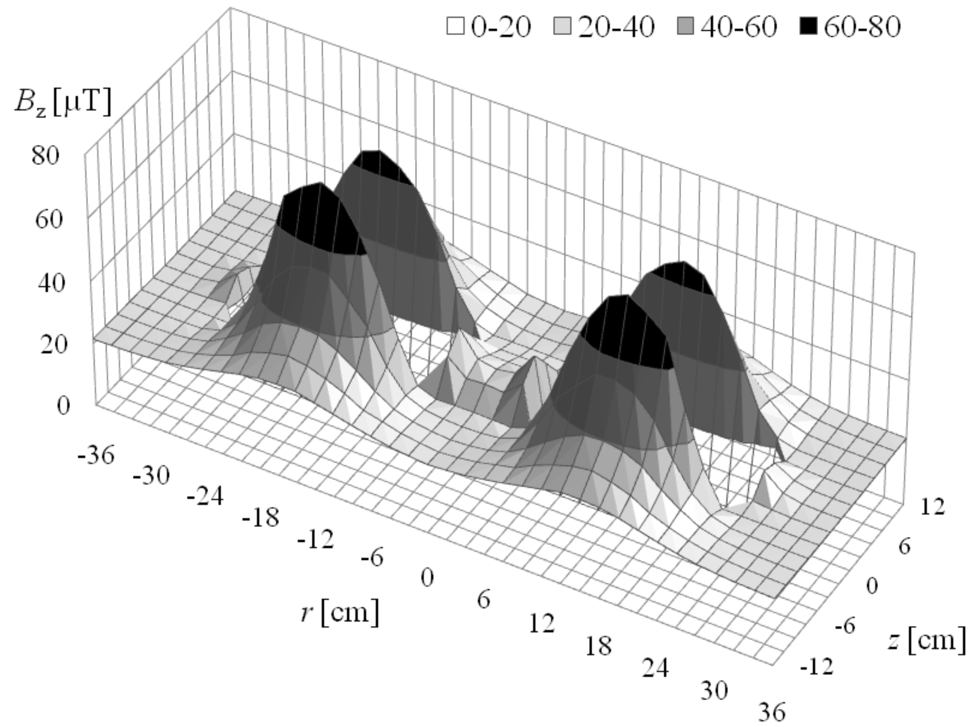

Fig. 7 Measured magnetic flux density in the axial direction when both modules were placed 10 cm apart in the radial direction.

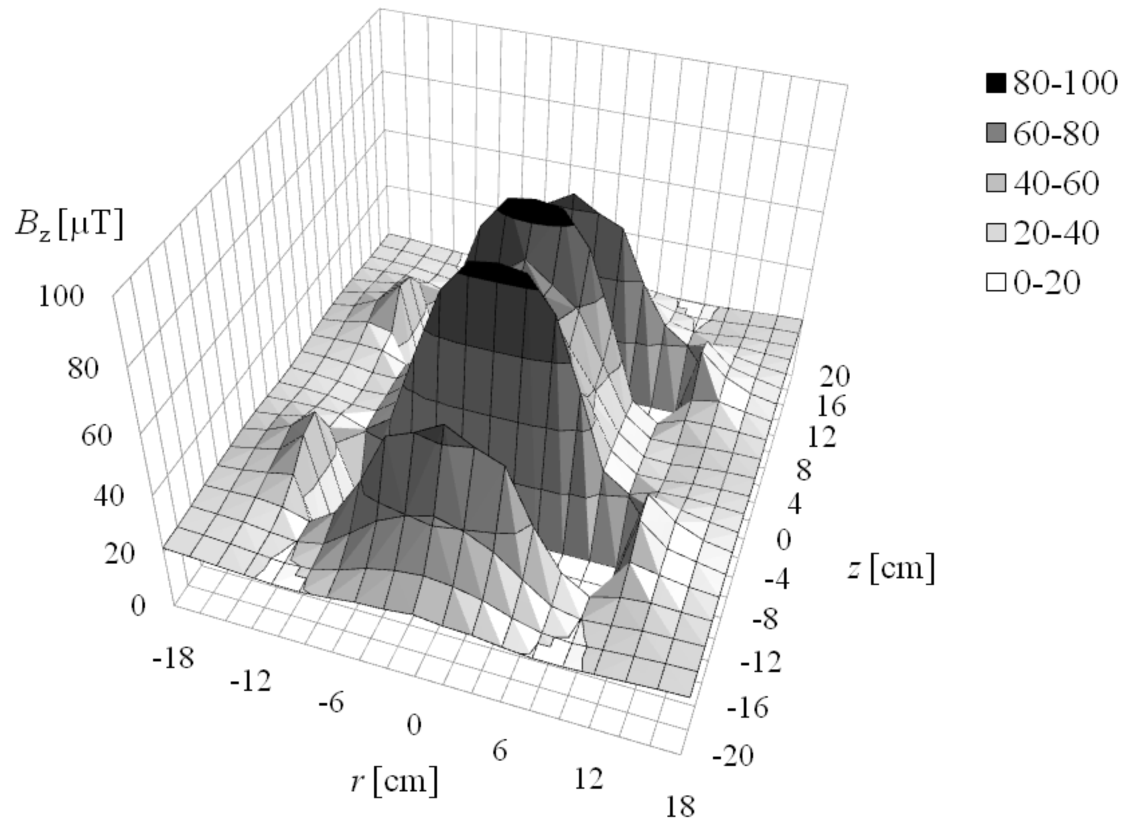

Fig. 8 Measured magnetic flux density in the axial direction when both modules were placed 10 cm apart in the axial direction.