HARVESTER SCAVENGING AC MAGNETIC FIELD ENERGY OF APPLIANCE CORDS USING PIEZOMAGNETIC/PIEZOELECTRIC ME TRANSDUCERS

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Abstract: In modern life, ac magnetic fields generated by power currents are among the most popular ambient energy sources. Ac magnetic fields exist along the power lines connected to electric appliances in use. A energy harvester based on piezomagnetic/piezoelectric composite magnetoelectric transducers is proposed, which is feasible for scavenging the ac magnetic field energy either from a single phase conductor or from a zip cord with two conductors wrapped together to carry currents in opposite directions. With ME transducers, ac magnetic fields from power lines are converted into electricity. The ME transducer-based harvester possesses the advantages of piezoelectric harvesters as well as it has a rather high ME transduction efficiency. And as the magnetostriction in piezomagnetic material will be saturated in strong fields, the harvester is immune from producing surging output in rush currents. The low frequency ME effect in ME transducers is decisive to the magnetic energy harvesting performance. Terfenol-D/PMN-PT/Terfenol-D laminates are fabricated to implement ME transduction. The maximum value of measured ME voltages at the optimal bias is about 0.2 V/Oe at frequencies less than 1 kHz. A harvester is implemented using two such ME transducers. The output power of the harvester is about 40 μW while scavenging the magnetic field from a zip-cord carrying 10 A current.

Keywords: energy harvesting, magnetoelectric transducer, power line, ac magnetic field

INTRODUCTION

Energy harvesting provides a promising final solution to power supply of microelectronics. However, even with the fast progress in transduction materials and devices, the actual harvesting performances significantly depend on the presence and intensity of ambient energy sources. It is obvious that the presence of ambient energy sources varies from time to time and from place to place as well. For example, the universal sunlight blacks out either at night or while being sheltered. In those cases, solar energy harvesters, usually solar cells can not operate. In modern life, electromagnetic fields/waves are a kind of general energy sources. Some investigations have been conducted to scavenge energies from RF sources, such as RF energies emitted by cell phone towers and television stations [1]. However, the field strengths from RF sources are rare, to generate enough power energy harvesters have to be placed close to a powerful transmitter or be equipped with transducers of substantially large energy receiving surface [2]. In Jan. 2010, RCA claimed a charger which is able to convert the energy in WiFi signals into electricity to power small devices. Power can be extracted from WiFi signals as the charger is carried around, or it can be left near a WiFi router at night to collect and store power for use the next day [3]. However some detractors suggest that the device would not generate a useful amount of power unless placed in the immediate vicinity of a high power broadcast. And on the other hand, RF energy scavengers in operation might deteriorate RF transmission except that the RF source is strategically designated a RF powering source as in Ref. [4].

As a matter of facts, the electricity power consumption occurs almost in every aspects of human daily life. There are electric power lines carrying currents where there is electricity power consumption. The magnetic fields resulting from the currents exist around power lines. As the power currents are considerably large than that in RF transmitters, in no sense, the strength of an RF energy source can be compared to that of magnetic fields accompanying electric power lines. Some researchers have conducted investigation on scavenging low frequency magnetic energy from electric power lines. Ahla et al considered a current transformer based energy harvesting scheme [5]. With the current transformer, the energy from the magnetic field around a phase conductor can be harvested efficiently. In their consideration, a phase conductor is spatially separated from another phase conductor in electric power lines and the space is large enough to install the transformer. Actually Rogowski Coils-based transformers are ready to provide such function. The secondary winding of a transformer is terminated to the power supply management electronics in an energy harvester. In the similar way, Zangl et al investigated energy harvesting from the electric field in the vicinity of the conductors of a high voltage overhead power lines to provide power supply for online condition monitoring devices [6]. One critical point in a transformer-based power line energy harvester is that the output of the secondary winding is straightforward proportional to the input. When a rush occurs in power lines a sharp variation will generate in the transformer output which might damage the follow-on electronics. Another point is that the transformer-based harvester is not feasible for the zip-cord power lines which are commonly used for electric appliances. As it is not easy to dissemble appliance cords into single cables, Zhang et al put energy harvesting transformers at appliance plugs [7]. Zhang's design constrains the feasibility of harvesters in such cases. The MEMS current sensors proposed by Leland et al ease this problem [8-9]. The current sensors undergo a different energy transduction mechanism from the electromagnetic induction in transformers, which is magneto-mechanical-electric transduction. The current sensor is constructed from a piezoelectric cantilever with a magnet mounted on its free end. It is mounted next to a cord in operation and produces an output of 50-60μW with a capacitive load while the cord carrying a current of 13 A_{RMS}. To produce optimal output, the cantilever is designed to resonate at the frequency of ac current. To resonate with line frequency (50-60 Hz) the length of the cantilever has to be large.

Here it is thought that piezomagnetic/ piezoelectric composite magnetoelectric (ME) transducers have been proven to be effective in magnetoelectric transduction, we thus propose a power line energy harvester based on ME transducers.

