DESIGN AND IMPLEMENTATION OF A HYBRID ELECTROMAGNETIC VIBRATION TO ELECTRICITY ENERGY HARVESTER FOR AC POWER LINES SENSORS

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Abstract: This paper presents and demonstrates a hybrid electromagnetic energy harvester device for harvesting electric energy from the magnetic field around an ac power line. The device is a combination of static transformer with an electromagnetic vibration-to-electricity energy harvester. It has been shown that the combination of these two features, i.e. using additional magnetic path for vibrating device and exploiting the transformed ac energy, improves the voltage level of the device. The rate of improvement is increased as the current through the line increases. The proposed device is useful for low frequency applications such as self-power measurement instruments installed on an ac power line.

Keywords: Electromagnetic energy harvester, energy harvesting, low frequency vibrations, smart grid sensors.

INTRODUCTION

Modernization of transmission and distribution power grids, so-called *smart grids*, requires thousand of monitoring sensors to be installed in the grids. The main requirements in development of sensors for smart grids are self-powering and plug-and-play features. The electromagnetic field around an ac power line can be used as an ever existing source of energy for measuring ac line parameters in a grid. On the other hand, wireless sensor nodes and networks facilitate installation of new measurement devices to an already existing grid [1,2].

Wireless sensor nodes are often low power devices, which require power sources range from hundreds of micro watts up to a few milli-watts. Battery is the easiest and the most common source of power for wireless sensor nodes. However, due to limited life time of batteries and high cost of maintenance, a combination of battery or super-capacitors with a micro-power generator has been recently considered a more attractive solution for powering of sensors. Micro-power generators or energy harvesters are small devices which convert available source of energy in surrounding environment (mainly vibration kinetic energy) into electricity [3].

Vibration-to-electricity is among the most popular techniques for harvesting energy. The piezoelectric, capacitive and electromagnetic energy harvesters have been suggested for converting mechanical vibration energy into electricity. Piezoelectric energy harvesters can provide electrical potential independent of vibration frequency which useful for low power applications. Capacitive energy harvesters convert the mechanical vibration energy into electricity via changing of capacitance; however, they required an external bias. The electromagnetic energy harvesters work based on Faraday's law and converter change of flux due to vibration into electricity. Electromagnetic energy harvesters are suitable alternatives for ac power lines since a piece of magnet installed on a beam within an ac field can be used as a controllable source of vibration. The amplitude and frequency of this vibration are proportional to the line current and frequency, respectively [3,4].

A conventional electromagnetic energy harvester uses a vibrating permanent magnet in front of a coil in which the flux paths are often enclosed within the air. Such a design is mainly useful for high frequency applications (e.g. micro-turbines) as the induced voltage in the coil is directly proportional to the frequency [4,5]. However, at low frequency applications such as 50/60 Hz ac power lines, the induced voltages in energy harvesters with air core are significantly low. On the other hand, a coil in an ac magnetic field is basically a transformer that can statically capture the energy of the field. Air cored transformer cannot efficiently transfer energy in small size and a transformer with iron core needs a dedicated frame for installation which is not suitable for plug-and-play applications.

The proposed device presented herein is basically an electromagnetic vibration-to-electricity energy harvester which uses a beam with a permanent magnet in an ac field. However, an extra magnetic path has been used in the device to increase the magnetic flux density, which in turns increases the induced voltage level in the coils. Furthermore, the proposed structure benefits its inherent ac energy transforming feature due to the time varying linkage flux in the ferromagnetic core. It has been shown that the combination of these two features, i.e. using additional magnetic path for vibrating device and exploiting the transformed ac energy, improves the voltage level of the device which makes it suitable for low frequency applications.

STRUCTURE OF A ELECTROMAGNETIC ENERGY HARVESTERS

An electromagnetic energy harvester is basically a vibrating permanent magnet against a coil. It operates based on Faraday's law: the induced voltage in the coil is proportional to the rate of change in the flux linkage. Thus, to increase the induced voltage level, the number of coil turns can be increased which is confined with available installation space, or alternatively the rate of flux change (vibration frequency) can be increased. The latter is impossible for ac lines in which the line frequency is fixed at 50/60 Hz. The induced voltage (emf) in a coil is:

$$emf = \frac{d\phi}{dt} = \frac{d\phi}{dx} \times \frac{dx}{dt} \quad , \qquad (1)$$

where φ, x, and t represent the flux linkage, displacement and time, respectively. The term $d\varphi/dx$ in (1) represents gradient of flux which is a function of device geometry and is also proportional to the magnitude of the flux. Thus, the direction of vibration (position of permanent magnet in the ac field), the relative location of coil and permanent magnet, and the strength of magnet are all among important design parameters. The last term in (1), dx/dt, can be represented as:

$$\frac{dx}{dt} = f_1(\omega, A_m) \quad , \qquad (2)$$

where f_1 is functions of vibration frequency, ω, and its amplitude, A_m. For example, in a linear vibrating system, if we assume $x=A_m \sin(\omega t)$ then:

$$\frac{dx}{dt} = \omega A_m \cos(\omega t) \, . \qquad (3)$$

The frequency, ω, is constant in an ac line; however, the amplitude of vibration can be increased if the mechanical resonant frequency of the device is matched with the ac line frequency. Therefore, based on (1) following rules can be used for the design of an efficient electromagnetic energy harvester for an ac power line:

i) The beam length is calculated such that the resonant frequency of the beam is matched with the power line frequency (50/60Hz);

ii) The amplitude of flux can be increased by using a strong magnet locating in a suitable direction based on Lorentz's law.

