A capacitive electric-field energy harvester with double-layer copper foil for 220V power line

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Abstract. The output power of electric-field energy harvesting is limited by displacement current produced in the capacitive coupling between the harvester and power line. This paper presents a capacitive electric-field energy harvester (CEFEH) that obtains energy from 220V power line by displacement current. The CEFEH consists of copper foil wound around the power line and ground electrode. In order to improve the output power of CEFEH, a double-layer copper foil is used to enhance the capacitive coupling, thereby increasing the displacement current. With the help of larger displacement current, the harvesting power of CEFEH with double-layer copper foil is 1.6 times higher than that of the single-layer copper foil. However, the electric-field energy around the 220V power line is very weak, which makes wireless sensor node unable to work directly. A power management circuit is designed for CEFEH. The test results show that the proposed CEFEH collects 2.468mJ in 400s and drives the ultra-low power wireless temperature sensor node to operation for 800ms. This CEFEH can be used in wireless sensor node with a short-term ultra-low power.

1. Introduction
The application of wireless sensor node (WSN) has benefited from the boom in smart grids and the internet of things. Battery as a universal power supply solution is increasingly hindering the large-scale and long-term application of WSN. There is a large amount of unutilized energy in the environment where WSN is distributed. In order to realize the wide application of WSN, unutilized energy harvested in the environment as a power supply is a promising solution [1-4]. The electric-field energy around substations and high-voltage transmission lines is very rich. Researchers have focused on electric-field energy harvesting in high-voltage environments [5-9]. However, the distribution of WSN is not limited to high-voltage environments. In smart factories and smart homes, 220V power lines are widely distributed. Therefore, some researchers use capacitive coupling between a single layer of copper foil and the power line to harvest the electric-field energy around the 220V power line[10-11]. However, the harvesting efficiency is low in this way. Inspired by this challenge, this work proposed a CEFEH with double-layer copper foil to harvest energy from 220V power lines by displacement current generated in the capacitive coupling. The principle of power line electric-field energy harvesting and the factors that affect the output power of the harvester are analyzed. In order to obtain electric-field energy more efficiently, a power management circuit is designed to control the charging or discharging process of CEFEH. The test shows that the charging power of CEFEH with double-layer copper foil can reach 11.75uW, while the charging power of CEFEH with single-layer copper foil is only 7.05uW. The wireless temperature sensor is successfully driven by the designed CEFEH for short period.
2. Optimization of the CEFEH

2.1. Principle analysis of CEFEH

The principle of electric-field energy harvesting is to conduct displacement current through capacitive coupling between conductive materials and power lines. The basic system of the electric-field induction energy extraction technology for 220V power line is shown in Figure 1 (a), and the distribution of internal capacitance is shown in Figure 1 (b). \( r_2 \) (3.5mm) is the radius of the power line and \( r_1 \) (0.5mm) is the radius of the conductor inside the power line. \( d \) (1.155mm) is the central distance between the power line and the inner conductor.

![Figure 1. (a) Electric-field energy harvesting system for 220V power line. (b) Capacitance distribution between conductive material and internal wires. (c) Equivalent circuit of CEFEH.](image)

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\[
C_{CH} = C_{CG} = C_{CN}
\]

2.2. Double-layer copper foil electrode structure

The coupling capacitance depends on the length of the copper foil. However, the excessively long copper foil increases the difficulty and damage of installation and the leakage of electric-field energy. Parallel copper foil is used to increase the coupling capacitance in the harvester. \( C_{L1} \) and \( C_{L2} \) are the distributed capacitances between the first and second layers of copper foil and the conductive wire in the power line, respectively. According to the equivalent conversion relationship of the capacitor, the distributed capacitance of the conductive wire and the copper foil can be expressed.

\[
C_{CH} = C_{L1} + C_{L2}
\]

![Figure 2. (a) Simulation model of double-layer copper foil structure harvester. (b) Simulation of current density in energy storing capacitor with double-layer copper foil structure. (c) Relationship](image)
between the number of electrode layers and the current density in storing capacitor. Finite element simulation was performed by ANSOFT software. A harvester model with a double-layer copper foil is shown in Figure 2 (a). The displacement current density at the center of the storing capacitor is shown in Figure 2 (b). The current density difference caused by the number of copper foil layers in the harvester from 1 to 8 was simulated. Due to the edge effect and the internal shielding electric-field, the double-layer copper foil electrode can obtain a large displacement current. The current from CEFEH with different structures is tested, and the results are shown in Figure 3. The harvester can be connected to the earth by connecting a metal water pipe or a grounded metal. Compared with the ground of induction electrode plate in high-rise building, the harvester connected to the earth plane has a higher output current. At the same time, double-layer copper foil is more advantageous for increasing the output current of the harvester.

