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Design of a 50 Hz Electromagnetic Energy Harvester

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Abstract

Energy harvesting has shown to be an effective technology to power wireless sensors and devices for Internet of the Things and Smart City related applications. In this paper, we propose a new design of a free-standing magnetic energy harvester around overhead power lines. The I-shaped core with a pair of magnetic collector plates at both ends can significantly increase the effective permeability and output power of the energy harvester.

1 Introduction

With the rapid development of smart grids, real-time environment and condition monitoring have been developed and widely used in smart grid systems. Wireless sensors are considered to be efficient tools for collecting data because of their low power consumption, quick deployment and low cost. However, the life expectancy of batteries of self-powering and sensing systems becomes a bottleneck in many applications, including smart grid applications. Batteries need to be manually replaced once every three to five years, and it results in high cost of labour.

Energy harvesting is a promising energy supply solution. There are several kinds of ambient energy sources around power lines and substations, such as solar, wind, electrical field and magnetic field. In recent years, magnetic energy harvesting has been proposed as an attractive technology for scavenging low frequency magnetic field energy around the power lines [1]-[3]. Unlike solar and wind energy which heavily rely on weather and environmental conditions, electromagnetic energy is stable and always exists near the power lines and substations. Magnetic energy harvesting can be a promising alternative energy solution to meet the energy demand of environment and condition monitoring sensors for smart grid applications.

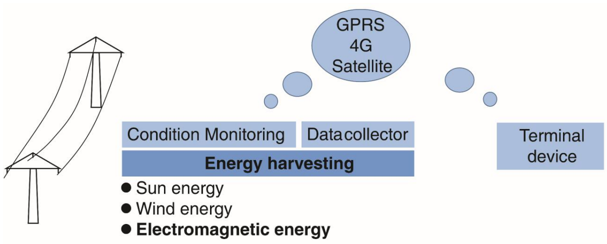

Figure 1. Ambient energy sources around power lines

A new design of a free-standing electromagnetic energy harvester is proposed and studied in this work. The proposed design can harvest more electromagnetic energy, reduce the magnetic core loss, and make the installation and winding convenient. The magnetic field in the proposed I-shaped core can be significantly increased, and the demagnetization factor is much reduced.

2 The Energy Harvester Design

2.1 The Principle of Traditional Rod Core Energy Harvester

At 50 Hz, the most efficient way to harvest the magnetic energy is to employ coils wrapped typically on magnetic cores. A free-standing magnetic energy harvester can be installed flexibly in any place where an alternating magnetic field exists. This study focuses on harvesting electromagnetic energy from overhead power lines at 50 Hz. Similar to the rod coil harvesting electromagnetic energy from an alternating magnetic field demonstrated in [1], for a soft magnetic rod with a coil wound around, the open circuit voltage of the coil V_{coil} can be calculated by Faraday's law of magnetic induction:

$$V_{coil} = N\omega B_{ex} A\mu_{eff} \tag{1}$$

where N represents the number of turns of the coil, ω is the angular frequency of transmission line current in rad/s,

B_{ex} is the external magnetic flux density in T_{rms}, A represents the area of the core in m^2, and μ_{eff} represents the effective permeability related to the shape and material properties of the core.

Fig. 1 shows the equivalent circuit of the harvesting coil with a load. A compensating capacitor $C = 1/(\omega^2 L_{coil})$ is added to compensate for the inductance of the coil inductive L_{coil}. This forms an energy harvesting loop. R_{coil} is the coil resistance that consists of copper wire resistance R_{copper} and the equivalent core resistance R_{core}. Based on the principle of maximum power transfer, the matching load is equal to the coil resistance R_{load}. This forms an energy harvesting loop, where V_{coil} is the voltage on the load, and the maximum output power is given as below:

$$P_{load} = \left(\frac{V_{coil}}{2}\right)^2 / R_{coil} \tag{2}$$

The power density of the energy harvester is given by:

$$\rho_{power} = \frac{1}{4}\frac{V_{coil}^{\ 2}}{R_{coil}} / Vol \tag{3}$$

Where Vol is the total volume of the energy harvester in m^3.