PIEZOMAGNETIC/PIEZOELECTRIC COMPOSITE ME TRANSDUCERS

Recently, the ME effect in piezomagnetic/ piezoelectric laminated composites has gained considerable attentions. Piezomagnetic effect or more commonly referred to as magnetostriction can be described most generally as the deformation of a body in response to a change in magnetization. When a ferromagnetic material is placed in magnetic field, magnetism occurs because of an unusual imbalance in the magnetic moments of the material's electrons. When this imbalance occurs the electrons can order in such a way that the net magnetic moment is in a particular direction, lowering the crystal symmetry and producing magnetostriction. All magnetic materials exhibit magnetostriction to some degree. Bian et al analyzed the magneto-mechano-electric coupling physics and concluded that the ME voltage coefficient at low frequency is directly proportional to the ME coupling factor while the ME voltage coefficient at resonance is directly proportional to the product of the ME coupling factor and the effective mechanical quality factor of the composite. This conclusion suggests that for low frequency transduction application, it is adequate to choose magnetic material with high piezomagnetic coefficient composited with piezoelectric material with strong mechano-electric coupling [10]. In the state of the art, the giant material Terfenol-D, an alloy of the formula TbxDy1-xFe2 (x ~ 0.3), possesses the largest magnetostriction and strongest magneto-mechanical coupling. Of piezoelectric materials, the lead magnesium niobate-lead titanate (PMN-PT) crystal has the highest mechano-electric coupling coefficient. We fabricated Terfenol-D/PMN-PT/Terfenol-D laminates, as schematically illustrated in Fig.1. The surface area of the laminates is 6 mm×6 mm with thickness of 1 mm for each layer. The maximum ME voltage coefficient retains 200 mV/Oe under optimal magnetic bias.

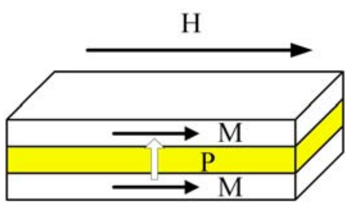

Fig.1: Terfenol-D/PMN-PT/Terfenol-D laminate

FIELD DISTRIBUTION AROUND POWER LINES

When the phase conductors are separated from each other and the space is large enough such as in the case of high-voltage overhead power lines, the field in the vicinity of one conductor can be simply taken as the field originated from the current I in the conductor and is straightforward determined by Biot-Savart law as

$$\vec{H}(x,y,z) = \frac{1}{4\pi}\int \frac{Id\vec{l} \times \vec{R}}{R^3} \qquad (1)$$

where $d\vec{l}$ is an element of the conductor, $\vec{R}$ is the distance vector from the filamentary conductor to point (x,y,z). From eq. (1), it is obvious that the field from a single conductor concentrically spins around the conductor. However, in a zip cord containing two phase conductors wrapped together, the field is the synthesis of the fields respectively from two currents of identical intensity but flowing in opposite directions. We computed the magnetic field surrounding a cord consisting of two wires shown in Fig.2 It is shown that the field in a plane perpendicular to an infinitely long current-carrying zip cord does not spin concentrically.

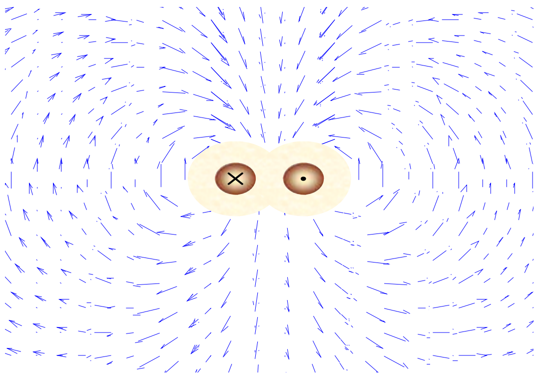

Fig. 2: The magnetic field in a plane perpendicular to a cord consisting of two wires carrying identical currents in opposite direction

In a plane perpendicular to a cord, for an area covering the cord there are two centers for field spinning in opposite directions. The average magnetic flux in the area is approximately zero as the two current-carrying conductors get quite close. This accounts for that in the case of a zip cord it is impossible to use a transformer for harvesting power line energy.

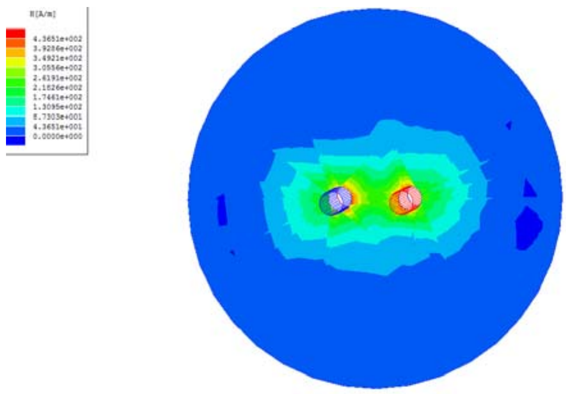

Fig. 3: The magnetic field distribution surrounding a cord consisting of two wires carrying identical currents in opposite direction

The generated field distribution from two conductors spaced at 3 mm carrying currents of identical strength (1A) flowing in opposite directions is simulated using Ansoft Maxwell 3 D as shown in Fig.3. From the simulation, in the range 4-6 mm from the center of two cables, the field intensities vary from about 10- 30 Oe (RMS) while the cord carrying current of 10 A_{RMS}. The actually measured maximum fields around a zip cord at varying currents are listed in Table 1. The probe is placed at point A as shown in Fig. 4, where the outer diameter of one conductor with cladding is $D \approx 4\,mm$, the double cladding thickness is $d \approx 2.42\,mm$ and $h \approx 2\,mm$.

