

Electromagnetic Energy Harvester on Overhead Power Distribution Lines for Atmospheric Sensors

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Abstract— In this paper we present a small, credit-card sized, and low-cost electromagnetic energy harvester that couples energy from one conductor of an overhead power distribution line. We use a rectangular coil, placed near the power line without encircling it, to extract electrical power from the time-varying magnetic field. The addition of a U-shaped electrical steel sheet (a high-permeability material typically used in transformers) near the coil significantly increases the magnetic flux through the coil and consequently raises the output power. Experiments have shown that the harvester with an optimal load resistance obtains 230 mW (AC) when the power-line conductor current is 50 Arms. The energy harvester is able to power a wireless gas sensor board having a carbon monoxide and an ozone sensors at 10 Arms. In this paper, we describe the design, modeling, and experimental study of the electromagnetic energy harvester with an output power range between several milliwatts to hundreds of milliwatts from an ac current up to 50 Arms. We anticipate that the energy harvesters could be installed inexpensively on the overhead power distribution lines by a utility operator using a hot stick.

Key words: Atmospheric Sensors, Hypothetical Energy Harvester

I. INTRODUCTION

Energy harvesters installed on electrical power lines (Fig. 1) have an ability to power sensors and wireless communication devices. They can be used by utility companies to power different sensors that monitor the conditions of the power lines. Since this condition monitoring would require uninterrupted operations and minimal maintenance, the energy harvesters are more feasible than batteries which need regular replacement from time to time. Another possible use of the energy harvesters is to provide energy for a wireless sensor network built on the power distribution grid. For example, the air quality report provided by present technology is not localized, if many atmospheric sensors could be installed on the power distribution grid to form a dense sensing network that enables people to obtain much more localized information about the present air quality. Energy harvesters that extract power from the electrical wires in a building were reported in. We envision that the energy harvesters installed on the overhead power distribution lines could power sensors for various interests:

- 1) Measurements useful to the power company: current; voltage; power and its flow direction; conductor temperature; AC frequency; phasing; outages; power theft data; etc.
- 2) Environmental sensors: particulate matter concentrations (PM2.5, PM10, etc.); local air temperature, relative

humidity, pressure; gases such as NOX, CO, CO2, O3, etc.

- 3) Other sensors: acoustic, optical, biological, vibration, acceleration, etc.



Fig. 1: Hypothetical energy harvester (to scale) attached to an overhead power distribution line

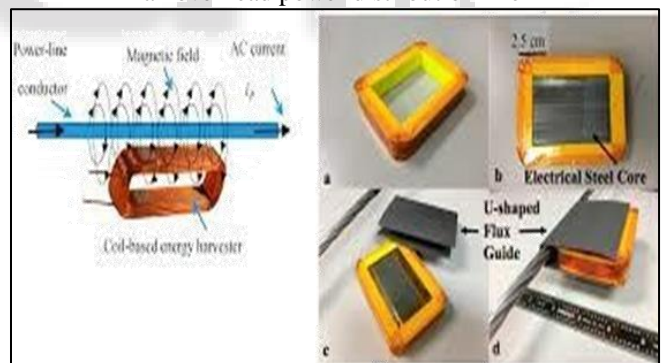


Fig. 2: (a)1250-turn coil; (b)Coil with a laminated electrical steel core; (c) and (d)Coil with a laminated electrical steel core and a U shaped flux guide.

II. ENERGY HARVESTER DESIGN AND MODELING

The energy harvester consists of a rectangular coil with a laminated electrical steel core is shown in Fig. 2b. To increase the output power from the harvester placed near the conductor without significantly adding volume to it, we made a U-shaped electrical steel sheet (flux guide) to direct more magnetic flux into the coil (Fig. 2d). The thin flux guide could eventually be embedded in the enclosure that contains the energy harvester. Energy harvesters that encircle the conductors could be challenging to install on the power distribution lines. The harvester in Fig. 2d is technically very

similar to a transformer, and we use an equivalent circuit of a current transformer to model it (Fig. 3). The power delivered to the load resistance, R_{Load} , assuming the inductor is a linear component, is

$$P_{Load} = \frac{(|I_p| \omega L_\mu)^2 * R_{Load}}{N^2[(R_{Wire} + R_{Load})^2 + (\omega L_\mu)^2]}$$

where L_μ , R_{Wire} , and N are the inductance, resistance, and number of turns from the secondary side of the current transformer, respectively (Table 1). The frequency is set to 60 Hz, and I_p is the current (rms) in the power line conductor.