Figure 1 shows the primary idea of energy harvesting from an ac line for powering a wireless sensor node. The permanent magnet attached to a beam vibrates due to the interaction of its magnetic field with that of ac line. The induced voltage in a coil

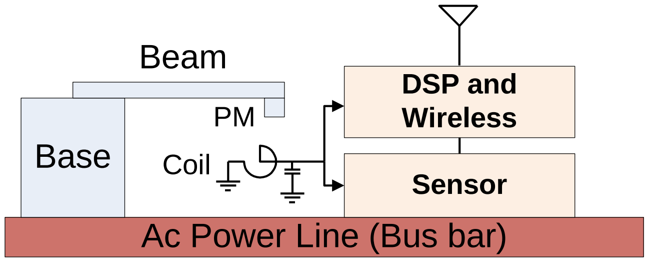


Fig.1 Schematic of a self-power wireless sensor node with an electromagnetic ac line energy harvester.

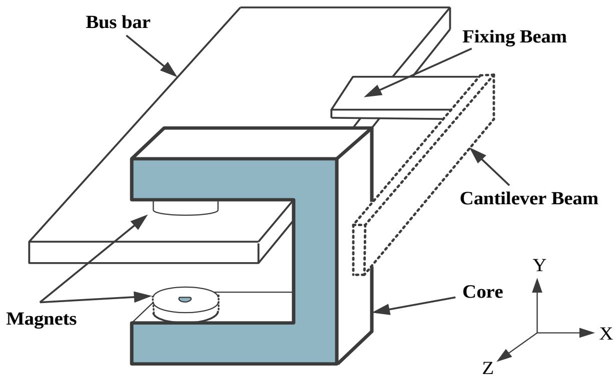


Fig.2 Schematic of the suggested hybrid electro-magnetic energy harvester for capturing power from an ac power line.

in the proximity of the vibrating beam can be used as a voltage source for powering any sensor device.

HYBRID ELECTROMAGNETIC ENERGY HARVESTER FOR AC POWER LINES

Figure 2 shows the schematic of the proposed device in which a ferromagnetic U shape core enclosed by a pair of NdFeB permanent magnets. The U core is attached to the free end of a cantilever that is anchored to a fixed frame. The U shape core acts as a less reluctant return path for the magnetic flux. Thus, the flux density within the air gap is increased. This helps to increase the gradient term $d\varphi/dx$ in (1) which enhances the induced voltage level. The coil in Fig. 1 can be realized by adding two series connected coil around the magnets in Fig. 2 (the coils are not shown in this figure). The induced voltage in each coil includes two components: one is due to variation of flux assuming a static core; and the other is due to vibration of magnets as they interact with the magnetic field around the ac power line.

Since the proposed device presents a combination of a static transformer with a vibration to electricity energy harvester, it is called *hybrid* electromagnetic energy harvester. Theoretically, the static component of the induced voltage is maximized when a magnetic flux path with minimum reluctance is selected. Considering the plug-and-play feature of the device, a core with a closed path cannot be used and the core must include an air gap to be readily installed. Various topologies can be used for locating the core with respect to the power line bus bar. We have selected a topology as shown in Fig. 2 as suitable topology since in this topology, the air gap is minimized.

To increase the induced voltage component due to vibration of magnetic, theoretically the beam must be design such that its resonant frequency is matched with the line frequency. We use the mass-spring-damper model to design the beam. Thus, the time-domain model of the cantilever beam can be expressed as:

$$M_e \ddot{X} + D\dot{X} + KX = F \qquad (4)$$

where M_e, D and K are the effective mass of the beam, damping coefficient, and mechanical stiffness. X is displacement and F is the electromagnetic force.

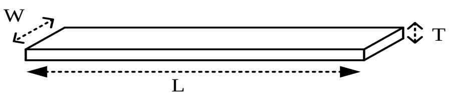


Fig.3 A simple beam with dimensions L, W, T.

