Energy scavenging power sources for household electrical monitoring

Eli S. Leland[1]*, Richard M. White[2], Paul K. Wright[3]

[1] UC Berkeley, Department of Mechanical Engineering
2111 Etcheverry Hall, Berkeley, CA 94720
[2] Berkeley Sensor and Actuator Center, UC Berkeley
Berkeley, CA 94720
[3] Center for Information Technology Research in the Interest of Society
Berkeley, CA 94720

Abstract

Household electricity monitoring comprises an important first step in devising effective residential energy usage strategies. Inexpensive, compact electric current sensors connected to wireless sensor networks are envisioned as a solution. This paper discusses the fabrication and testing of devices that couple to magnetic fields surrounding wires carrying AC current, with a view to developing both energy scavenging power sources for wireless sensor nodes and passive, proximity-based current sensors. Devices were constructed from cantilever-mount piezoelectric bimorphs and NdFeB permanent magnets. In energy scavenging operation, devices generated 208 μW of power in a 419 kΩ load resistor when coupled to a space heater cord carrying 9.4 A_{RMS}, and 345 μW in a 491 kΩ load coupled to a 13 A_{RMS} current. In current sensing operation, sensitivities up to 74 mV/A were observed, with highly linear sensor behavior ($R^2 > 0.99$). Sensitivity varied with the inverse of distance from the conductor core, in agreement with theory. This research was conducted on meso-scale devices, but the design principles involved show promise for MEMS-scale devices.

Keywords: Current sensor, Energy scavenging, Energy harvesting, Piezoelectric bimorph, Wireless sensor network

1 - INTRODUCTION

In recent years the prospect of human-induced climate change and increasing pressure on the world's energy supply have spurred interest in finding technological remedies to these global concerns. Energy efficiency has been cited repeatedly as an important component to any global energy plan [1]. In most residential and small commercial situations, however, little detail about actual end-use of electric power is available beyond what is measured by the electric meter that connects each dwelling or small business to the power grid. In addition, programs such as demand response seek to reduce the load on the electric power distribution system on days of peak demand through reduction of electricity end-use [2]. Applications such as these call for a better way to measure and monitor the actual end-use of electric power.

Researchers envision a system that uses cheap, accurate, and reliable sensors to monitor the electric power usage of every appliance in a home or business. Linked together through a network of low-power wireless radios, such a system would offer a more complete and detailed picture of electric power end-use and would provide an important component in devising effective energy efficiency strategies. Continuing developments in low-power sensor radio designs [3] and microfabrication techniques suggest that this type of solution is an increasingly realistic possibility.

This research seeks to develop new devices that couple to the alternating magnetic field surrounding a current-carrying appliance cord, with a view to both measuring the electric current flow and powering a wireless sensor node to communicate with a broader power-sensing network. Such a device is comprised of a cantilever-mount piezoelectric bimorph with NdFeB magnets attached to its free end. The magnets couple to the alternating magnetic field surrounding the power cord, driving the bimorph to generate a voltage that can be used either for current measurement or power generation. In sensor mode this device operates passively, requiring no supply power in order to generate a signal. Experimental results suggest this design offers significant promise as both an accurate, passive, non-contacting current sensor and an effective energy scavenging power source for wireless sensor nodes.

The use of energy scavenged from the environment to power wireless sensor nodes has been studied extensively. Light [4], thermal gradients [5], and vibrations [6] have all shown promise as ambient energy sources that can be used to power sensor nodes. Applications for self-powered wireless sensor nodes have included monitoring temperature [7] and machine tool condition [8]. Several types of non-contacting current sensors using a variety of magnetic materials are available, including current transformers, Hall sensors, Rogowski coils, magnetoresistive current sensors, and fluxgate sensors [9, 10]. This paper presents a device that couples to an AC magnetic field to both generate power through energy

* Contact author: Tel. 510-643-6546, Fax: 510-643-6547, email: esleland@berkeley.edu

scavenging and to measure electric current. The results presented herein pertain to prototype devices in the meso-scale size range (2-3 cm^3), but the authors intend to apply the same design principles to a MEMS-scale device going forward.

2 - THEORY

The intensity of the magnetic field B at a radial distance r from the center of a single wire of infinite length carrying current i is calculated as in Eq.1.

$$B = \frac{\mu_0 i}{2\pi r} \qquad (1)$$

In Eq. 1, μ_0 is the permeability of free space, equal to 4π x 10^{-7} henries/meter. The magnetic field is directed circumferentially around the wire using the "right-hand rule." Equation (1) shows that the magnetic field intensity is directly proportional to the current in the wire and inversely proportional to the distance from the wire. For a wire carrying an alternating current, the intensity and direction of the magnetic field will vary in phase with the current.

