A MANAGEMENT CIRCUIT FOR VIBRATING ENERGY HARVESTER

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Abstract: A piezoelectric/magnetostrictive composite vibrating energy generator is introduced, and its output characteristic is analyzed. In order to increase the maximum output power of the vibrating energy harvester, a new up-conversion matching circuit is proposed, which can change the low frequency vibrating signal into a narrow bandwidth signal focused on a higher frequency. The matching circuit with a small-size permalloy transformer has a stronger capacitor charging power due to up-conversion. It can obviously improve the charging time and the storing energy at capacitor. In order to increase the output power, a power management circuit can release the energy for driving power load in a short time. Experiments show that the management circuit can drive a WSN node with an output power of 75mW at a distance of over 60m.

Keywords: energy harvesting, vibrating generator, power management circuit, frequency-changeable matching circuit, instantaneous discharged circuit

INTRODUCTION

Due to the nature of some structures in many applications, such as the status monitoring in danger circumstance, implantable medical devices in animal and embedded smart sensors in buildings, the micro-sensor array system must be completely embedded in the structure, with no physical connection to the outside world. In long-lived systems where battery replacement is difficult and in applications 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 source energy within their environment into electrical energy [1]-[3].

Among many types of energy, electricity is the most commonly used form for modern devices. There are many ways to complete electrical conversions. The most familiar ambient energy source is solar power. Photocells convert light to electricity [4]. Thermal energy is another ambient energy source. Thermocouples convert heat to electricity when placed across a temperature gradient [5]. The existing energy source is a necessary condition for the energy harvesting application.

Another general type of transducer converts the mechanical energy contained in a vibrating, movement object and gravitational field into electrical energy, such as self-winding watches that wind themselves from the swing of a person's arm, a capacitively tuned vibration absorber [6], and a foot-powered radio identification "tag" over several meters during walking [7]. A magnet attached to the mass induces a voltage in a coil as it moves and magneto-electric generators convert mechanical energy to electricity [8]. Because of strong power density to convert the vibrating energy from environmental power source into electric energy, vibrating energy harvester may have many advantages over other self-powered methods and can be used in many fields. A potential and promising renewable power supply is the use of miniature vibrating energy harvester. The vibrating energy harvesters based on piezoelectric/magnetostrictive composites have good energy conversion efficiency in small size. The maximum output power of over 1 mW can be obtained under a load resistance of 1 megaohm and an acceleration of 1 g [9].

The conventional management circuit of the vibrating energy harvesting circuit consists of an ac-dc rectifier, a storing capacitor/battery, and a dc-dc converter [10]-[12]. A synchronized switch harvesting on inductor (SSHI) can allows a typical gain of eight [13]. The output voltage induced from piezoelectric material should be rectified in order to charge the capacitor/battery with a proper current. However, due to the capacitive output impedance of the piezoelectric vibrating source, it has proven difficult to directly charge for a large storage supercapacitor of 1F since the charging current will rapidly decrease at a heavy load. The normal matching circuit with a bulky transformer hardly works at low frequency or varied vibrating frequencies.

This paper proposes a new management circuit for the vibrating energy harvester, which can change the low frequency vibrating signal into a narrow bandwidth signal focused on a higher frequency. A matching circuit with a small-size permalloy transformer has a stronger capacitor charging power. It can obviously improve the charging time and the storing energy at capacitor. In order to increase the output power, a power management circuit can release the energy for driving power load in a short time.

VIBRATING ENERGY GENERATOR

Fig. 1 shows the vibrating energy harvester structure based on piezoelectric/magnetostrictive composites. The transducer is fixed in this structure, and two U-type magnets in two sides are vibrated. The piezoelectric PZT-5H plate (P plate) with dimensions of 12 mm ×6 mm ×1 mm is located at the center of two magnetostrictive Terfenol-D plates (M plates) with same sizes. Terfenol-D plates are magnetized and oriented along the longitudinal direction, which has the highest longitudinal magnetostrictive strain (λ>1000 ppm) under a dc magnetic bias (H_{dc}) of 600 Oe. The PZT-5H plate works at d_{31} model, which is polarized along the thickness direction. The magnetic loop consists of four NdFeB magnets with dimensions of 10 mm ×6 mm ×5 mm and two magnetic yokes with dimensions of 10 mm ×18 mm ×2 mm. The remnant magnetism is 1.39 T. The distance of up and down magnets is 6 mm and the gap of left and right magnets is 14.2 mm.

