Energy Harvesting from Electromagnetic Energy Radiating from AC Power Lines

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Abstract

There has been considerable interest in energy harvesting for wireless sensor networks. Energy harvesting from thermal sources such as body heat and mechanical sources such as human motion have been proposed. There are also sensor network systems that harvest energy from the visible part of the electromagnetic spectrum. However, ambient light levels in indoor environments are typically significantly lower than those found outdoors and highly dependent on the nature of the indoor environment considered. Recently, low-power clock synchronization using electromagnetic energy radiating from AC power lines was proposed. In this paper, we go a step ahead and try to answer the question: Can energy be harvested from the electromagnetic energy radiating from AC power lines and use it to operate a wireless sensor network with a low duty-cycle? We find that such energy harvesting appears promising.

1 Introduction

Many schemes have been proposed recently focussing in the development of systems capable of harnessing useful electrical energy from existing environmental sources, especially in the wireless sensor networking community [6, 21]. Photo-Voltaic conversion of visible part of the electromagnetic spectrum to electrical power is well established and Photo-Voltaic cells provide relatively high efficiency over a broad range of wavelengths. These devices are typically low cost and provide voltage and current levels that are close to those required for micro-electronics. Conversion of ambient RF signals to useful electrical energy is far more challenging due to the broadband, low intensity nature of the signals typically present. An example of a system drawing energy from RF signals are crystal radio kits [17] that draw their power directly from AM radio stations, which play audibly through high-impedance headphones without needing a local energy source. One of the examples of similar harvesting scheme is the aftermarket modules that flash LED's using energy from electromagnetic waves when a cell phone uses its radio. Rather than relying on the limited energy scavenged from ambient radiation, other approaches actively beam power from a transmitter to remote devices. The dream of wirelessly broadcasting power to an urban area dates back to the turn of the 20'th century and Nicola Tesla [3], who experimented with grandiose concepts of global resonance and gigantic step-up coils that radiated strong, 150 kHz electromagnetic fields able to illuminate gas-filled light bulbs attached to a local antenna and ground at large distances [23]. Recently researchers have experimented with microwave transmission of power in domestic environments [2]. At much lower power levels, short-range wireless power transmission is now commonplace in passive Radio Frequency Identification (RFID) systems [11], which derive their energy inductively, capacitively or radiatively from the tag reader.

Researchers have explored the possibility of extracting power from the magnetic fields from high-voltage power lines [10]. Many of these techniques use a current transformer to convert the magnetic fields to usable current. A recent work [9] describes energy harvesting from power lines attached to electric motors. Solutions based on current transformers require that the single current carrying wire be passed through it. There are some commercial products[22] which can be snapped on a high-voltage single wire. All similar techniques are quite limited in applications because of their placement constraints.

Recently, Anthony Rowe *et.al.* designed an LC tank based receiver circuit tuned to the AC 60Hz and used the received signal for clock synchronization [19]. In this paper, we investigate the feasibility of harvesting energy from the magnetic fields emanating from the AC power lines in addition to synchronization. Average available power from this harvesting scheme is lower than the requirements of a typical sensor node, so the node should only be turned on when enough energy has been accumulated for the useful work. The mismatch in duty-cycles and wake-up times of different nodes in a network will severely constrain the coordination among nodes. Therefore, by powering a wireless sensor device through the magnetic fields we can also exploit the dual advantage of maintaining the clock synchronization using the same signal. It was established in [19] that nodes may remain synchronized for long periods of time without exchanging messages because of the global clock from the EM fields. However, other energy harvesting schemes with limited available power may not be practical if frequent communication is required just to maintain the clock synchronization.

2 Motivation

From Ampere's law[7] [8], we know that the magnetic field generated from a group of closely bundled wires is dependent on the net current flowing through them. Given that the live and neutral wires carrying current in opposite directions are usually placed close together, the magnetic fields produced by them should cancel each other. It is however, interesting to note that there exists electromagnetic energy in typical home and office areas either due to separation distance between live and neutral wires or imbalances in ground loop [14]. Earlier studies [5] also suggest that the ambient magnetic field in homes vary from 0.01 to 10 Gauss near appliances and typically exceeds 100 Gauss in industries with heavy electrical machinery. Additionally, we observed in our experiments that the cancellation of magnetic field is almost negligible if the separation between the wires is more than a few inches. This magnetic field can be converted to electrical energy source with clever design and careful placement of sensor devices. A typical office space building has a dense network of power line cabling, and some of those wires would carry currents in the orders of 5-10 amperes. The ubiquity of power lines and the magnitude of current running through them in any human occupied environment makes energy harvesting from the stray electromagnetic fields seem attractive.