Consider the case of a typical appliance cord, in which two wires are placed side-by-side and physically connected by the cord's insulation (Fig. 1). The AC currents in the two wires are 180 degrees out of phase with one another. These two currents result in magnetic fields that are equal in magnitude and opposite in sign, whose centers are physically offset from one another by the distance $2d$ between the centers of the two wires. It can be seen from Fig. 1(a) that along the centerline perpendicular to the plane of the two magnets, the two magnetic fields B_0 partially cancel, resulting in a field of intensity B_c parallel to this centerline. At a height h above the power cord along this centerline, the value of B_c is described by Eq. 2.

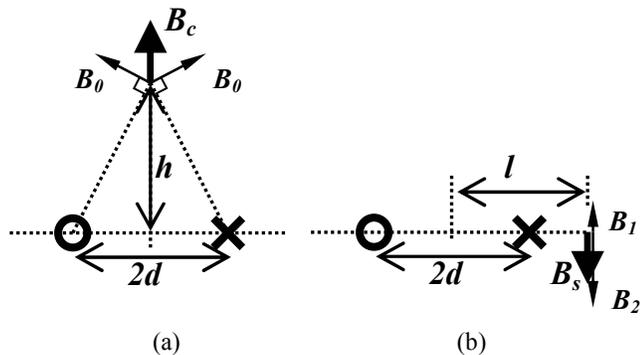$$B_c = \frac{\mu_0 i}{\pi}\left(\frac{d}{h^2 + d^2}\right) \qquad (2)$$

(a)   (b)

Figure 1 – Schematic of a two-wire appliance cord and the associated magnetic field (end view). This diagram follows the convention wherein "x" represents current flow into the page and "o" represents current flow out of the page.

The additive nature of the two magnetic fields along this centerline make it a good location for a magnetic current sensor. Consider standard #16 gauge two-wire appliance cord with a dimension $2d$=3.5 mm between the centers of the wires. With 10 amperes of current, the magnetic field at h=5 mm measures 2.5 gauss at the centerline.

Figure 1(b) illustrates the field in the plane of the appliance cord. At a distance l to the side of the centerline between the two wires the magnetic fields again cancel, with the field from the nearer wire dominant. The resulting magnetic field B_s is perpendicular to the plane of the appliance cord and has the value shown in Eq. 3.

$$B_s = \frac{\mu_0 i}{\pi}\left(\frac{d}{d^2 - l^2}\right) \qquad (3)$$

For the same standard #16 gauge appliance cord, the magnetic field will measure 3.2 gauss at a distance l=5 mm to the right of the center point.

3 - EXPERIMENT

Experiments were undertaken to evaluate the potential of coupling to the magnetic fields surrounding wires carrying AC current for both energy scavenging and current sensing.

Prototype devices were constructed using piezoelectric bimorphs from Piezo Systems Inc. and high-strength NdFeB permanent magnets from K&J Magnetics. Custom-machined aluminum brackets were fabricated to provide rigid cantilever mounts for the devices. A variable transformer was used to generate currents of zero to 13 A in dual-conductor appliance power cord and zero to 48 A in a 1 meter length of 500 MCM PVC-insulated single-conductor copper cable of the type used for electric power distribution in buildings. A 1500 watt electric space heater was also used as a current source. The space heater had two power settings, one drawing 9.4 A and the other 13 A. All currents were verified using a Veris Hawkeye 922 current sensor. Measurements were taken using a Fluke digital multimeter and a Tektronix digitizing oscilloscope. All voltages and amperages reported in this paper are root-mean-square values. A variable-frequency vibrometer was used to measure the resonance frequencies of the prototypes.

3.1 - Energy scavenging generator operation

A piezoelectric energy scavenging generator was constructed to couple to the power cord of a 1500 W space heater. The active element was a Piezo Systems T215-A4SS-103X bimorph measuring 31.8 x 3.2 x 0.38 mm. Copper foil was used to connect electrically to the bimorph's outer electrodes. Two axially-poled NdFeB disc magnets measuring 9.5 mm (diameter) x 1.6 mm (thickness) were sandwiched around the free end of the bimorph.

