A MAGNETOELECTRIC ENERGY HARVESTER AND MANAGEMENT CIRCUIT

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Abstract: This paper proposes an H-type magnetoelectric (ME) composite structure consisting of a fork Fe-Ni magnetostrictive substrate and PZT piezoelectric plates. The fork composite structure has a higher ME voltage coefficient and a higher ME power output relative to other ME composite structures due to its higher quality (Q) factor. The fork composite structure can obtain an output power of 61μW at an ac magnetic field of 0.2Oe. In order to increase the output power, a new power management circuit is presented, which can collect/store the energy in a long time and release the energy for driving load in a short time. Experiments show that the instantaneous discharge circuit can drive a WSN node with an output power of 75mW at a distance of over 60m.

Keywords: energy harvesting, electromagnetic generator, power management circuit, Fe-Ni/PZT fork structure, instantaneous discharged circuit

INTRODUCTION

Wireless sensor networks have been applied in many places. Sensors are distributed in the large-scale complex region and completely embedded in detected objects. In long-lived systems where battery replacement is difficult and in applications consisting of completely embedded structures with no physical links to the outside world. It is difficult that sensor motes continuously work for a very long time. A promising alternative to batteries is the use of energy harvesting that converts existing sources energy within their environment into electrical energy [1]-[4].

There are a lot ambient energy sources such as thermal, electromagnetic, mechanical, biochemical and optical energies [5]-[8]. A micro piezoelectric generator collects the energy from the pipe vibration [2]. A system-in-package power-condition circuitry for a self-powered system is used for micro piezoelectric generator [9]. However, the vibrating source is a necessary condition for the vibrating energy harvesting.

Electromagnetic sources are generally ubiquitous. The electromagnetic self-powered system may have many advantages over other self-powered methods and can be used in many specific fields [5]-[8]. A potential and promising renewable power supply is the use of miniature ME energy harvester. Composites made of piezoelectric materials and giant magnetostrictive rare-earth iron alloys have become an attractive topic in recent years due to their large magnetoelectric response [10]. Piezoelectric/magnetostrictive composites have better ME properties than single phase materials [11]. However, due to the low Q value, it has proven difficult to further enhance the ME voltage coefficient since the voltage gain is directly proportional to the Q value. High efficiency magnetoelectric transducers with a higher Q value may be applied in electromagnetic energy harvester to produce enough energy.

In the conventional management circuit, AC-to-DC or DC-to-DC converters for vibration-powered piezoelectric generators have been used [12]. An integrated exponential charge pump can be used for stepping up the tiny input voltage and providing a higher output voltage [13]. However, theses vibration self-powered management circuits can be used in the cases of either strong input power or weak load.

This paper proposes a Fe-Ni/PZT H-type fork magnetoelectric composite structure and a high efficiency energy management circuit for the magnetoelectric energy harvester. Fe-Ni/PZT H-type fork composite structure with a higher Q value generates a stronger electric output power relative to the traditional composite structures. The management circuit of the energy harvesting continuously gathers weak energy from the fork composite structure in long period and provide a high-power output in a very short cycle. It can drive the wireless sensors at a distance of over 60 m.

MAGNETOELECTRIC COMPOSITE TRANSDUCER

Fig. 1 shows two magnetoelectric composite structures: (a) the H-type fork transducer and (b) the rectangle composite. The H-type fork magnetoelectric composite structure is composed of two same-size rectangle composites. The piezoelectric PZT-8H plates with dimensions of 12.0mm×6.0mm×0.8mm are symmetrically located at the mechanical anchor of the elastic Fe-Ni alloy substrate where the displacement is zero. The Fe-Ni alloy is magnetized and oriented along the longitudinal direction, which has the highest longitudinal magnetostrictive strain (λ~100ppm) under a dc magnetic bias (H_{dc}) of 100 Oe. The PZT-8H works at d31 model, which is polarized along the thickness direction.

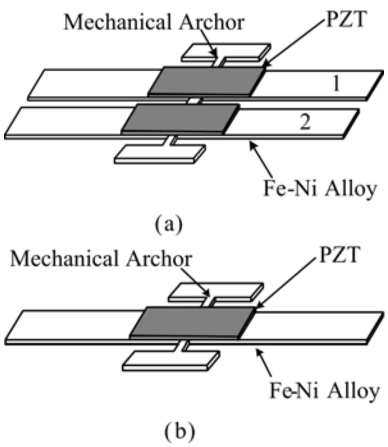

Fig. 1: ME composite structure: (a) H-type fork structure and (b) rectangle structure.

Due to the symmetrical H-type composite structure, the same vibrating waves are induced from two beams of the Fe-Ni alloy substrate under a dc magnetic field of 100Oe and an ac magnetic field of 1 Oe. The vibrating energy can be converted into electricity through PZT plates. The waves of the beams are superimposed and intensified in the resonant frequency. Higher amplitude can be obtained in the resonant fork structure due to higher quality value.

