

# Energy Harvesting from Electromagnetic Field Surrounding A Current Carrying Conductor

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**Abstract** — With the rapid expansion of portable consumer and industrial devices, there is a present need for small, wireless, and portable power sources. Aside of traditionally used batteries, energy harvesting is one of the options that seems particularly attractive and cost efficient. This paper presents a novel method of retrieving energy from an electromagnetic field surrounding a current-carrying conductor. The device consists of a piezoelectric material sandwiched between two permanent magnets. The force created by the interaction of the field with the magnets actuates the piezoelectric, which in-turn generates electric energy. The Comsol Multiphysics modeling software was used to optimize the performance and geometry of the device. The operation of the energy harvester was verified experimentally and tested under various load conditions. The proposed energy harvester, with its modular design, allows for convenient output power adjustment enabling it to be applicable to a wide array of applications.

## I. INTRODUCTION

Present portable devices are constantly evolving into lighter, faster, and smaller versions of their previous self. While the package sizes become smaller the requirement for faster speeds comes at a price. These portable devices are deficient at best when it comes to power usage. These devices often drain their power supply in a matter of hours versus their previous, slightly slower counterparts. This has created a need for a low cost and novel way to power these portable devices. Energy harvesting is a growing field and one that could answer the consumers cry for better and more reliable power sources. Energy harvesting is attractive due to its clean operation and overall stability [1]. This research paper discusses the use of piezoelectric material to harvest energy from an electromagnetic field surrounding a current carrying conductor. There are many ways to scavenge power using a piezoelectric; however, the source is primarily kinetic energy. It comes in many forms, including human motion, vibrations, fluid flows and etceteras. Our design utilizes vibrations generated by the magnetic fields of wires carrying AC current.

The University of California at Berkeley, introduced the concept of piezoelectric energy harvesting from vibrations generated by the alternating magnetic field around an AC power cord [2]. The device was used to scavenge power and also used as a current sensor. These devices had two magnets, attached at the end of a piezoelectric bimorph, and were mounted to custom-machined aluminum brackets. The two magnets coupled the alternating magnetic field of an AC power cord affecting the bimorph to generate a voltage. As a result, when this device was coupled with a current carrying 9.4 A rms, the device produced 208  $\mu\text{W}$  of power in a 419 k $\Omega$  load resistor and similarly, 345  $\mu\text{W}$  coupled to 13 A rms of current. In the current sensing operation of the device, the maximum sensitivities was 74 mV/A with a correlation coefficient greater than 0.99.

Presently, the Research Center of Sensors and Instruments, of Chongqing University in China, have investigated a similar concept [3]. The device was made up of a piezoelectric cantilever beam, with a magnetic circuit attached to the free end of the beam, and a mass to tune the resonant frequency. The magnetic circuit had three NdFeB magnets connected by two magnetic yokes, in series, to enhance the magnetic flux density. The AC current in the power cord generated a magnetic field, which was coupled to the magnet, creating a vibrational force on the piezoelectric material. The harvester produced 1.58 mV using a 216 k $\Omega$  load resistor under 50 Hz resonant frequency of 6 A rms current.

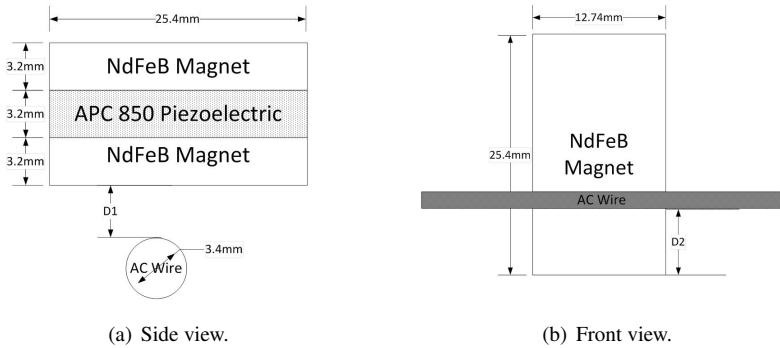
The harvester presented in this research comprises of a 850 type piezoelectric material (American Piezo Ceramics International, Ltd.) [4] sandwiched between two Neodymium permanent magnets (K&J Magnetics, Inc.) [5]. The magnetic force created by the interaction between the wire and the two NdFeB magnets actuates the piezoelectric, which then generates electric energy. We explored three configurations of magnets, one with horizontal poling, and two sets with vertical poling. The vertical poling magnets has different depth. The scope of this research is to power a sensor that measures voltages on a power distribution line [6]. Power distribution lines produce a substantially larger magnetic field as compared to household electrical wires. This research aims to investigate the energy harvesting potential of a power distribution line, with comparisons to the current research conducted on only household electrical wires. The device produced from this research is easy to assemble, and capable of incorporating a modular type design which allows for the output power of the harvester to be adjusted.