The resonance frequency of the generator was tuned to 60 Hz in order to couple maximally with the AC current supplied by the electric power grid. The resonance frequency was tuned

by adjusting the position of the magnets relative to the free end of the bimorph. Once properly adjusted, the magnets were fixed in place using cyanoacrylate glue.
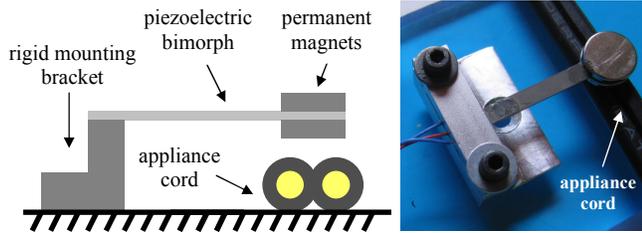

Figure 2 – Schematic and photograph of energy scavenging generator device.

Power transfer to a resistive load – The energy scavenging generator and space heater appliance cord were mounted as shown in Fig. 2, with the centerline of the bimorph approximately 5 mm above the centerline of the power cord. A variable resistive load was used to measure the power output of the generator. Results are shown in Fig. 3 for power output with the space heater running at each of its two settings. With a 9.4 A current in the heater cord the energy scavenging generator's maximum power output was 208 μW to a 419 kΩ load resistor. With a 13 A current in the heater cord, the generator's maximum power output was 345 μW to a 491 kΩ load resistor. These optimal load resistances match the output impedance of the generator to within 15%.
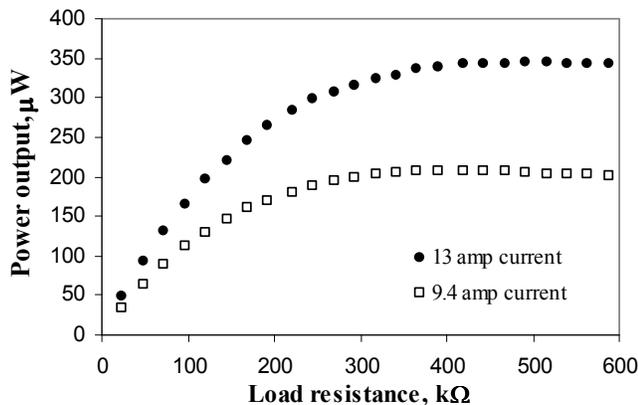

Figure 3 – Experimentally measured power output in energy scavenging operation, coupled to a space heater power cord.

Power transfer to a capacitive load – The generator's output was rectified using a DF005M full-wave bridge rectifier and used to charge a 1000 μF capacitor. The capacitor was charged from zero to 5 volts in 196 seconds, representing an average power transfer of about 64 μW. It is important to note that this charging circuit is highly inefficient, as much of the generator's output does not contribute to charging the capacitor.

3.2 - Current sensor operation

A second prototype was built to evaluate the device's potential as a current sensor. It was constructed using a Piezo Systems Q220-A4-203YB bimorph measuring 31.8 x 6.4 x 0.5 mm. This bimorph came from the supplier pre-mounted

to a small section of printed circuit board and with lead wires attached. The same magnets were used as mentioned previously, and the device's resonance frequency was measured at 110 Hz

The sensor was first coupled to a dual-conductor appliance cord carrying varying increments of current up to 13.4 A. Experimental data were taken and are shown in Fig. 4. A linear regression reveals a sensitivity of 74 mV/A and a high degree of linearity ($R^2 = 0.999$).
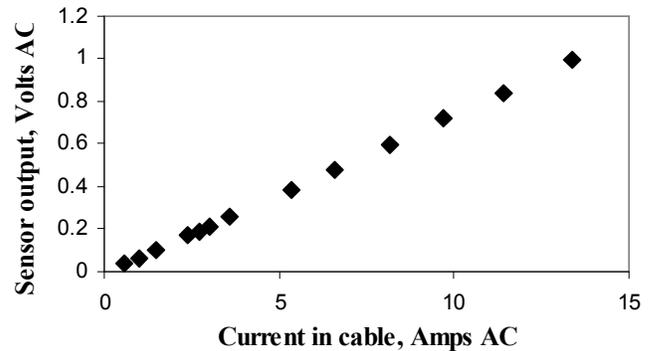

Figure 4 – Experimentally measured current sensor response, coupled to an appliance power cord.