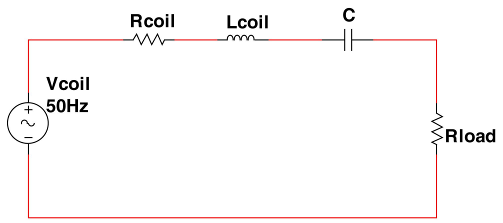

Figure 1. The equivalent circuit of the harvesting coil with a matched load.

2.2 Design of an I-shaped Energy Harvester

The open circuit voltage of coil V_{coil} is related to N, ω, B_{ex}, A and μ_{eff}. The values of ω, B_{ex} are related to the external magnetic field environment. Assume that the length of core and the winding number N are unchanged, the values of A and μ_{eff} are directly influenced by the energy harvester design. As the energy harvester does not form a closed loop, it results in a demagnetizing field. The effective permeability μ_{eff} is much lower than relative permeability μ_r for a uniform cylindrical core. The μ_{eff} can be derived as follow [4]:

$$\mu_{eff} \approx \frac{\mu_r}{1 + N_d \mu_r} \tag{4}$$

Where N_d is the demagnetization factor related to the core shape, the relative permeability μ_r related to the core material. If the uniform cylindrical core length l to diameter d ratio is $m = l/d$, N_d can be calculated using Stoner's formula:

$$N_d = \frac{1}{m^2 - 1}\left[\frac{m}{\sqrt{m^2 - 1}}\ln(m + \sqrt{m^2 - 1}) - 1\right] \tag{5}$$

It can be seen from (4) and (5) that the effective permeability μ_{eff} is related to the relative permeability μ_r and core shape.

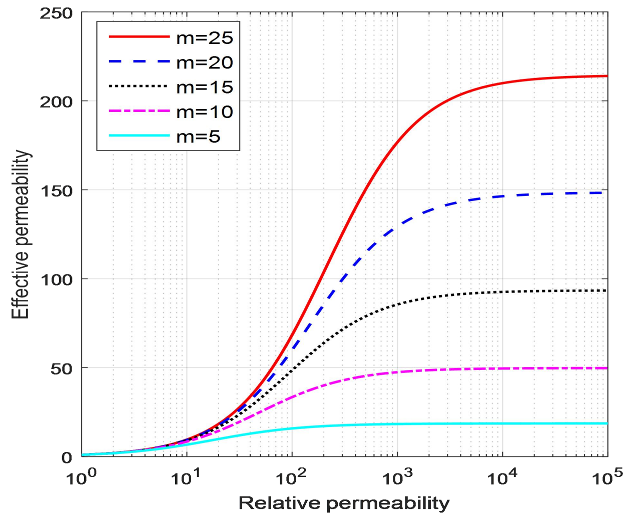

Figure 2. The effective permeability of five different length to diameter ratios as a function of relative permeability.

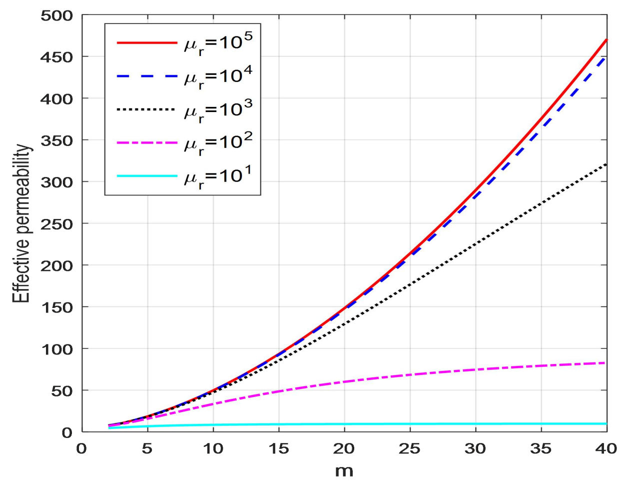

Figure 3. The effective permeability of as a function of the length to diameter ratios

The relationship between μ_{eff}, μ_r and m is presented in Fig. 2 and 3. If m is given, for an increasing μ_r, the value of μ_{eff} surges and finally becomes stable with a knee point of μ_r. For a given μ_r, μ_{eff} increases with the growth of m. In reality, m is no greater than 15 due to the limit of size in practical application. Therefore, μ_r only needs to be above 1000 to almost reach the maximum value of μ_{eff}. For a long and thin rod core, its μ_{eff} can be higher, but it becomes bulky and can be easily broken. In order to increase μ_{eff}, we propose an I-shaped core as shown in Fig. 4b.