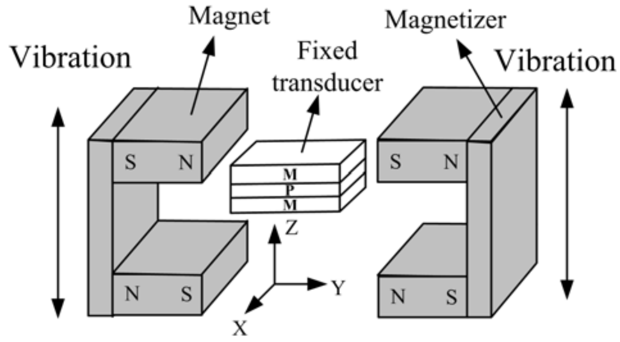

Fig. 1: Vibrating transducer structure.

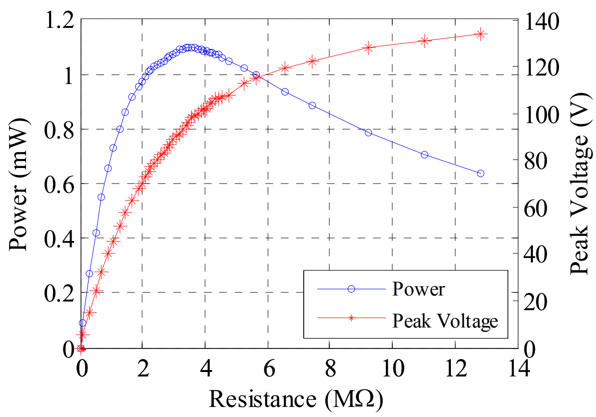

Fig. 2: Output power and voltage as a function of load resistance.

In the vibrating transducer structure, the piezoelectric/magnetostrictive transducer is located at center of two U-type magnets in y axis and can obtain the maximum magnetic field change at four locations in z axis (z=±3mm or z=±9.8mm) while two U-type magnets are vibrated. Therefore, one or multiple piezoelectric/magnetostrictive transducers are located at the four locations in order to efficiently convert the vibrating energy into the ac magnetic energy. The large strain can be obtained in two Terfenol-D plates. A strong electric power can be produced in the PZT-5H plate.

Fig. 2 shows the output power and the voltage as a function of load resistance under an acceleration of 0.5g and a resonant frequency of 31.7 Hz. The output voltage increases with the load resistance and a voltage of over 100V can be obtained at a resistance of over 4 megaohm. The maximum output power of 1.1mW can be obtained under a load resistance of 3.59 megaohm. For a large charging supercapacitor, the charging power is very weak due to capacitive output characteristic of vibrating transducer. Normally the output power induced by vibrating transducer is less than 10 microwatt at a load capacitor of 1F. The charging time for a capacitor of 1F is more than 10 hours at a voltage of 0.5V. Therefore, the vibrating piezoelectric/magnetostrictive transducer can not directly charge for a large capacitor.

MANAGEMENT CIRCUIT OF VIBRATING ENERGY HARVESTER

The management circuit of the ME energy harvesting is composed of an up-conversion circuit, a matching circuit, a rectifier, a burst pulse generator, and an instantaneous discharge circuit, as shown in Fig. 3. A matching circuit with an up-conversion circuit is designed at a higher frequency point where the transducer has maximum output voltage. In order to increase the output power from the supercapacitor, an instantaneous discharging circuit is designed.