3 Feasibility Study

The magnetic field at a point P at a distance r from an infinitely long conductor carrying an alternating current with a peak amplitude of I_o and frequency ω is:

$$B = \frac{\mu I_0 sin(\omega t)}{2\pi r} \tag{1}$$

where B is the magnetic flux density and μ is the magnetic permeability given by $\mu_r \times \mu_0$ (μ_r is relative permeability). The magnitude of the magnetic flux acting on a coil with N turns, cross sectional area A placed with its plane perpendicular to the magnetic field is given by:

$$\phi = NBA$$

The induced voltage on the coil due to the rate of change of the magnetic flux acting on it will be:

$$V = \frac{d\phi}{dt} = \frac{NA\mu I\omega cos(\omega t)}{2\pi r} \tag{2}$$

The above equation shows that the net voltage induced on the coil placed in a magnetic field increases proportionally with frequency, number of turns, and area. It decreases proportionally with the distance. It is interesting to note that the induced voltage can be increased with a coil with high relative permeability. In the following section, we describe the experimental setup and our observations.

4 Experimental Study

4.1 Experiment Setup

We need to measure the average power that can be extracted from the magnetic fields emanating from AC power lines, in order to understand the feasibility of proposed energy harvesting system. We conducted controlled experiments where we observed the power available from various arrangements of current carrying conductors and configuration of inductors in the magnetic field associated with the conductors.

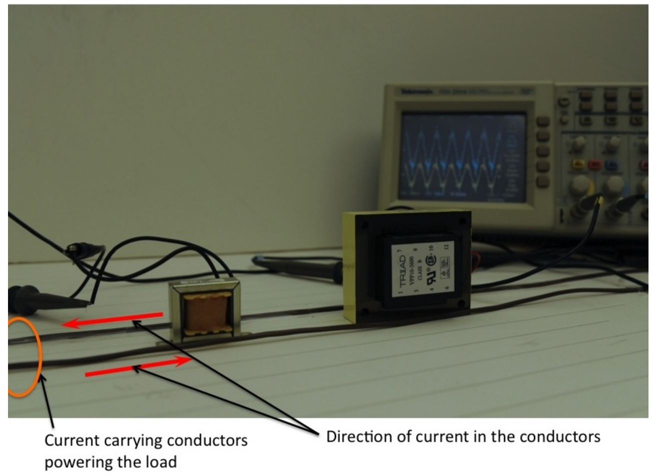

Figure 1. Experimental setup showing the inductors placed in between two parallel conductors carrying the live and return current. We measured the voltage across the inductors to estimate the maximum power available from the magnetic field.

The experimental setup is shown in Figure 1. We laid two parallel conductors on a graduated flat board, and these conductors were used to power a load consisting of ten light bulbs of 100 Watts each in parallel. When the complete load is applied, a current of 8.4 Amps flows through the conductors. We explored many inductors for conducting our experiments.The parameters of the inductors are shown in table 1. The results presented in the paper are using two inductors with inductance values of L = 15H and L = 4.50H. The experiments for each of the inductors were conducted separately in order to avoid any magnetic coupling effects.

We present the results for the following experiments:

- Measured induced voltage on the inductors for varying distances from a pair of conductors, where the distance between the conductors is very high (> 15 inches).
- Change the supplied load and measure the induced voltage
- Keep the conductors at a distance of one inch apart with the inductors between the conductors and measure the variation of the induced voltage along with the height of the inductors from the plane of the conductors.
- Measure the voltage induced on the inductor when placed over a bunch of wires passing in a metal conduit typically seen in buildings.