Fig. 2 shows the ME output voltages of different connections of the fork structure and the rectangle structure under an AC magnetic field of 0.2 Oe. The maximum ME conversion coefficient can be obtained at the resonance of the composite structure. In the fork composite structure, the resonant output voltages of one beam and the series output voltage of two beams under an ac magnetic field of 0.2Oe are 1.2V and 1.76V, respectively. The maximum output voltage of the rectangle composite structure is 0.3V.

Fig. 3 shows the ME output voltages of the fork structure and the rectangle structure under the AC magnetic fields. The output voltage of the transducer has a near linear function of AC magnetic intensity. The output voltage of H-type ME transducer can reach 12V under the excitation of an AC magnetic intensity of 1Oe, which is over 5 times higher than the output of the rectangle structure in the same size. The Q value of the H-type fork composite structure is 430. The Q value of the rectangle composite structure is 170. An output power of 61uW is obtained under an ac magnetic field of 0.2Oe. This fork composite structure can obtain higher ME conversion efficiency relative to other traditional composite structures.

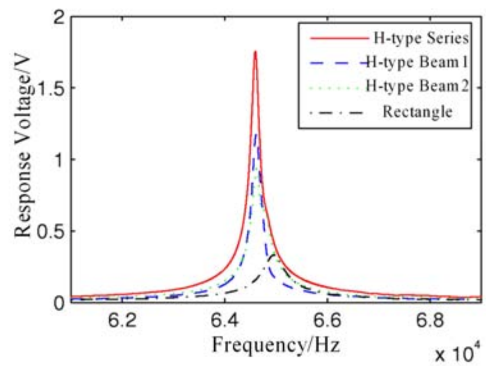

Fig. 2: Outputs of two structures and different connections as a function of frequency (Hdc=0.2Oe).

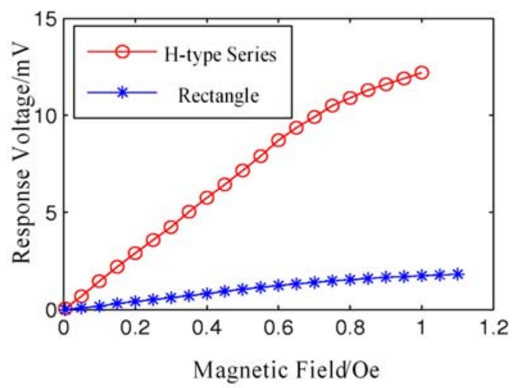

Fig. 3: Output voltages of two structures as a function of ac magnetic field.

MANAGEMENT CIRCUIT OF ENERGY HARVESTING

The management circuit of the ME energy harvesting is composed of a matching and stepping-up circuit, a rectifier, a burst generator, and an instantaneous discharge circuit, as shown in Fig. 4. A matching circuit is designed at the frequency point where the transducer has maximum output voltage. In order to increase the output power from the super capacitor, an instantaneous discharging circuit is designed.

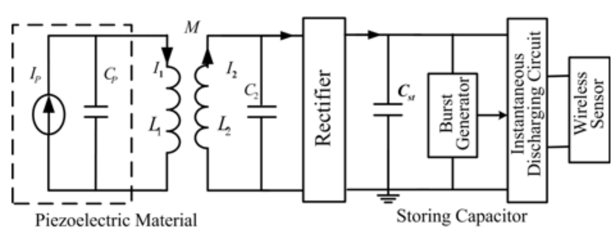

Fig. 4: Management circuit of ME energy harvesting.

The equivalent circuit of the piezoelectric material in the magnetoelectric transducer is a parallel circuit of an ac current source I_P and an equivalent capacitor C_P [14]. The resonant frequency in the primary coil loop of the transformer is identical with the frequency in the secondary loop. The output resistance of the piezoelectric material equals the equivalent resistance of the transformer. By using matching circuit, a 20%-100% more energy across the storing capacitor C_{st} can be obtained.

The power instantaneous discharged circuit is composed of a separate-excited stepping-up circuit and a burst signal generator, as shown in Fig. 5. The power instantaneous discharged circuit can remarkably increase the output power during a short time in order to provide enough energy for load.

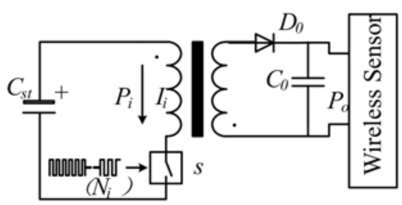

Fig. 5: Power instantaneous discharged circuit.

As the analog switch S is closed, the voltage of the storing supercapacitor can be discharged and a large discharge current is produced across the primary coil of the transformer. A negative voltage across the secondary coil is generated and the diode D_0 is switched off.