The device was mounted on a length of 500 MCM power cable as illustrated in Fig. 5. The bimorph was screw-mounted to a 12.5 cm length of aluminum angle with a thickness of 3.2 mm, which was in turn fastened to the cable using zip ties. Aluminum spacers of 3.2 mm thickness were used to provide clearance for the free end of the bimorph. Another spacer was placed atop the section of PCB in order to form a rigid clamp, thus minimizing the mechanical strain in the PCB and maximizing the strain (and thus the output voltage) of the bimorph.
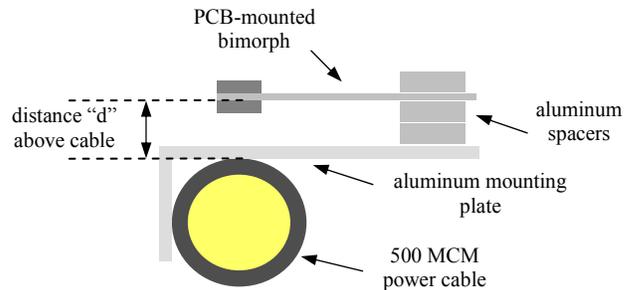

Figure 5 – Schematic of current sensor mounted on single-conductor power distribution cable.

The sensor's RMS voltage output was measured as the amperage in the power cable varied up to 48 A. Three sets of data were recorded, using one, two, and three spacers between the bimorph's PCB mount and the aluminum angle plate. These measurements were used to examine how the sensor's signal varied with its distance from the center of the conductor.

The experimental results for current sensor operation are shown in Fig. 6 and summarized in Table 1.
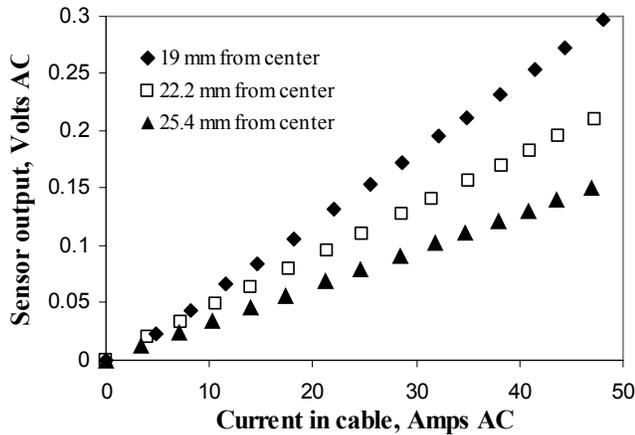
Figure 6 – Experimentally measured current sensor response at varying distances from the conductor core.

The experimental data show highly linear current sensor response. Closer examination of the sensitivity data shows that the ratio of the first and second sensitivities matches the ratio of the second and third sensitivities to within 2 percent. This observation indicates that the sensitivity of the device is proportional to the inverse of its distance from the center of the conductor, in agreement with theory.

Table 1 – Experimental data for current sensor operation.

No. of spacers	Bimorph distance to conductor center (mm)	Sensitivity (mV/A)	R^2 (linear regression)
1	19	6.08	0.998
2	22.2	4.46	0.999
3	25.4	3.22	0.999

4 - DISCUSSION AND CONCLUSIONS

Several important observations can be drawn from this research. When coupled to an appliance cord as an energy scavenging generator, the devices developed in this study present a promising power source for sensor networks. Commercially available wireless nodes use about 60 mW of power during send and receive operations [11, 12]. Assuming an efficiency of 80% for conditioning and storage of the scavenged energy, these generators could power a sensor node at a duty cycle between 0.28% and 0.46%. Conservatively estimating an average of 200 ms to perform a send/receive operation, such a duty cycle is sufficient to perform 50 to 80 data transmissions per hour. Duty cycles in this range are adequate for many present day sensor network applications. It is important to note that these are conservative estimates based on commercially available technology and that duty cycles will continue to improve with advances in low-power radios and microprocessors.

For current sensing operation, the devices developed in this study show highly linear behavior. It is also useful that sensitivity varies with the inverse of the distance to the center of the current carrier. This property allows two calibrated

sensors fixed some known distance apart to measure current accurately without knowing the precise distance of either sensor to the center of the current carrier. This concept could be scaled up to an array of several sensors capable of measuring current without requiring precise alignment to the conductor [13].

Finally, the meso-scale devices presented in this paper show potential for scaling down to the MEMS level. Developments in novel deposition of piezoelectric materials [14, 15] and magnetic materials [16] at the microscale are particularly encouraging. The authors intend to pursue a proximity-based MEMS current sensor in their future work.

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