## II. HARVESTER DESIGN

The design layout of the harvester is shown in Fig.1. The harvester consists of a 25.4 mm x 12.74 mm x 3.2 mm APC 850 piezoelectric material placed in between two permanent magnets. The two magnets create an attraction force which holds the harvester as one unit. The harvester is placed on vicinity of an AC current conducting wire. An insulated AWG 16 wire was used. The horizontal distance between the wire and the harvester is called D1, as shown in Fig.1(a), and the vertical distance, called D2 in Fig.1(b). The functional prototypes of the harvesters are shown in Fig.1(c). The topmost harvester contains two 25.4 mm x 12.74 mm x 1.6 mm K&J B82X0 NdFeB magnets[4]. The other two harvesters, Magnet 2 and 3, have 25.4 mm x 12.74 mm x 3.2 mm K&J BX082-N52 NdFeB and K&J BX081-N52 NdFeB magnets respectively. Magnet 1 Harvester's a residual flux density is 13,200 Gauss, while Magnet harvesters 2 and 3's residual flux density are 14,800 Gauss

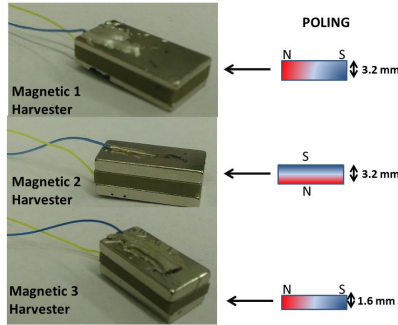
[5].

Fig.2 shows the complete circuit design and experimental set up. Fig.2(a) displays the



(a) Side view.

(b) Front view.



(c) Actual harvester.

Fig. 1. Harvester design layout

schematic of the circuit, while Fig.2(b) presents the actual experimental setup. The current in an AC wire was 6 A rms comes from an adjustable isolation transformer (called "AC SOURCE" in Fig.2(a)). The harvester was connected to a resistive load of 1 M $\Omega$ . The output power is computed using the output voltage value and the load resistor's resistance. The two distances, D1 and D2, were varied. A grounded aluminum foil was used to create a Faraday cage around the wire and the harvester to shield the assembly from external electric field. The voltage output was measured to record with shielding and without shielding. A Rigol DS1052E oscilloscope was used recorded the output voltage waveform.

### III. EXPERIMENTAL RESULTS

#### A. Environment Effect

There are many forms of environmental background signals, such as mechanical building vibrations and stray electrical fields present in the laboratory that could affect the results