Number of turns, N	Inductance, L_μ	Resistance, R_{Wire}
1250	2.78H	107.6Ω

Table 1: Parameters for the secondary

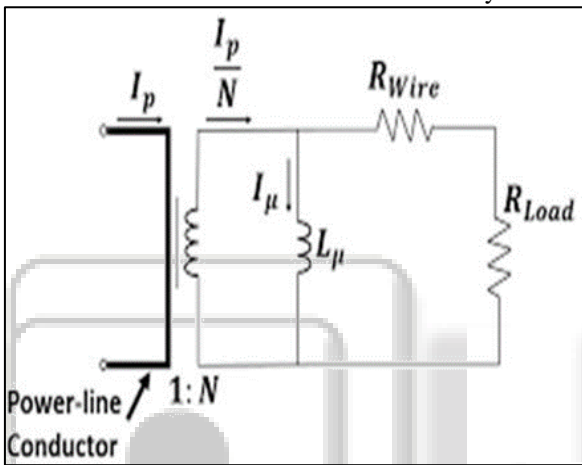


Fig. 3: Equivalent circuit for the energy harvester using a current transformer model

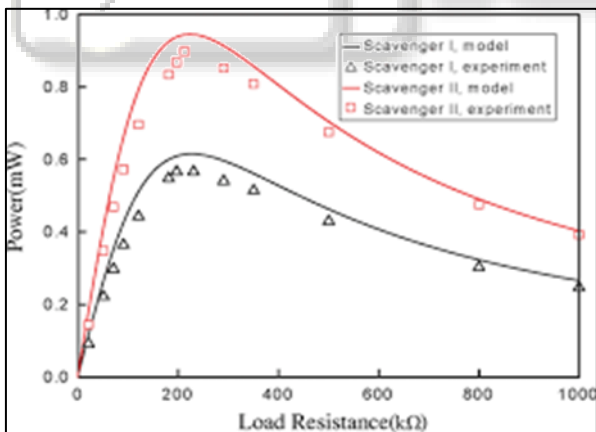


Fig. 4: AC output power from the energy harvester Verses load resistance ($I_{Arm}=10$)

III. EXPERIMENTAL RESULT AND DISCUSSION

The energy harvester (Fig. 2d) was tested with varying load resistances when the current in the power-line conductor is 10 Arms, in which the inductor still behaves linearly. Figure 4 shows both the model predicted by Eq. (1) and the experimental results, and they are very close to each other. The power output of the harvester without the flux guide is also shown here. We found that the maximum output power increases 300 times by adding the flux guide. In Figure 5, we

show the output power of the harvester as we change the primary current in the conductor from 0 to 50 Arms. The load resistor at each measurement point was adjusted to obtain the maximum output power for each power-line current. It was found that saturation occurred in the flux guide as the primary current reached about 15 Arms and persisted till 50 Arms. With saturation in the flux guide, the harvester was still able to deliver more power when increasing the current, but at a lower increasing rate comparing to the theoretical prediction.

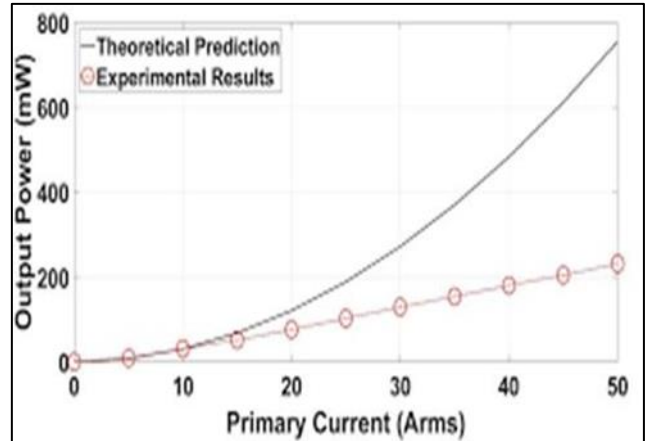


Fig. 5: AC output power from the optimally loaded energy harvester versus primary current

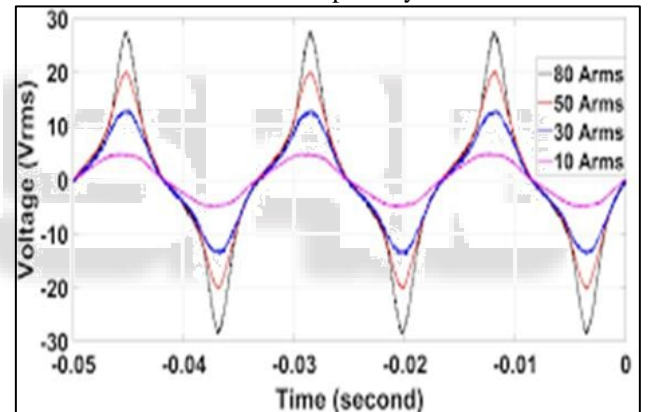


Fig. 6: Waveforms of the voltage across the load resistance with respect to four different primary current