4.2 Experiment Observations

In this section, we measure power drawn from the inductor when it is placed in an alternating magnetic field originating from the magnetic fields. It is explained in Section 5 that power drawn from a source is near its maximum with a matched impedance load. In our system, the inductor is the source of the voltage, and will be used to drive a sensor device. Figure 2 is the screenshot of the oscilloscope showing voltage across two different inductors placed between two parallel wires carrying 8.4A current in the opposite direc-

Table 1. Various inductors used in the experiment, their series resistance values and corresponding capacitor values to ensure maximum energy transfer

Inductance (mH)	Resistance (Ohms)	Matched Capacitor (μF)
15000	980	0.47
11513	852	0.62
4500	49	1.56
3550	118.5	1.98
1700	21	4.2
1500	40	4.7
320	10	22

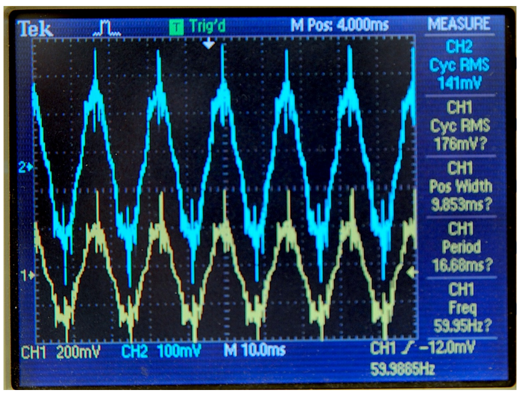

Figure 2. Oscilloscope capture of voltage across two inductors when placed in the magnetic field as shown in Figure 1. Channel 1(yellow) of the oscilloscope is connected the to coil with L=15 H, and channel 2(blue) to the coil with L=4.5 H. The RMS voltage can be seen on the top right corner.

tions (corresponding to 1000W load). The RMS voltage at the terminals of the inductor is shown at top right corner of the figure. Channel 1 of the oscilloscope is connected to the inductor with inductance value 15 H and channel 2 to the one with 4.50 H.

Power measured from a single current carrying conductor is shown in Figure 3. The inductor is placed in the same plane as the wire. Power available from the inductor varies inversely with the distance as described in Section 5. On the other hand, if the location of the coil with respect to the single wire is fixed, the voltage across it drops when the return current wire is moved closer to the other wire. In the case when the conductors are close to each other, the magnetic fields cancel out and the magnitude of this cancellation depends on the distance between the two wires. This phenomena is shown in Figure 4. Magnetic fields however, do not cancel out when the inductor is placed between the wires or vertically above the plane of the conductors. In this configuration, the horizontal components negate each other, but the vertical components of magnetic fields add up. The variation of peak-to-peak voltage across the inductors with the height above the conductor plane is shown in Figure 5.

We also measured the voltage across the inductor when placed close to typical electrical wiring installations supplying normal load of computers and lights in our lab (shown in

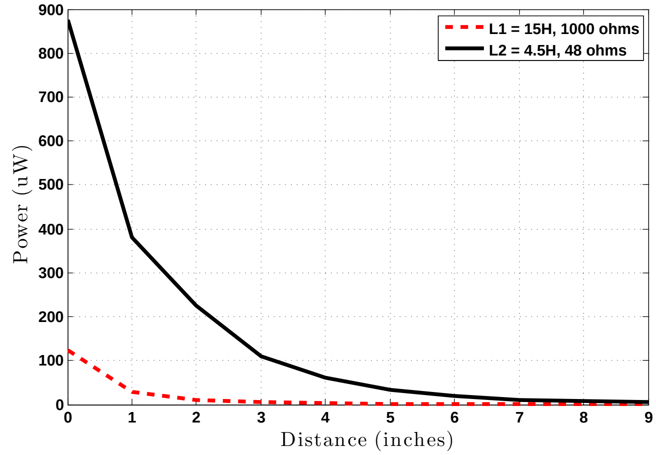

Figure 3. The variation of induced power with distance from a pair of alternating current carrying conductors where the distance between the conductors is high (> 15) inches

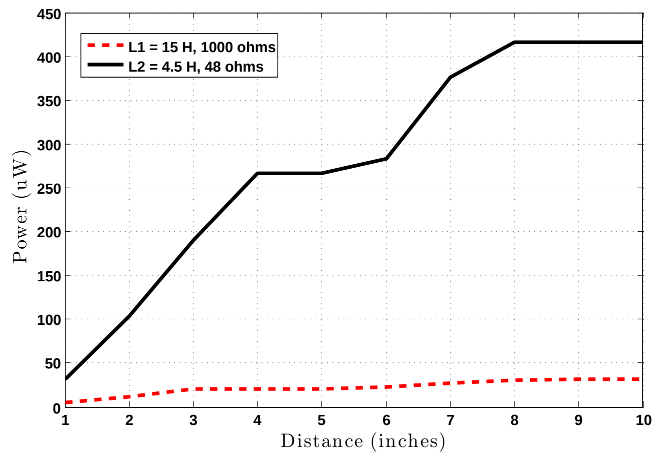

Figure 4. Variation of induced power on inductors when placed one inch away from live conductor. X-axis is distance between the conductors.