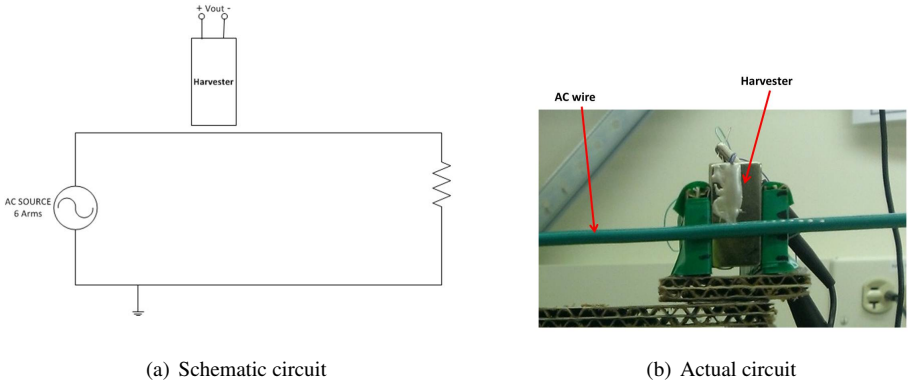


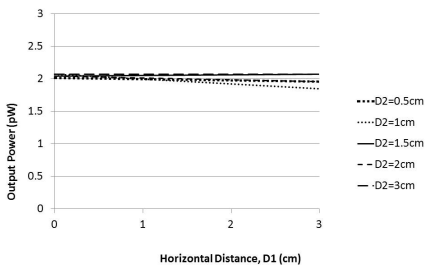
Fig. 2. Schematic and actual circuit

of the experiments. This section presents the results of the tests of the environmental background noise affecting the harvester. The experiment were conducted for various distances D1 and D2. The output voltage of the harvester was measured when the wire did not conduct any current. Fig.3 shows the output power from the harvester with shielding present. Similarly, Fig.4 presents the output power when no shielding was present. The horizontal axis represents the distance D1. D1 was varied from 0 cm to 3 cm. Each of the graphs were plotted for one vertical distance value of D2 which was varied from 0.5 cm to 3 cm.

Fig.3 show power harvested with only the environmental background noise present for all three harvesters with shielding. Then results indicate that there is no significant difference in power harvested from the background noise for D1 and D2 being varied. The power level is in pW range, and it is of no practical value. The percent differences between the highest output power and the lowest output power were 12.11 %, 10.56 %, and 10.32 % for Magnet 1, Magnet 2 and Magnet 3 Harvester respectively.

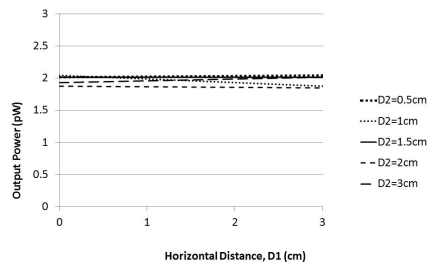
Similarly, Fig.4(a), shows power collected by harvesters without shielding. The highest percent difference among the output powers was 11.56 % for Magnet 1, 10.51 % for both Magnet 2 and 3 Harvester. These values are small enough to conclude that the output power was not affected by D1 and D2 when there was no shielding and no current in the wire.

Magnet 1 Environmental Power Output (With Shielding)



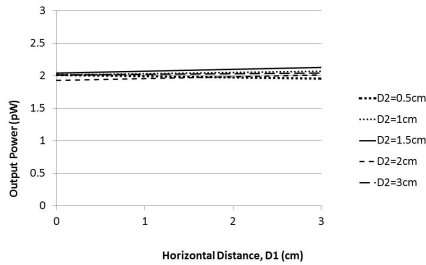
(a) Magnet 1 Harvester.

Magnet 2 Environmental Power Output (With Shielding)



(b) Magnet 2 Harvester.

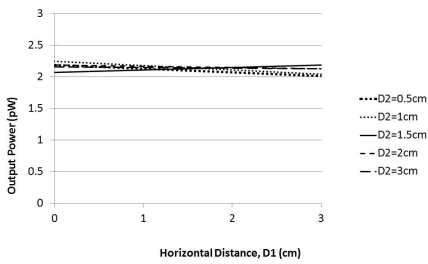
Magnet 3 Environmental Power Output (With Shielding)



(c) Magnet 3 Harvester.

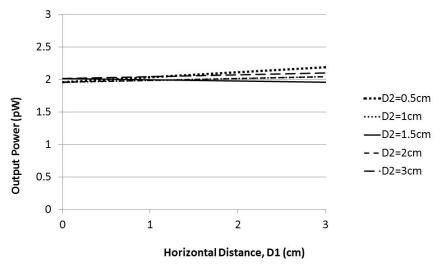
Fig. 3. Environment output power (with shielding)

Magnet 1 Environmental Power Output (Without Shielding)



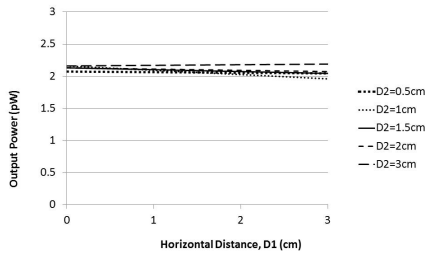
(a) Magnet 1 Harvester.

Magnet 2 Environmental Power Output (Without Shielding)



(b) Magnet 2 Harvester.