3 Simulation Results

Fig. 4 shows two energy harvesting cores. One is a rod (a) without attachment and the other is an I-shaped core (b) with a pair of magnetic collector plates. The core is an ideal material with a conductivity of zero and a relative permeability of 2000.

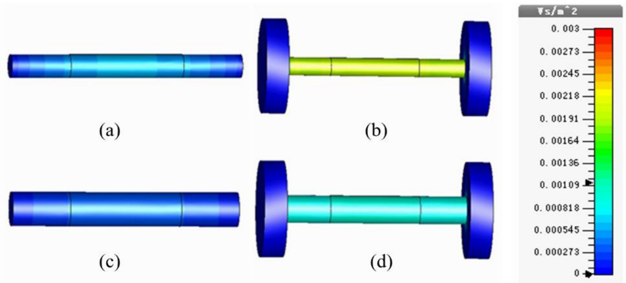

Figure 4. The simulated magnetic flux density inside the solenoid and the I-shaped core when an external magnetic field density of 6.5 μT_{rms} is applied.

There are four core shapes, including (a) φ: 2 cm × 20 cm solenoid; (b) φ: 2 cm×20 cm rod core and a pair of magnetic plates φ: 10.5 cm × 2.5 cm; (c) φ: 3cm × 20 cm rod core; (d) φ: 3 cm × 20 cm rod core and a pair of magnetic plates φ: 10.5 cm × 2.5 cm, where φ is the product of diameter and length. The winding number N is 1000 for all cores (the diameter of winding and the resistivity for the copper wire is 0.33 mm and 0.22 Ω/m respectively).

The conductivity of the core is set to be zero to eliminate the eddy current loss. The hysteresis loss is ignored due to a low-frequency electromagnetic field and low coercive force. Therefore, the magnetic properties of two cores with different shapes can be researched. The cores are simulated using CST EM Studio software. We first model the magnetic core, setting it as a Mn-Zn ferrite material [5], and then adding a copper coil. The Mn-Zn soft ferrite belongs to non-metallic materials and has been used as magnetic material widely.

A Helmholtz pair was used to generate the required magnetic field. The diameter of the Helmholtz coil is 1 m. The pair of Helmholtz coils is separated by 50 cm. Each coil has 30 turns of copper wire. The alternating current in the coil is 121 mA to generate a uniform alternating magnetic field of 6.5 μT at 50 Hz. The harvester was placed in the middle of the Helmholtz pair. The equivalent circuit of the harvesting coil has been explained in section 2.1. We measure the voltage V_{coil} on the load, and calculated the maximum output power and power density of each energy harvester.

Table 1. The parameters of the different core designs (μ_r = 2000 and N = 1000)

Core Type	Rod (a)	I-shape (b)	Rod (c)	I-shape (d)
Effective cross section area (cm^2)	3.14	3.14	7.07	7.07
Magnetic flux density (mT_{rms})	0.38	1.38	0.22	0.65
Magnetic flux (μWb_{rms})	0.119	0.433	0.156	0.46
Effective permeability	58.6	212	33.6	100.3
Wire resistance (Ω)	104.5	104.5	152.2	152.2
Open circuit voltage (mV_{rms})	37.6	136	48.5	144.8
Output power (μW)	3.38	44.25	3.86	34.44
Power density (nW/cm^3)	53.8	89.3	27.3	60

The simulation results are summarized in Table 1. The resistance of the copper wire on the I-shaped core is the same as that on the rod, but the effective permeability of the I-shaped core is much greater. The open circuit voltage and output power of the I-shaped core are increased significantly with a pair of magnetic collectors at both ends compared to a single rod core. Although the volume of the I-shaped core is larger than the rod core, its power density is increased compared to the rod core. Therefore, the I-shaped core shows a much better performance than that of the rod core. In summary, an I-shaped core that is composed of a long and thin inner rod and a pair of thick and big magnetic collector plates can generate a much greater output power.