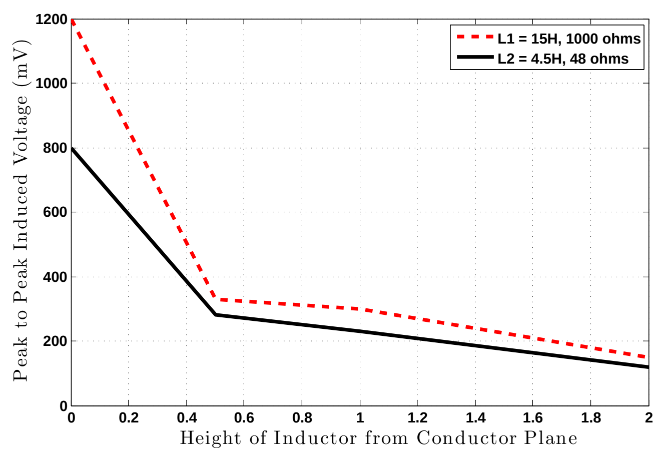

Figure 5. Induced voltage on an inductor placed between two alternating current carrying conductors that are one inch apart. X-axis denotes the height of the inductor from the conductor plane.

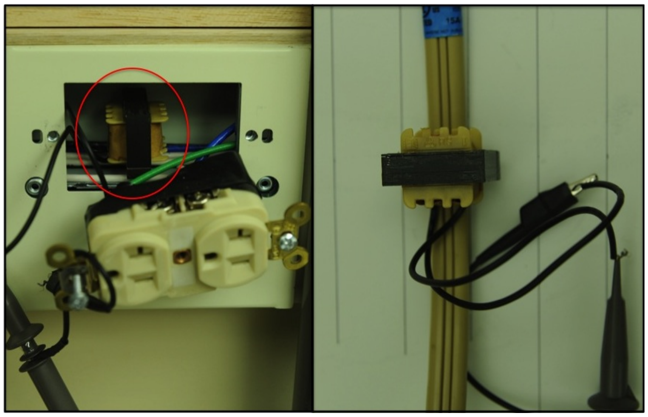

Figure 6. Inductor placed close to the wires in a conduit in a computer lab & capturing magnetic field close to a commercial high amperage cable.

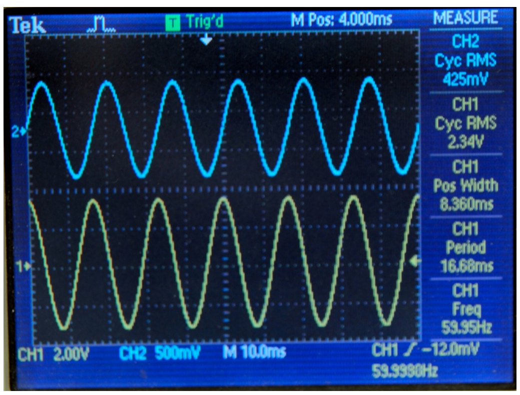

Figure 7. Oscilloscope capture of voltage across parallel combination of L and C (Table 1), when placed in the magnetic field.

the left side of Figure 6). When the 15 H inductor was placed close to the wires in a conduit, we saw 412 mV across the inductor. When coil is placed vertically above the cable in which live and neutral are bundled together in same shielding, the induced voltage was 340 mV.

When a matched capacitor is connected in parallel to the inductor, we observe the resonance effect, where all the charge on the inductor is transferred to capacitor and vice-versa without any reactive losses. Some charge nevertheless, is lost because of the series resistance of the coil and leakage current in capacitor. Figure 7 shows the voltage across the tuned LC parallel circuit for each of the two inductors.

5 Design Considerations

The choice of components for the energy harvesting circuit is extremely critical. There are delicate tradeoffs that need to be made maximum energy conversion.