For a simple cantilever beam with the dimensions L, W, T as shown on Fig. 3, M_e and K can be calculated as:

$$M_e = \frac{33}{144} M_b, \qquad (5)$$

$$K = \frac{EWT^3}{4L^3}, \qquad (6)$$

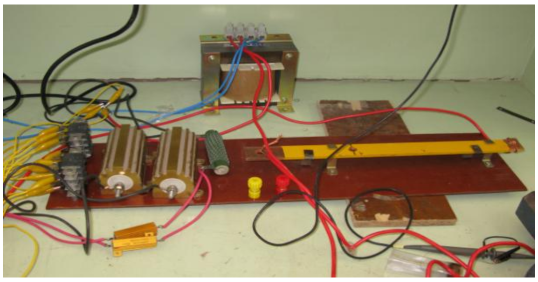
where $M_b = \rho LWT$ is the physical mass and E is the Young module of the beam (ρ is mass density). When an extra proof mass, M_{pf} , similar to the U core on Fig. 2 is added to the end of the beam, the effective mass can be calculated as:

$$M_e = M_{pf} + \frac{33}{144} M_b \qquad (7)$$

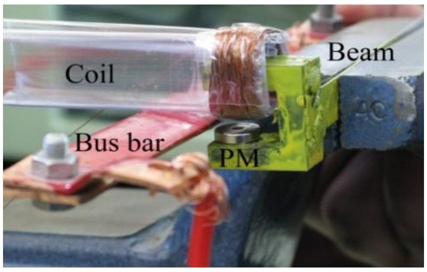
Using (4) and assuming a small damping coefficient, the resonant frequency of the beam will be close to its natural frequency, ω_n, which is given by:

$$\omega_n = \sqrt{K / M_e} \qquad (8)$$

Therefore, the length and width of the beam can be designed such that ω_n is matched with the line frequency.



(a)



(b)

Fig.4 The photos of the test setup.

EXPERIMENTAL TEST RESULTS

Test setup

Figure 4(a) depicts the components of the test setup, including a 400 W, 220/6V line transformer, a bus bar and the resistive loads. The snap shot of the vibrating electromagnetic energy harvester, bus bar and coil have been shown in Fig.4 (b). Considering the line frequency 50Hz as the resonant frequency of the beam, L=35.8 mm is calculated based on design equations (4)-(7). Also, considering the available space in the air gap, a coil with a 160 turns was used in this test. In a detail design procedure for a device, the number of coil turns and the air gap length can be obtained based on a trade-off between the space and reluctance of the path.

A 220V single phase ac voltage is applied to the primary winding of the transformer that can potentially supply up to 6V/60A at the secondary winding. Various high-power resistances were used to adjust the bus bar current at different levels. The hybrid energy harvester device was fixed on a base and for testing the device, the bus bar was placed in the air gap of U core as shown in Figs. 2, and 4b. The 160-turn coil was mounted on top of the bus bar surrounding one of the vibrating magnets. The test procedure included two parts: static mode and hybrid mode. In static test, the magnets were removed to only measure the induced voltage due to the ac field. In the hybrid mode, the vibrating magnets were used to measure the total induced voltage in the coil.

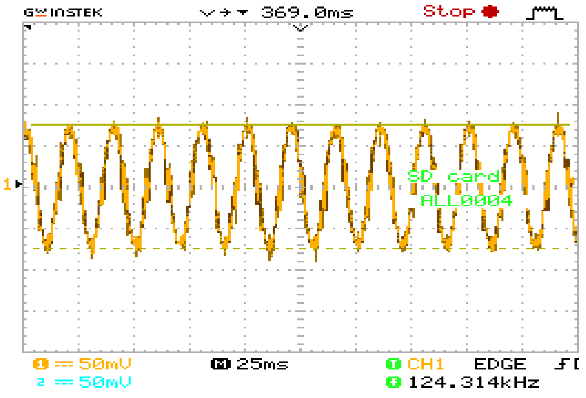


Fig.5 The sample of the induced voltage at I_{bus}=40A

Table I- Summary of the test results.

I_{Bus}	Induced Voltage Static mode	Induced Voltage Hybrid mode	Percentage of Improvement
30(A)	115.3 mV	132.6 mV	15.0 %
40 (A)	142.0 mV	169.3 mV	19.2 %
47 (A)	150.0 mV	197.3 mV	31.5 %

Experiment test results

A sample measured waveform of the induced voltage in the coil for bus bar current I_{bus}=40A is shown on Fig. 5. The waveforms at different current levels were used to measure the induced voltage of the beam. The device was tested at three different currents I_{bus}=30, 40 and 47 (A) and in each test the voltage of the core was measured with and without vibrating energy harvester. The induced voltages corresponding to different bus bar currents are summarized in Table I showing that usage of vibrating electromagnetic beam improves the level of induced voltage from 15% at 30A up to 31% at 47A. As these results show, increasing the current increases the contribution of vibrating energy harvesters in the induced voltage. This can also be justified based on the saturation of the core due to increasing the bus bur current which reduces the flux gradient.

CONCLUSION

A hybrid electromagnetic energy harvester device for harvesting electric energy from an ac power line has been presented. The device is a combination of a static transformer with an electromagnetic vibration to electricity energy harvester. The device has been used an extra magnetic path to increase the magnetic flux density, which increases the induced voltage level.

The test results shows that the combination of vibrating energy harvesters with static transforming phenomenon can improve the induced voltage more than 30% at 50A bus bar current. This energy harvester is useful for powering of measurement instruments installed on an ac power line. Using a suitable beam length to resonate at line frequency increases the vibrating amplitude of the beam leading to higher level of the induced voltage.

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