4 Experiment Results

A pair of Helmholtz coils is made to generate a uniform alternating electromagnetic field similar to the electromagnetic environment near the power line. A magnetic flux density of 6.5 μT_{rms} is generated. The I-shaped core can be combined with the rod core and plates as shown in Fig. 5. The core material is Mn-Zn soft ferrite. The rod core has a diameter of 3.2 cm and its length is 23 cm. The additional magnetic collector plates of the I-shaped core has a diameter of 10.5 cm and thickness of 2.5 cm. The diameter of winding and the resistivity for the copper wire is 0.33 mm and 0.22 Ω/m respectively.

Two types of cores with different winding number are placed into the Helmholtz coil and the circuit with a compensating capacitor and a matched load is built to get the maximum output power for the harvesting coil as shown in Fig. 1. As shown in Fig. 6, the output power of I-shaper core is shown to be higher than the rod core. The measured output power of the I-shaped core is 4.5 mW, which is 6.8 times of that of the output power harvested by the rod with 40000 windings. The resulted power density of I-shaped coil is 7.28 μW/cm^3 with 40000 turns, which is double of the rod coil under the same electromagnetic environment.

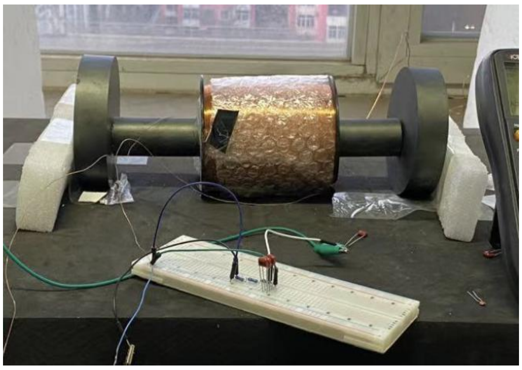

Figure 5. The I-shaped core is placed into the Helmoholtz coils

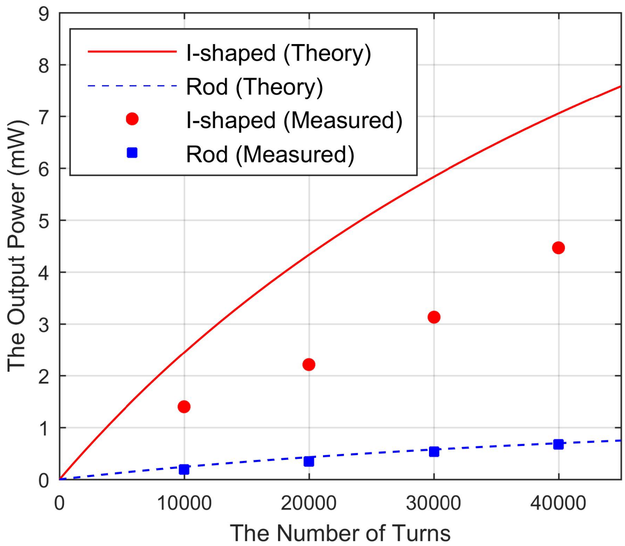

Figure 6. The output power of the two coils as a function of the winding number.

5. Conclusions

The study in the paper assumes a magnetic field of 6.5 μT, which represents a location around 1.5 m above the ground under a standard overhead transmission power line (400kV L12) [6]. In order to increase the output power, for the external condition, the I-shaped coil can be placed in a position closer to the power line or substation to increase the external magnetic flux density. The proposed free-standing I-shaped coil can be installed on the pylon, the weight and size of the harvester can be increased appropriately within a certain range. For the coil itself, a pair of bigger plates and a longer inner rod can reduce the demagnetization factor and increase the effective permeability significantly. The I-shaped coil can be fabricated easily. The harvester can be a very practical and inexpensive solution to supply condition monitoring sensors with magnetic field energy harvesting.

6. Acknowledgement

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7. References

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