5.1 Resonance Circuit

In our system, the magnetic field is being converted to an induced EMF (ElectroMotive Force) with an inductor. The magnitude of the induced EMF is directly proportional to the inductance, which in turn depends on the number of turns, the permeability of the core, area of the coil and its orientation with respect to the magnetic field. An off the shelf

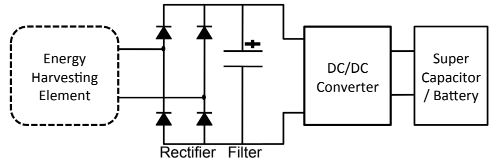

Figure 8. Typical Energy Harvesting Circuit.

inductor of high inductance, inspite of getting high induced voltage may not necessarily give high power output. This is so because coils with higher inductance values tend to have high resistance due to the large number of turns. This limits the maximum derivable power.

The maximum energy transfer theorem states that, maximum power can be obtained from a source if the load impedance is the conjugate of the source impedance. We can estimate power available from magnetic field by assuming that we have a perfectly matched load which is connected across the inductor. Typically, the matched load for an inductor would be a capacitor in series with a resistance equal to R_L such that:

$$f = \frac{1}{2\pi\sqrt{LC}}$$
$$R_L = R_S$$

where f is the frequency of the AC power (for example, 60 Hz in the US), and R_S is the series resistance of the inductor. Now that if the load is matched, average power dissipated in inductor and capacitor is zero, hence maximum available average power is given by the following equation:

$$P = \frac{V_{rms}^2}{R_S}$$

It can be understood from the above equation that the available power depends entirely on the properties of the coil. Mathematically,

$$P \propto \frac{\mu^2 N^2 A^2 I_0^2}{d_t^2 R_S}$$

where, μ is the permeability of the inductor core, N is number of turns, A is effective cross section area I_0 is the current flowing in the inductor and d_t is the distance of the coil from the conductor. For a given magnetic field strength and the distance of the coil from the wire:

$$P \propto \frac{\mu^2 N^2 A^2}{R_S}$$

5.2 Energy Harvesting Circuitry

The design of an energy harvesting system is challenging since the power derived from ambient sources tends to be unregulated, intermittent and small. A typical energy harvesting ciruit is shown in Figure 8.

Microelectronic devices and rechargeable batteries usually require a DC power supply. Hence a power conditioning circuitry is necessary to rectify the AC power to stable DC power. Typically a power conditioning circuit is sensitive to the efficiency of power extraction. Ottoman et al. [15, 16] derived the optimal DC voltage required to maximize the power extraction under the direct connection of the load to an AC-DC rectifier of a piezoelectric power generator. They also presented an adaptive solution using the DC-DC convertoer to achieve automated power optimization. A sensorless buck-boost converter running in discontinous mode was used by Lefeuvre et al. [13] to track the optimal working points of the generator. Badel et al. [1], Guyomar et al. [4], Richard et al. [18], and Xu et al. [20] developed several conditioning circuits to increase piezoelectric power generation that incorporated electronic switches and inductors to shape the delivered voltage. Na Kong et al. [12] recently proposed a two-stage power conditioning circuit consisting of an AC-DC converter followed by a DC-DC converter for a vibration-based energy harvesting system.

6 Limitations

Not unlike many other energy harvesting schemes, there are some limitations of using magnetic fields of the AC power lines. Firstly, magnetic field strength from the power lines is significant only in their close proximity, which limits the freedom of placement of harvesting system close to the AC wires. However, we can extract power even if the wires are laid inside the wall and the device is placed on the wall at a distance of few(2-3) inches. If the power cables are deployed in metal conduits then most of the magnetic field is constrained inside it, which nullifies any possibility of harvesting energy. Second limitation of the system is that a highly efficient power transfer circuit is required to store charge in a super-capacitor with minimum losses.

7 Conclusions

Performance improvements in battery technology and the power requirements of electronics are not keeping pace with the increasing demands of many wireless sensor networking applications. For this reason, there has been considerable interest in the development of systems capable of extracting usable electrical energy from existing environmental sources. Such sources include ambient electromagnetic energy, thermal gradients, vibration and other forms of motion. In this paper, we have provided a feasibility study of harvesting electrical energy from stray electromagnetic energy of AC power lines. We conducted many experiments with various off-the-shelf inductors and current carrying conductor combinations. The results are promising in that with easily available components, up to 1-2 mw of power can be harvested. As future work, we intend to construct an inductor that is optimized for harvesting energy in this context. Also, we need to design and implement energy-harvesting circuits with high power-transfer efficiency.

8 References

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