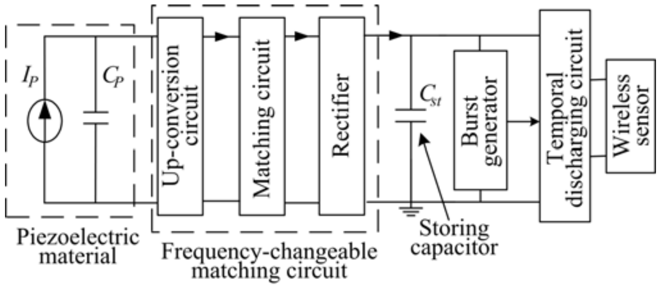

Fig. 3: Energy harvesting management circuit.

The traditional matching circuit with an inductor and a transformer can obviously improve the output power and the transducer output efficiency. Fig. 4 shows a traditional transformer matching circuit. The maximum output power can be obtained while working frequency is equal to the resonant frequency of the primary and secondary transformer loop. That is, the working frequency of the matching circuit can be expressed as

$$f_{Transducer} = \frac{1}{2\pi\sqrt{L_1 C_p}} = \frac{1}{2\pi\sqrt{L_2 C_2}}. \qquad (1)$$

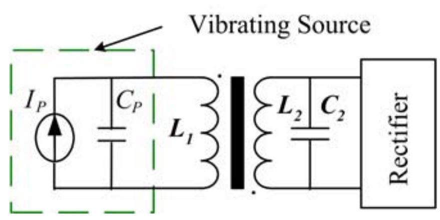

Fig. 4: Traditional transformer matching circuit.

Normally, the capacitance of the vibrating transducer is less than 10 nF, and the vibrating frequency is less than 100 Hz. Thus, a bulk transformer with a large primary inductance of more than 253H is necessary. Besides, due to the narrow bandwidth of the resonant loops, the matching circuit can not work at varied vibrating frequency.

In order to decrease the transformer size and work at varied vibrating frequency, a nonlinear frequency-changeable matching circuit is proposed as shown in Fig. 5. A capacitor and a switch with a small on-state resistance are connected in the primary loop of the transformer in series. The working frequency of the switch is a high fixed frequency (500-1000 Hz). The output signal frequency of the vibrating transducer is modulated to new frequencies by using the switch.

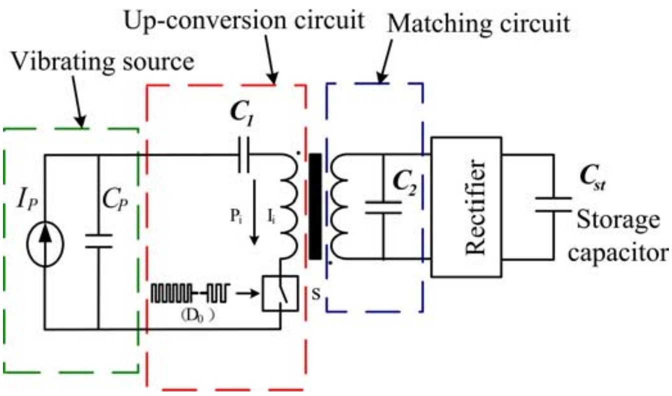

Fig. 5: Frequency-changeable matching circuit.

Fig. 6 shows vibrating spectrum and up-conversion spectrum. The switch can move the most energy (>50%) to a higher frequency (~500 Hz) by changing the frequency and the duty cycle of the switch control signal. The primary and secondary resonant loops of the transformer can enhance the energy at the resonant frequency. Thus, the matching circuit can be designed for a higher frequency (500 Hz) where the transducer has maximum output power. The charging time can reach 8 minute at a voltage of 500 mV, which is over 6 times shorter than the time of the normal matching circuit in the same transformer. The weight of the new transformer at a working frequency of 500 Hz is 10 times lighter than that of the traditional transformer at a working frequency of 50 Hz.

