A Self-powered Piezoelectric Energy Harvesting Circuit with Frequency Conversion for Wireless Sensor Network

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Abstract: This paper presents a self-powered piezoelectric energy harvesting circuit using frequency conversion. A vibration energy harvesting principle is introduced. Due to a capacitive characteristic of the piezoelectric vibration transducer, an energy harvesting circuit is proposed for matching the capacitive impedance. The energy harvesting circuit consists of a matching circuit with up-conversion, an ac-dc rectifier, a storage supercapacitor, a control unit and a dc-dc converter. The electric energy derived from the piezoelectric element charges the supercapacitor C_{st} by using the matching circuit and the ac-dc rectifier. The small-size matching circuit can be obtained by using an up-conversion switch circuit. The step-up dc-dc converter can be switched on by the control unit when the voltage of the supercapacitor reaches a threshold voltage. A stronger power can be obtained by the supercapacitor discharge and the wireless sensor node can be drived.

Keywords: energy management;self-powered;frequency conversion;wireless sensor

INTRODUCTION

Over recent years, the development of wireless sensor network(WSN) has highlighted a wider range of applications relative to traditional networks due to flexible distribution of WSN sensor nodes. But the power supply for the sensor nodes has brought greater challenges. Energy harvesting from ambient space offers a convenient approach to solver this problem. Systems with self-powered supply units have a longer life. The piezoelectric effect converts mechanical strain into electrical voltage. This strain can come from many different sources, such as human motion, low-frequency vibrations and acoustic noise. The piezoelectric device has been used to gather the energy of vibration [1], rotation [2], magnetoelectric [3], etc.

The power management circuit is significant to energy harvest efficiency, and the electric output of the piezoelectric device cannot directly be applied to drive a WSN node while the output power is much less than the power consumption of a wireless sensor node. A few authors present some kinds of circuits. Ottman et al. [4] described an approach to harvesting electrical energy from a mechanically excited piezoelectric element. In this circuit the energy can be stored by using a full-wave rectifier. Ottman analyzed the optimal power flow of piezoelectric device, but the energy harvest efficiency cannot achieve the maximum point. Liu et al. [5] presented a power management circuit based on matching the source impedance and switched-capacitor network, but in low frequency applications(<50Hz) the size of the matching inductance is very large. So the system cannot be small enough for the practical application.

In this paper, we present a self-powered piezoelectric energy harvesting circuit for wireless sensor network. The energy harvesting circuit consists of a matching circuit with frequency conversion, an ac-dc rectifier, a storage supercapacitor, a control unit and a dc-dc converter. The matching circuit can maximize the storing power, and the frequency conversion circuit can make the system much smaller.

VIBRATION ENERGY HARVESTER [6]

Wen et al. designed a vibration energy harvester, which is based on a Terfenol-D/PZT/ Terfenol-D composite transducer. The harvester consists of a cantilever beam, a magnetic circuit, and a ME transducer. External vibration induces relative motion between the transducer and magnets. The relative motion causes the magnetic field to change in Terfenol-D. The changing magnetic field will generate stress in the transducer. The transducer generates voltage output.

Fig.1 shows that the energy harvester can generate a peak voltage of 110V from an acceleration of 1g at a resonant frequency of 33Hz. Fig.2 shows that the maximum output power reaches 406μW across a 1.5MΩ resistor.

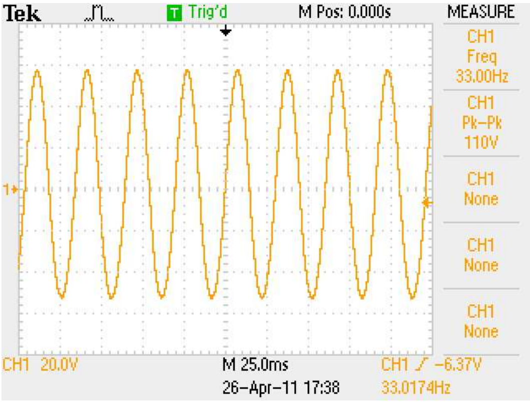

Fig. 1: The output of the harvester.