Every burst trigger signal is composed of a lot of pulses. The on-time t_{on} of a pulse is much less than the discharge constant. The variation of the input voltage (V_i) at a discharge period is very small. In order to obtain more storing energy, a supercapacitor with a large capacitance and a small leakage current is used. The output power of the instantaneous discharge circuit may be expressed as

$$P_0=\frac{V_0^2}{R}\left[\frac{\delta}{1-\delta}+\frac{Lf_0}{R(1-\delta)}\left(e^{-R\delta/Lf_0}-1\right)\right]. \quad (1)$$

In order to improve the instantaneous discharge power from the primary coil to the secondary coil, the discharge current (I_i) across the primary coil has to reach the maximum at the discharge period. Setting $dI_i/dt=0$, we find that the time at the maximum current is

$$t_m=\frac{1}{r_1-r_2}\ln(r_2/r_1)\approx 2LC_{st}\ln(R/L). \quad (2)$$

By adjusting the duty cycle of the trigger pulse, the maximum output power can be obtained at $t_{on}=t_m$. The duty cycle can be expressed as

$$\delta=2f_0LC_{st}\ln(R/L). \quad (3)$$

Fig. 6 shows output powers at different duty cycles. The theoretical arithmetic is identical with the experiment results. The discharged power of the proposed circuit reaches 120mW and the discharge time can last for 620ms at the triggering signal with a frequency of 30kHz and a duty cycle of 75%.

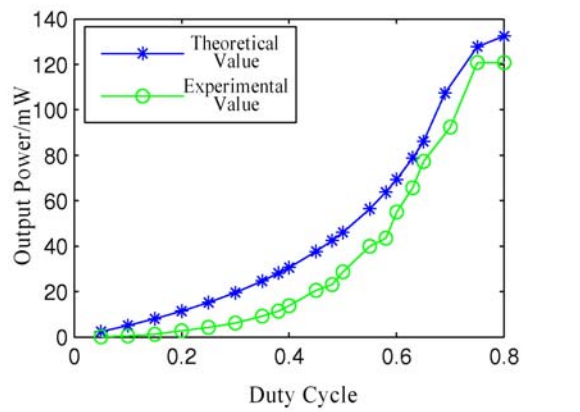

Fig. 6: Output powers as a function of duty cycle

EXPERIMENT

The load of the ME energy harvester management circuit is a wireless sensor network node that is composed of sensor units (humidity SHT11), a high-speed lower-power 8-bit processing (ATmega32L), and a low-power transceiver (CC1100). The operating time (600ms) of the humid sensor is much longer than that of other sensors. The normal communication distance of the sensor node is 50-130 meters under a working voltage of 2.7-3.5V under a transmitting frequency of 915MHz and a data-transmitting rate of 250 kbps. The current and the power of the node are less than 25mA and 75mW at a time interval of 620ms, respectively. The necessary energy of the sensor node in a working cycle is less than 12mJ.

The analog switch with a power consumption of 1μW is closed or opened by a trigger signal with a frequency of 30 kHz and a duty cycle of 75%. While the charging voltage across the storing supercapacitor is 0.45V, the electrical energy from the storing supercapacitor can be discharged into the wireless sensor by closing the analog switch (Fig. 5). The energy provided by the instantaneous discharging circuit at one discharging period is 54 mJ. The energy from the instantaneous discharging circuit can drive the operation of the wireless sensor.

While the output energy of the instantaneous discharging circuit is not enough to drive the transceiver (CC1100) of the wireless sensor with a transmitting power consumption of 75mW at a long distance, the error code will be produced. Fig. 7 shows the data-losing ratio as a function of distance. The lost data ratio is zero at a supercapacitor voltage of over 0.36V under a communication distance of 60m. The lost data ratio increases with the communication distance. The maximum transmitting distance of the wireless sensors is 130m under a storing voltage of over 0.45V.

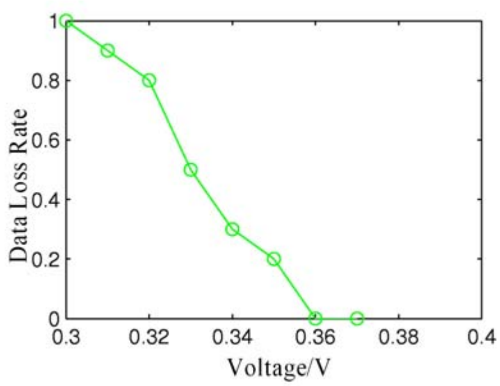

Fig. 7: Data loss rates as a function of the voltage across storing supercapacitor.

CONCLUSION

This paper presents a new ME Fe-Ni/PZT fork composite transducer structure with a high Q value. The developed resonant fork composite structure shows a higher ME sensitivity, a higher ME voltage coefficient and a stronger output power relative to the conventional rectangle structure. A new management circuit of the energy harvesting with the matching circuit, the storing energy circuit and the instantaneous discharge circuit can accumulate weak ME energy in long period and provide a higher power output in a very short cycle. The ME energy harvester and the management circuit can meet the wireless sensor power supply requirement and drive wireless sensors at a long distance.

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