The electric output can not directly be applied to drive a WSN node as the output power of the composite transducer is much less than the power consumption of a wireless sensor node (75mW/18mW at transmitting/receiving data). Here, a power supply management circuit is necessary to store the electric energy in long time and discharge a higher power at a short interval for the WSN node operation[14]-[15].

The power instantaneous discharged circuit is composed of a separate-excited fly-back stepping-up circuit and a burst signal generator, as shown in Fig.7. N_i is the pulse number of the burst triggering signal. P_i is the discharge power from the storing capacitor. I_i is the discharge current across the primary coil of the transformer. D_0 is the rectifier diode. C_0 is the filter capacitor. P_0 is the output power of the instantaneous discharging circuit. The power instantaneous discharged circuit can remarkably increase the output power during a short time in order to provide enough energy for load.

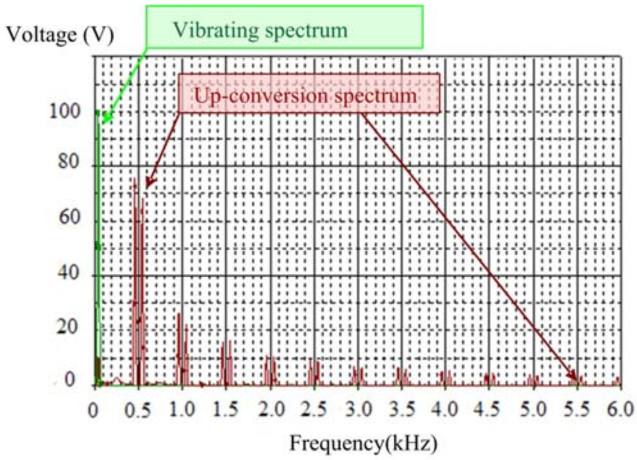

Fig. 6: Vibrating and up-conversion spectrum.

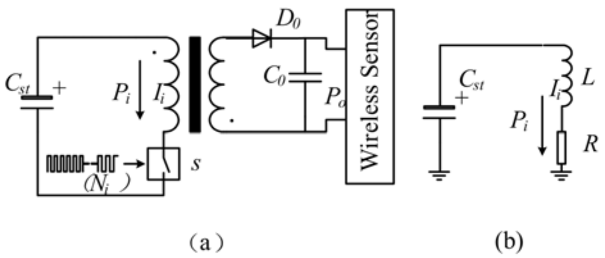

Fig. 7: Fly-back power instantaneous discharged circuit.

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. The discharge equivalent circuit is shown in Fig.7(b). *R* is the equivalent resistance of the analog switch and the primary coil. *L* is the inductance of the primary coil. Every burst trigger signal is composed of a lot of pulses. The on-time of a pulse is much less than the discharge constant. The variation of the input voltage 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.

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. The current and the power of the node are less than 25mA and 75mW at a time interval of 620ms, respectively.

Fig. 8 shows the driving power in wireless sensor. The experimental results show that the discharged power of the proposed circuit reaches 110mW and the discharge time can last for 620ms. Thus, this management circuit can provide enough power for wireless sensors at a distance of 60-130 meters.

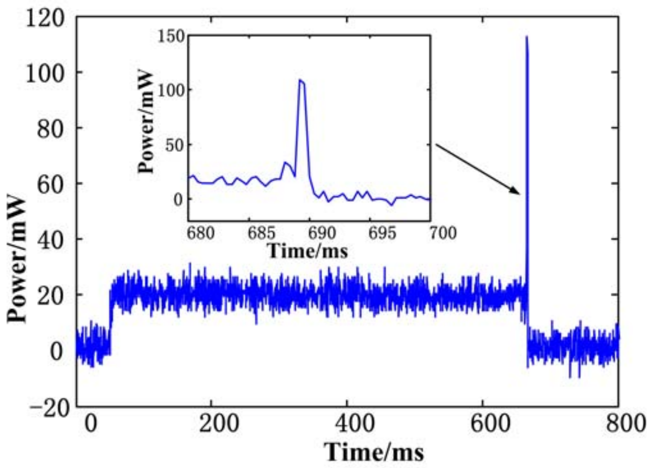

Fig. 8: Driving power in wireless sensor.