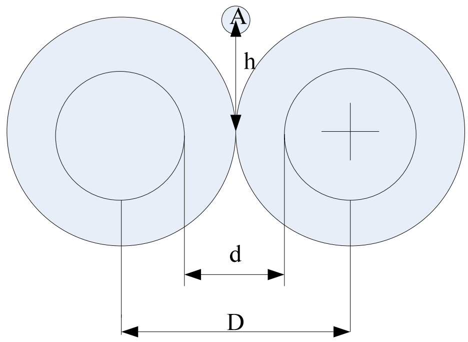

Fig. 4: Measurement of magnetic field from a cord consisting of two wires carrying identical currents in opposite directions

The values are less than the theoretical ones in that the measured values are the average in the inductive area of the probe. The inductive area of the probe is about 4 mm×4 mm. From the measurement, it is predicted that the maximum field from a zip cord carrying 10 A current is 16 Oe.

Table 1: Measured maximum fields around a zip cord at varying currents

Currents(A)	Fields(Oe)
1	5.84
1.5	6.17
2	6.42
2.5	6.86
3	7.09
3.5	7.32
4	7.51
4.5	8.25
5	8.48
5.5	9.19

ME TRANSDUCER-BASED POWER LINE ENERGY HARVESTER

The proposed harvester is comprised of composite ME transducers. In operation, the harvester externally embraces one appliance cord as schematically illustrated in Fig.5, whether the cord contains a single wire or two wires as it is a zip-cord. As the filed is spinning, it is more efficient while each ME transduction element harvests a smaller portion of the field. In the case of a zip-cord, the transducers placed at positions A, B (marked in Fig.5) will produce the strongest output. Thus for such application, it is appropriate to fabricate a harvester using two ME transducers. To get rid of the counteraction of outputs from two transducers, the magnetostrictive material with a quadratic magnetostriction is used as in this case the magnetostriction is related to the square of a field and is not sensitive to the signs of fields. The resulting ME response is also immune from the signs of fields.

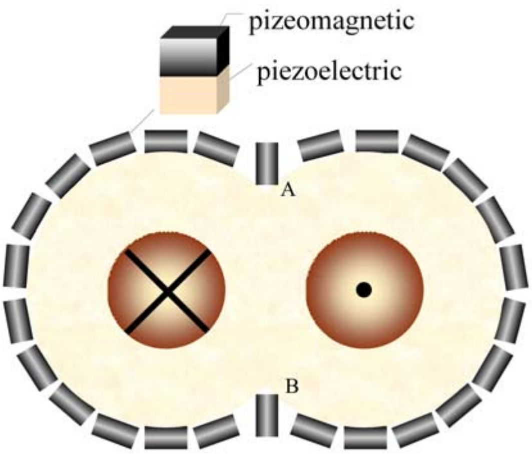

Fig. 5: The schematic configuration of composite ME transducers for scavenging the ac magnetic field surrounding an appliance cord

The prototypes of the proposed harvester are fabricated with the above mentioned Terfenol-D/PMN-PT/Terfenol-D laminate ME transducers. One harvester contains two transducers. Permanent magnets are used to bias the transducers. At 50 Hz, the total ME voltage coefficient is measured as around 2×0.2 V/Oe. While placed on a zip cord carrying current of 10 A_{RMS}, the practical maximum voltage output is around 2×2.5~3V and the optimal power output to a capacitive load is ~40μW. Even the practical output is less than the theoretical prediction, the results show the validity of the proposed harvester design.

CONCLUSION

An energy harvester is presented to scavenge ac magnetic field energy originated from appliance cords. The harvester is comprised of multiple piezomagnetic/ piezoelectric composite ME transducers. In operation, the transducers externally embrace one appliance cord, whether the cord contains a single wire or two wires as it is a zip-cord. With the state-of -the-art performances of ME transducers, with only two transducers, a harvester can produce several ten μW power output while scavenging a zip cord carrying 10 A current. As in operation, there are no constrain for the dimension of a harvester along the length of a cord, more ME transducers can be contained in a harvester to achieve higher output. Even equipped with the magnets to bias the transducers, the ME transducer-based power line harvester can be compact in size. And as its electric output is actually from the piezoelectric layer, it has all the features of piezoelectric harvesters. Compared with the transformer-based harvester, the ME transducer-based harvester has an attractive technical merit: the harvester is immune from producing surging output in rush currents as the magnetostriction is saturated in strong field. The surging output in a harvester is harmful to the follow-on electronics.

ACKNOWLEDGEMENT

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