Magnet 3 Environmental Power Output (Without Shielding)

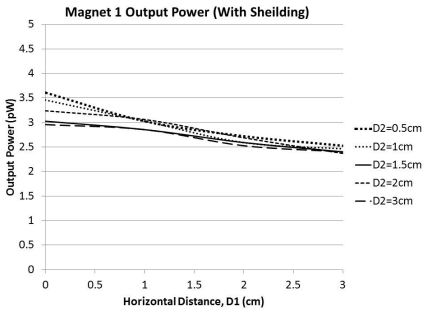


(c) Magnet 3 Harvester.

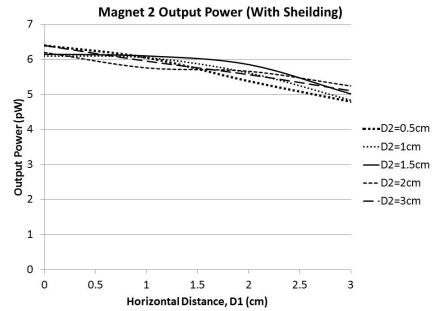
Fig. 4. Environment output power (without shielding)

### B. Electromagnetic Effect:

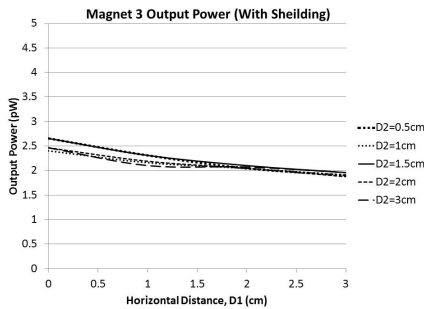
This part of the paper discusses the results when the wire conducted an AC current of 6 A rms. The output voltage across a 1 M $\Omega$  resistor load was measured when the horizontal distance, D1, and vertical distance, D2, were changed. Fig.5 shows the output power graphs with shielding and Fig.6 shows the result without shielding. The horizontal axis represents the distance D1. Each graph is plotted for a constant D2.



(a) Magnet 1 Harvester.



(b) Magnet 2 Harvester.

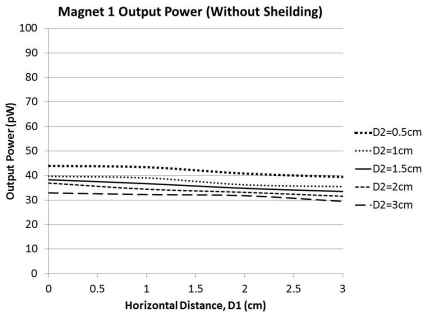


(c) Magnet 3 Harvester.

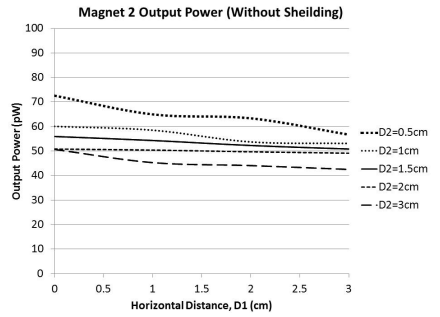
Fig. 5. Output power (with shielding)

Fig.6 shows that as the horizontal distance D1 increased, the output power decreased (since magnetic field decreases [7]). The influence of D2 is not easily distinguishable. The highest output power is 6.4 pW, which is the output power of the Magnet 2 Harvester at D1 = 0 cm and D2 = 0.5 cm.

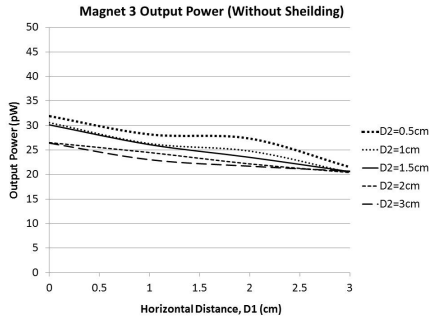
Fig.6 shows output power for the harvester with no shielding. The output power decreased when the horizontal distance D2 increased. Also, as the vertical distance D1 increased, the output power decreased for all three sets of magnets. The position where D1=0 cm and D2=0.5 cm produced the highest output power of 72.59 pW. This behavior is identical with the case when the shielding was present (max power for the same D1 and D2). The



(a) Magnet 1 Harvester.



(b) Magnet 2 Harvester.



(c) Magnet 3 Harvester.