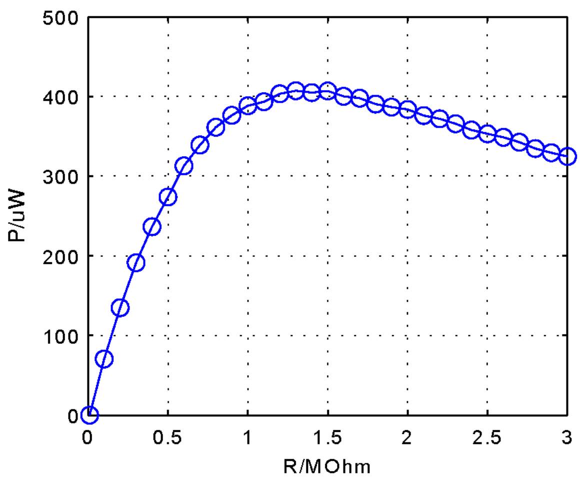

Fig. 2: Output power versus load resistance.

However, the output power of the harvester cannot drive wireless sensor node directly. An energy management circuit is necessary to govern the electricity storing and releasing. It is expected to discharge a much higher power at a short interval for the valid WSN node operation.

PRINCIPLE OF ENERGY MANAGEMENT CIRCUIT

The energy management circuit is composed of a matching circuit with frequency conversion, a rectifier, a storage supercapacitor, a control unit and a dc-dc converter, as shown in Fig. 3. The PZT element can be equivalent to a parallel circuit with a current source $i_p(t)$ and an equivalent capacitor C_p [7]. The PZT element charges C_{st} with the matching circuit and AC/DC unit. The controller can supply pulse signals to matching circuit and DC/DC unit. Step-up DC/DC converter starts to work when the voltage of the supercapacitor reaches the threshold voltage. The power discharged by the supercapacitor can drive the wireless sensor node(about 615ms/20mW for receiving and 5ms/110mW for transmitting).

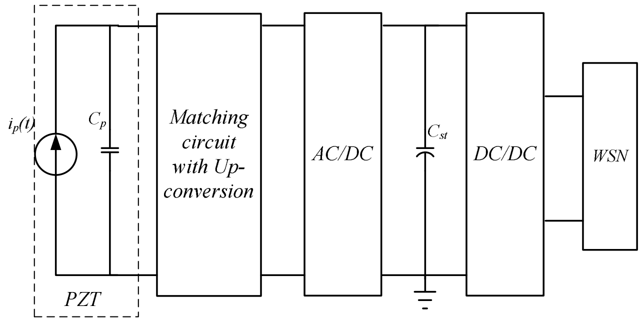

Fig. 3: Energy management circuit

Matching circuit with frequency conversion

The matching circuit is composed of a bilateral switch *S*, a matching transformer and a capacitor C_2, as shown in Fig. 4. $i_p(t)=I_p\sin(\omega_0 t)$, M is the coefficient of mutual-induction.

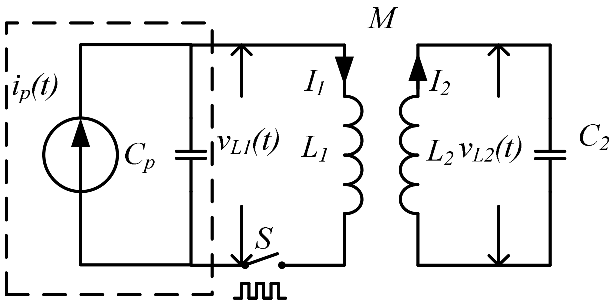

Fig. 4: Matching circuit with frequency conversion

It is supposed that a switch period lasts from t_o to t_2. The switch is turned on from t_o to t_1, and turned off from t_1 to t_2. The operation of the circuit may be divided into two stages based on the switch on and off. Fig. 5 shows the equivalent circuit when the switch is on; Fig. 6 shows the equivalent circuit when the switch is off. R_1 is the equivalent resistance of the first loop, R_2 is the equivalent resistance of the second loop. $V_{L1}(t)$ is the voltage of L_1, $V_{L2}(t)$ is the voltage of L_2.