![Figure 3](image)

**Figure 3.** Derived current from different harvester structures

### 3. Energy management circuit

Due to the low energy density of the electric-field around the 220V power line, the harvesting power of CEFEH is below several tens of microwatts, which makes WSN unable to be directly operated. One strategy for driving WSN is to charge the energy storing capacitor and then release the energy for a short time. Because CEFEH has smaller capacitance and larger internal impedance, it is difficult to impedance match to obtain better output power. Therefore, the energy management circuit for CEFEH is designed according to reference [6], as shown in Figure 4.

In Figure 4, $S_1$ composed of two MOSFETs is a bidirectional switch, which is used to change the low frequency of voltage to high frequency on the harvester. Due to the change in frequency, small inductors can achieve the same matching effect as large inductors. The switch control circuit, consisted of an ultra-low power voltage comparator (TS881) and a resistor, diode, etc., can generate pulse signal of up-converting oscillation circuit. $C_S$ (47uf) is the energy storing capacitor. $S_2$ is an N-channel MOSFET, and its control signal is provided by the voltage monitor (STM1061) and the voltage divider circuit. When the voltage across energy storing capacitor reaches 11V, the switch $S_2$ opens. When the voltage across energy storing capacitor drops to 4V, the switch $S_2$ closes. The wide-input LDO (TLV704) is used for instantaneous charging circuit, which can convert the energy released by the energy storing capacitor into an instantly stable 3.3V power output.

![Figure 4](image)

**Figure 4.** Energy management circuit schematic
4. Tests and results
Changes in the charging voltage of the energy storing capacitors of the four harvester structures are tested without an energy management circuit. The test results are shown in Figure 5 (a).

![Figure 5. (a) Charging voltage of energy storing capacitors in different harvester structures. (b) Waveform with load test](image)

Under the same ground condition, the charging power of the single-layer and double-layer copper foils are approximately 7.05\(\mu\)W and 11.75\(\mu\)W, respectively, as shown in Figure 5 (a). The charging power of double-layer copper foil has increased by nearly 1.6 times. The charge and discharge tests are performed at CEFEH with energy management circuit. The storing capacitor is 47\(\mu\)F and the load is 1\(K\)\(\Omega\). The energy management circuit has excellent performance in charge and discharge, as shown in Figure 5 (b). The storing capacitor is charged from 0V to 11V and then immediately discharged to 4V in 400s. The charging power is about 7.1\(\mu\)W, which can release about 2.468mJ. Since the equivalent impedance \(X_L\) is reduced by the energy management circuit, the charging power of CEFEH is also reduced.

An ultra-low power WSN consisting of an RF module (NRF24LE1) and a temperature sensor (SI7050) is designed for CEFEH, as shown in Figure 6(a).

![Figure 6. (a) An ultra-low power WSN with an RF module (NRF24LE1) and a temperature sensor (SI7050). (b) Temperature data acquisition and transfer](image)
Figures 6. (a) Experimental photograph with CEFEH, the energy management circuit, and WSN. (b) Wireless sensor power consumption. (c) Voltage waveform across the energy storing capacitor and WSN for sending data. (d) 24-hour indoor temperature measured by a sleep-powered wireless temperature sensor

The average power of the wireless sensor before sleep is 30mW for 25ms, and the power consumption can be calculated as 0.75mJ, as shown in Figure 6 (b). The energy consumed by the wireless temperature sensor during sleep is calculated as 0.775mJ for 800ms at 3.28V, as shown in Figure 6 (c). The wireless temperature sensor consumes 1.525mJ during the whole process. The utilization efficiency of the energy management circuit can be calculated as

\[ \eta = \frac{1.525}{2.468} \times 100% \approx 61.8\% \]  (2)

Figure 6 (d) shows the results of the measured 24-hour temperature data.

5. Conclusion

This work analyzes the basic principles of harvesting electric-field energy from 220V power line. An CEFEH with double-layer copper foil is proposed. The output power of CEFEH without energy management circuit can reach 11.75uW, which is almost 1.6 times that of single-layer copper foil. The energy management circuit is designed and manufactured. In the test, the charging power of CEFEH with energy management circuit can reach 7.1uW, and the single release energy is about 2.468mJ, which can ensure that the wireless sensor sends data every 280s. Energy management circuit transfer efficiency is 61.8%. A new power solution is provided by CEFEH for industrial or architectural applications, which effectively reduces energy consumption and saves a lot of resources.

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7. References

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