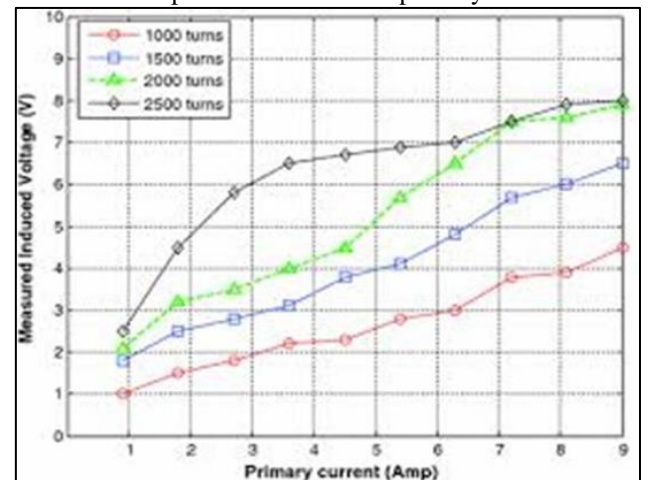


Fig. 7: Waveforms of the measured induced voltage across the load resistance with respect to four different Primary currents

We find that the secondary-side inductor, L_{μ} shown in Fig. 3 actually behaves non-linearly as the current transformer couples to the power-line conductor. When the current, I_{μ} , flowing through the inductor rises due to either the high primary current or high load resistance, it increases the magnetic flux, and the flux guide becomes saturated. Hence the inductor in the circuit is no longer a linear component, and this is why there is a discrepancy between the theoretical model and experimental results (Fig. 5). Four waveforms of the voltage on a fixed load resistance are shown in Figure 6, which correspond to current in the conductor of 10 Arms, 30 Arms, 50 Arms, and 80 Arms. This demonstrates that the voltage waveform is sinusoidal when there is no saturation (at 10 Arms), and it is gradually distorted as the flux guide is saturated by the increased magnetic flux due to the rising current in the conductor. When the primary current reaches 80 Arms, the flux guide would become heavily saturated. Moreover, the saturation would act as a protection for the load since it could prevent too much power from entering the circuit due to an abrupt increase in the primary current (i. e. lightning strikes on the power line.). The energy harvester was connected to a power management circuit using an LTC 3108 stepup converter to operate a commercial gas sensor board from SPEC Sensors (Fig. 8a), and the sensor board broadcast (with a Bluetooth Low Energy radio having a typical range of 132 ft) and stored data to an Android™ phone. Fig. 8 b shows how the output from an ozone sensor exposed to a brief burst of ozone. The sensor board can function with the energy harvester when the conductor current is larger than 10 Arms.

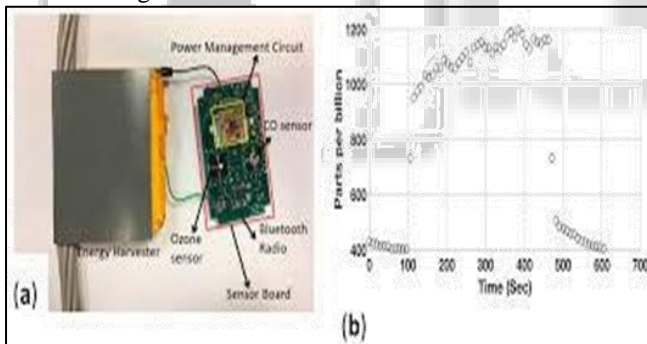


Fig. 8: (a) Energy harvester, power management circuit, (b). Ozone concentration from sensor response to and sensor board attached to an overhead brief ozone exposure distribution conductor

IV. CONCLUSION

In summary, we have shown a small, long-life, and low-cost electromagnetic energy harvester that can provide an AC output power of 230 milliwatts when placed near a power-line conductor carrying 50 Arms. The harvester could power atmospheric sensors, as well as sensors that collect information of interest to power companies. Saturation was observed in the flux guide, and we plan future work to focus on modeling the nonlinear behavior of the magnetic material and mitigation of the saturation. We also plan to optimize the harvester's shape for maximum power output and test various magnetic materials for the core and flux guide

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