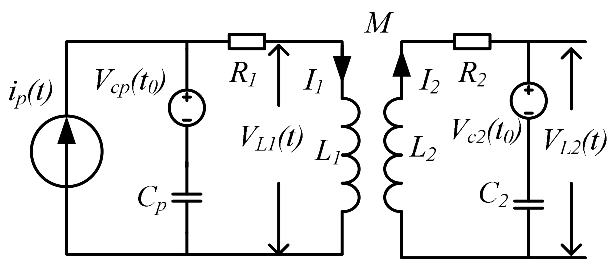

Fig. 5: Equivalent circuit when the switch is on

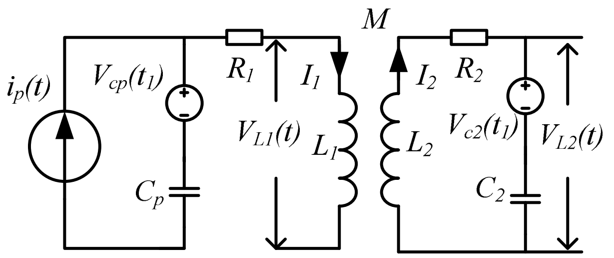

Fig. 6: Equivalent circuit when the switch is off

When the switch is on, as shown in Fig. 5, the first loop equation can be expressed as

$$V_{Cp} + V_{L_1} + V_{R_1} - V_M = 0 . \quad (1)$$

Then

$$(L_1 - nM)\frac{d^2 i_{L1}(t)}{dt^2} + R_1 \frac{di_{L1}(t)}{dt} + \frac{1}{C_p} i_{L1}(t) = 0 . \quad (2)$$

The current of the first loop can be calculated as

$$i_{L1}(t) = I_1 e^{-\beta_1 t}\cos(\omega_1 t) . \quad (3)$$

Then

$$v_{L1}(t) = L_1 \frac{di_{L1}(t)}{dt} = \frac{I_1 L_1}{\sqrt{\beta_1^2 + \omega_1^2}} e^{-\beta_1 t}\sin(\omega_1 t + \alpha) . \quad (4)$$

where

I_1 is the maximum current of the first loop, $\beta_1 = \frac{R_1}{2L_{equal}}$, $\omega_1 = \sqrt{\frac{1}{L_{equal}C_p} - (\frac{R_1}{2L_{equal}})^2}$, $L_{equal} = L_1 - nM$, $M = \mathrm{k}\sqrt{L_1 L_2}$, 0<k<1, n is the turns ratio of the transformer, $\tan\alpha = \frac{\beta_1}{\omega_1}$.

When the switch is off at t_1, the voltage of C_p can be calculated as

$$v_{cp}(t) = v_{cp}(t_1^+) + \frac{1}{C_p}\int_{t_1^+}^{t} i_p(t)dt . \quad (5)$$

The second loop equation can be expressed as

$$v_{c2}(t) + v_{R2}(t) + v_{L2}(t) = 0 . \quad (6)$$

Then

$$L_2 \frac{d^2 i_{L2}(t)}{dt^2} + R_2 \frac{di_{L2}(t)}{dt} + \frac{1}{C_2} i_{L2}(t) = 0 . \quad (7)$$

The voltage of L_2 can be calculated as

$$v_{L2}(t) = L_2 \frac{di_{L2}(t)}{dt} = \frac{I_2 L_2}{\sqrt{\beta_2^2 + \omega_2^2}} e^{-\beta_2 t}\sin(\omega_2 t + \gamma) . \quad (8)$$

The voltage of L_1 can be expressed as

$$v_{L1}(t) = n v_{L2}(t) = \frac{nI_2 L_2}{\sqrt{\beta_2^2 + \omega_2^2}} e^{-\beta_2 t}\sin(\omega_2 t + \gamma) . \quad (9)$$

where I_2 is the maximum current in the second loop, $\beta_2 = R_2/2L_2$, $\omega_2 = \sqrt{\frac{1}{L_2 C_2} - (\frac{R_2}{2L_2})^2}$, $\tan\gamma = \frac{\beta_2}{\omega_2}$, assuming that the transformer is ideal.

Based on the analysis above, the output voltage of L_1 can be written as

$$v_{L1}(t) = \begin{cases} \frac{I_1 L_1}{\sqrt{\beta_1^2 + \omega_1^2}} e^{-\beta_1 t}\sin(\omega_1 t + \alpha), t_0 \le t \le t_1 \\ \frac{nI_2 L_2}{\sqrt{\beta_2^2 + \omega_2^2}} e^{-\beta_2 t}\sin(\omega_2 t + \gamma), t_1 \le t \le t_2 \end{cases} . \quad (10)$$

From equation (10), the working process of the circuit is as follows. The voltage of L_1 is lower after a damped oscillation in the second loop of the transformer at the end of the last switch period. The switch is turned on at t_0^+, the voltage of L_1 may jump higher to the voltage of C_p due to equation (5). When the switch is turned off at t_1^+, a damped oscillation may occur in the second loop, meanwhile L_1 can output a damped oscillation waveform. The circuit has finished the whole work during a switch period.

