A Frequency Conversion Circuit for Piezoelectric Vibrating Energy Harvesting

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Abstract. More and more piezoelectric power generators are used in the field of energy harvesting in recent years, which are the typical capacitive power sources. The piezoelectric power generator is difficult to achieve maximum power output when it works in a low-frequency energy harvesting system. A frequency conversion management circuit is proposed in this paper, which can achieve the conjugate impedance matching between the power generator and the management circuit. The experiment result shows that the frequency conversion management circuit can obtained 411% more energy compared with traditional management circuit.

Keywords: Vibration energy harvesting · Energy harvesting management circuit · Impedance matching

1 Introduction

With the development of sensor and power electronics technologies, the size of sensors and wireless network nodes become smaller, the power consumption is getting lower, correspondingly. These electronic devices are usually powered by batteries, and used in many applications, such as monitor bird migration, earthquake warning and bridge deformation detecting [1–3]. Because the battery capacity is limited, it is difficult to replace batteries in many applications.

An alternative solution is using the piezoelectric power generator to convert ambient energies into electrical energy. The energy management circuit is the interface circuit between the piezoelectric generator and the electronic load, which is responsible for transferring, storing and releasing the output power of the piezoelectric generator.

A standard energy harvesting management circuit is shown in Fig. 1, which uses a rectifier between the piezoelectric generator and the load R. The structure of the standard management circuit is simple and easy to implement, but the circuit cannot achieve the conjugate impedance matching between the power generator and the management circuit.

A parallel synchronous switch harvesting on inductor (P-SSHI) was first introduced by Guyomar [4]. Experimental results reveal that the P-SSHI management circuit can

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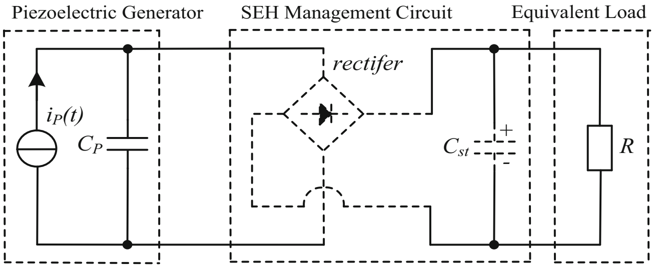

Fig. 1. Standard energy harvesting management circuit

increase the efficiency of energy harvesting by over 800% as compared to the standard energy harvesting management circuit [5–7].

However, when the piezoelectric generator outputs low frequency and weak electrical power, using the P-SSHI circuit to drive a high power load, such as the wireless sensor node, a large storage capacitor (hundreds milli-faradas) is required. Because of the equivalent internal capacitance of the piezoelectric generator is small (nano-faradas), the P-SSHI circuit cannot achieve the impedance matching when using the lager storage capacitor, large amount of energy of the piezoelectric generator is consumed in the internal capacitor.

This paper proposed frequency conversion management circuit for weak low-frequency vibration energy harvesting. This circuit can be achieved impedance matching with the piezoelectric generator at a high resonance frequency.

2 P-SSHI Management Circuit for Energy Harvesting

2.1 Piezoelectric Generator Equivalent Model

Vibration energy in ambient can be converted into electrical energy by the piezoelectric generator, when the external force F perpendicularly acts on the polarization plane of the piezoelectric ceramic, the piezoelectric generator can generate charges Q and output an AC signal, the relationship between Q and F can be expressed as:

$$Q = d_{33}F \tag{1}$$

Where d_{33} is the longitudinal piezoelectric constant. From (1), the piezoelectric generator can be equivalent as a capacitor, the capacitance of the piezoelectric generator can be expressed as:

$$C_p = \frac{\varepsilon_0 \varepsilon_r S}{d} \tag{2}$$

Where ε_0, ε_r, S and d are the vacuum dielectric constant, the relative permittivity, the piezoelectric area and the thickness of the piezoelectric, respectively. From (2), the equivalent capacitance C_p depends on the size and material of the piezoelectric generator. Therefore the equivalent model of the piezoelectric generator is composed of an AC current source parallel with the equivalent capacitor C_p and an equivalent resistor [8, 9]. Normally, the equivalent resistor of the piezoelectric generator can be ignored, and the equivalent internal capacitance is very small (nano-faradas).

2.2 P-SSHI Management Circuit

At present, P-SSHI management circuit is widely used in vibrating energy harvesting, its typical equivalent circuit is shown in Fig. 2. The switch S_1 series connects with the inductor L_1 then parallel with the piezoelectric generator. The AC power can be changed to DC power and restored in the storage capacitor C_{st} by using the P-SSHI circuit.

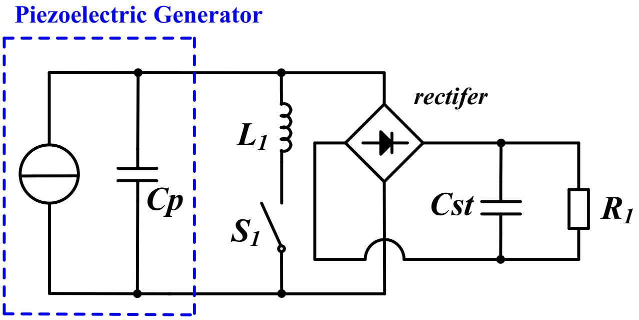

Fig. 2. P-SSHI management circuit.