CONCLUSION

This paper introduces a vibrating energy generator based on the piezoelectric/magnetostrictive composite. The maximum output power of the energy harvester can be obtained under a large load resistance. In order to increase the maximum output power for the large capacitor load, a new matching circuit for the vibrating energy harvester is proposed. This up-conversion circuit can change the low frequency vibrating signal into a narrow bandwidth signal at a higher frequency. The matching circuit with a small-size permalloy transformer has a stronger capacitor charging power at a higher frequency. Thus, the up-conversion and matching circuit can obviously improve the charging time and the storing energy at capacitor. An energy management circuit can release a stronger power for driving a heavy load in a short time. Experiments show that the management circuit can drive a WSN node with an output power of 75mW at a distance of over 60m.

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REFERENCES

[1] Ping Li, Self-powered Piezoelectric Wireless Micro-sensors by Absorbing Electromagnetic Energy, *Proc. of the Third IEEE International Conference on Sensors*, 2004, 99-102

[2] Ping Li, Self-powered Wireless Sensor by Collecting Electromagnetic Energy in Inhomogeneous Structure, *The 4th IEEE Conference on Sensors*, 2005, 28-31.

[3] Ping Li, Enhanced Magnetoelectric Effects in Composite of Piezoelectric Ceramics, Rare-earth Iron Alloys, and Ultrasonic Horn, *Applied Physics Letters*, 2007, 90(2), 022503.

[4] Dondi D., Modeling and Optimization of a Solar Energy Harvester System for Self-Powered Wireless Sensor Networks, *IEEE Trans. Ind. Electron.*, 2008, 55(7): 2759-2766.

[5] D. M. Rowe, Low cost miniature thermoelectric generator, *Electron. Lett.*, 1991, 27, 2332-2334.

[6] Davis and G. Lesieutre, An actively tuned solid-state vibration absorber using capacitive shunting of piezoelectric stiffness, *J. Sound Vibration*, 2000, 232(3): 601–17.

[7] Shenck and J. A. Paradiso, Energy scavenging with shoe-mounted piezoelectrics, *IEEE Micro*, 2001, 21: 30–42.

[8] Alfredo Vazquez Carazo, Novel piezoelectric-based power supply for driving piezoelectric actuators designed for active vibration damping applications, Journal of Electroceramics, 2001, 7:197-210.

[9] Xianzhi Dai, Modeling, characterization and fabrication of vibration energy harvester using Terfenol-D/PZT/Terfenol-D composite transducer, *Sensors and Actuators A*, 2009,156(2):350-358.

[10] Xinping Cao, Electromagnetic Energy Harvesting Circuit With Feedforward and Feedback DC-DC PWM Boost Converter for Vibration Power Generator System, *IEEE Trans. Power Electron.*, 2007, 22(2): 679-685.

[11] Geffrey K. Ottman, Adaptive Piezoelectric Energy Harvesting Circuit for Wireless Remote Power Supply, *IEEE Trans. Power Electron.*, 2002, 17(5): 669-676.

[12] Ahmadreza Tabesh, A Low-Power Stand-Alone Adaptive Circuit for Harvesting Energy From a Piezoelectric Micropower Generator, *IEEE Trans. Ind. Electron.*, 2010, 57(3): 840-849.

[13] Lauric Garbuio, Mechanical Energy Harvester With Ultralow Threshold Rectification Based on SSHI Nonlinear Technique, *IEEE Trans. Ind. Electron.*, 2010, 54(4): 1048-1056.

[14] Ping Li, A magnetoelectric energy harvester and management circuit for wireless sensor network, *Sensors and Actuators A*, 2010,151(1): 100-106.

[15] Ping Li, A magnetoelectric energy harvester and management circuit, *PowerMEMS 2009*, Washington DC, USA, December 1-4, 2009: 21-24.