EXPERIMENT

In the circuit, C_p=2.7nF; C_2=50nF; L_1/L_2=20; R_1=1.3kΩ; R_2=71Ω; The switch frequency and the duty cycle are 1kHz and 10%, respectively. The theoretical and experimental waveforms of L_1 are shown in Fig. 7 and Fig. 8, respectively.

Compared with the theoretical curve, the experimental curve has a lower magnitude due to the leakage of the mutual-induction and the loss of the wire resistance.

The main frequency has been converted to 3kHz(>>30Hz), as shown in Fig. 8. Fig. 9 shows that a supercapacitor of 0.47F can be charged to 1.2V in 35 min. The upper waveform is the voltage of the supercapacitor, and the lower waveform is the voltage of the wireless sensor node, as shown in Fig. 10. The rated voltage of the sensor node is 3.3V. Fig. 10 shows that the circuit can drive the sensor node.

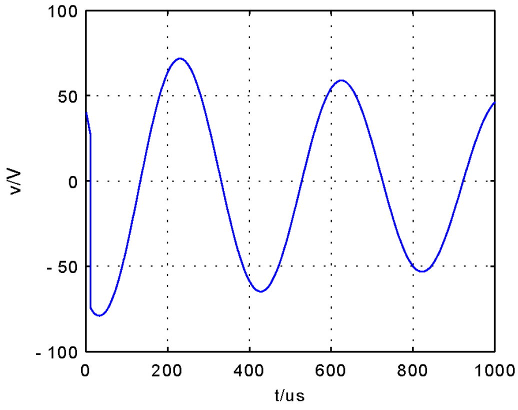

Fig. 7: Theoretical waveform of L_1

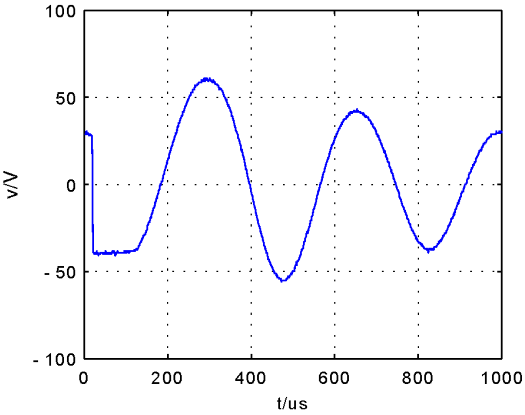

Fig. 8: Experimental waveform of L_1

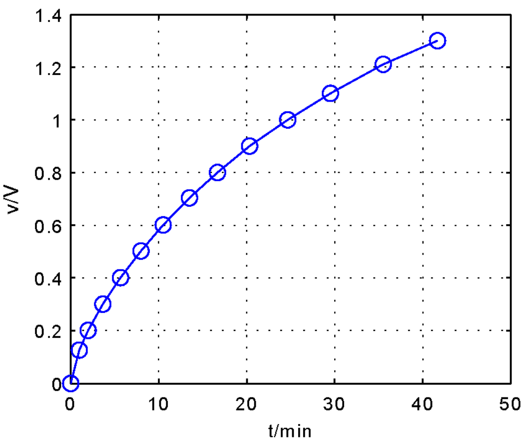

Fig. 9: Experimental charging process

CONCLUSION

In this paper, a self-powered piezoelectric energy harvesting circuit for wireless sensor network is presented. A small matching circuit is obtained using frequency conversion. The circuit can charge a supercapacitor of 0.47F to 1.2V in 35 min, and when the voltage of the supercapacitor reaches the threshold voltage, the circuit can drive wireless sensor node with a higher power consumption. An operation cycle is 620ms.

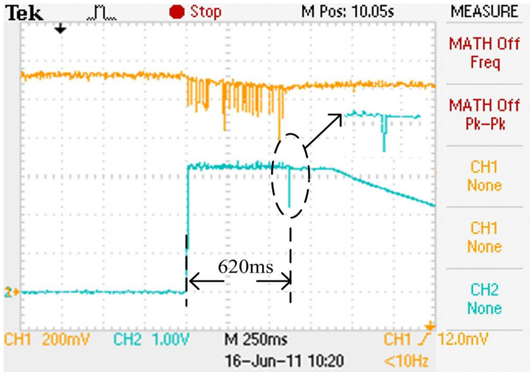

Fig. 10：Experimental discharging process

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