Fig. 6. Output power (without shielding)



maximum output power was observed for the set up with no shielding. In this case because the harvester was exposed to an electric field produced by the wire. Magnet 2 Harvester produced the highest output power, while Magnet 3 Harvester produced the lowest output power. These results were the same for both the shielded and non-shielded case.

### C. COMSOL Modeling

A COMSOL Multiphysic model of the harvester was constructed to help with understanding of the harvester operation. The physics used were Magnetic Fields (AC/DC) and Piezoelectric Devices (Structural Mechanics). A preliminary model in 2 dimensional geometry is shown in Fig.7. The top and bottom rectangular boxes represent the two magnets with 1.4 Tesla remanent flux density. The middle piece shows the deflected piezoelectric. The top boundary of the piezoelectric is at a floating potential and bottom boundary is grounded. The right side of the piezoelectric is fixed in place. A current of 6 A rms is flowing through the wire (circle in Fig. 7). The deflection is the results of magnetic field of the wire acting on the magnet. We are currently working on optimization accuracy of the model.

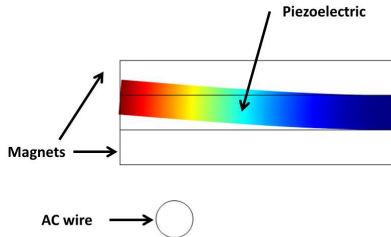
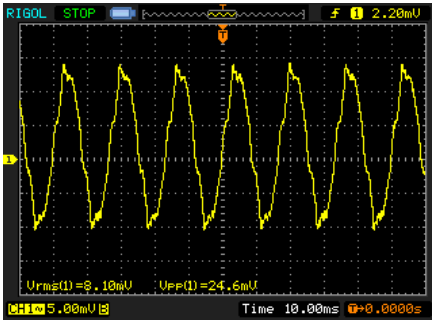


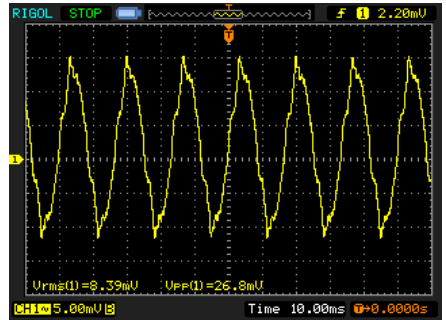
Fig. 7. COMSOL Multiphysic model

### D. Modular Design

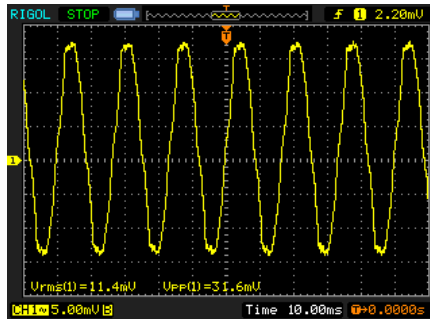
Even though all of the harvesters produced power, the output power of one harvester is very small. For that reason, parallel combinations of the harvesters were investigated. Since Magnet 2 Harvester produced the maximum output power, two of these harvesters were connected in parallel with 1 M $\Omega$  resistor load without shielding. The waveforms in Fig.8 show the output voltages for Magnet 2 Harvester (a), Fig.8(a), and Magnet 2 Harvester (b), Fig.8(b). The waveform in Fig.8(c) presents the output voltage waveform of the parallel combination of these two harvesters.



(a) Individual output voltage.



(b) Individual output voltage..



(c) Parallel combination output voltage.

Fig. 8. Modular design output voltage

Based on the data of Fig.8, the individual output power was computed as 70.39 pW and 65.61 pW. The sum of the output powers for the parallel combination of the two harvesters was 136 pW, while the measured output power was 129.96 pW.

#### IV. CONCLUSIONS

Overall, as both the horizontal and vertical distances, D1 and D2, increased, the output power decreased. When the setup was shielded, the effect of D2 was inconclusive since the output power was not affected when this distance was varied. The maximum output power was observed when the magnet was closest to the wire (D1=0 cm and D2= 0.5 cm) for both cases, with and without shielding.

Because the harvester's individual output power was small, the next step will be toward combining harvesters and finding more robust materials. Also, an actual power line produces higher magnetic field than the wire used in this research. Better materials for both the magnet and the piezoelectric could increase the output power. Our plan is to explore flexible materials to allow for more deflection. The COMSOL model will assist us with this task.

#### V. ACKNOWLEDGMENTS

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