When the piezoelectric generator outputs low frequency and weak energyin order to drive high power wireless sensor node, a large storage capacitor C_{st} (hundreds milli-faradas) is required in the P-SSHI circuit. In this case, the storage capacitor C_{st} is much larger than the equivalent internal capacitor C_p.

In Fig. 2, the first resonant loop is composed of the internal capacitor C_p and the inductor L_1. The secondary resonant loop is composed of the inductor L_1 and the storage capacitor C_{st}. Because of $C_{st} >> C_p$ and piezoelectric generator outputs low frequency signal, the resonant frequency between the first and secondary resonant loop are different, the impedance matching of this two resonant loops cannot be achieved at the same time. As a result, energy harvesting efficiency is very low, large amount of energy is consumed in the management circuit and there is not enough energy to drive the high power load directly.

3 Frequency Conversion Management Circuit for Vibrating Energy Harvesting

3.1 Principle of Frequency Conversion Management Circuit

The frequency conversion management circuit is shown in Fig. 3, including a matching circuit, a rectifier bridge, an intermediate capacitor and a DC-DC circuit. Most of the time, the piezoelectric generator is in open circuit and the management circuit is not operating. When the management circuit is working, the energy transfers from the piezoelectric generator to the intermediate capacitor C_{int}. The DC-DC circuit can transfer the energy from the intermediate capacitor C_{int} to a large storage capacitor C_{st}. Therefore, the output energy from the piezoelectric generator can be continuously accumulated to the C_{st} in a long period.

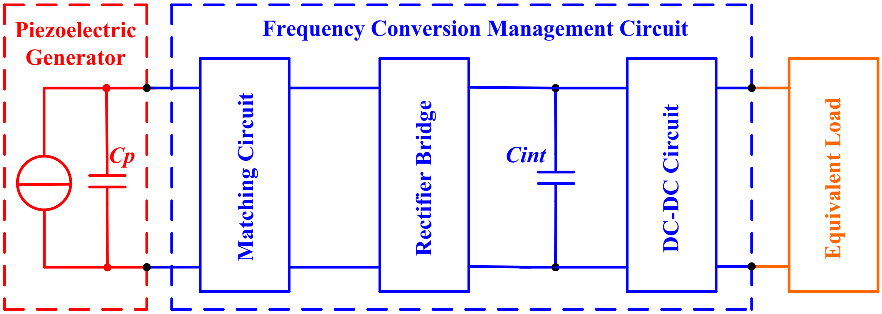

Fig. 3. Management circuit for vibrating energy harvesting.

3.2 First Stage of Energy Transferring

The matching circuit is shown in Fig. 4, which is composed of a bilateral switch K_1 and a transformer. L_p and L_s are the inductance of the primary and secondary coils in the transformer, respectively. M is the mutual inductance of the transformer. R_{1n} is equivalent input resistance of the primary resonance circuit. $T_1(t_0 - t_2)$ and $D1$ are the period and duty circle of the switch K_1, respectively. $t_0 - t_1$ and $t_1 - t_2$ are the turn-on time and turn-off time of the switch K_1, respectively.

Most of the time, the piezoelectric generator is in open circuit and the management circuit is not operating. When the piezoelectric generator output voltage reaches maximum, the switch K_1 is closed under the control signal. There is thus the energy transfers from the piezoelectric generator piezoelectric generator to the inductor L_p.

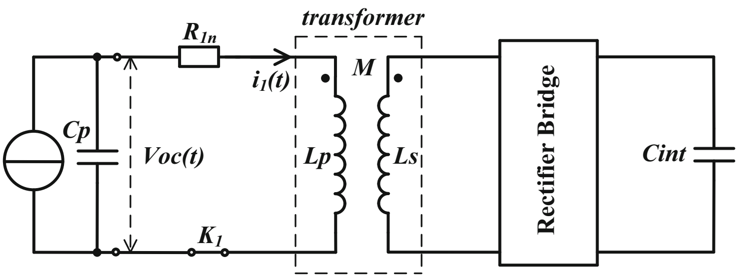

Fig. 4. Matching circuit.

With the piezoelectric generator output voltage reaches maximum, the switch K_1 is closed, the piezoelectric generator is connected to the $C_p - L_p$ resonant circuit. When $t_0 = 0$, the average current $\overline{I_1}$ of the $C_p - L_p$ circuit can be calculated by:

$$\begin{aligned}\bar{I}_1 &= 1/T_1 \int_{t_0}^{t_1} V_{oc(t)} t/L_p dt \\ &= D_1^2 V_{oc(t)}/2T_1 \end{aligned} \tag{3}$$

$V_{oc}(t)$ is the voltage of the piezoelectric generator. The voltage of the inductor L_p can be expressed as:

$$V_{Lp}(t) = \frac{I_{1P}L_P}{\sqrt{\omega_1^2 + \beta_1^2}} e^{-\beta_1(t-t_0)} \sin[\omega_1(t - t_0) + \alpha] \tag{4}$$

I_{1p} is the maximum current, the damping coefficient is β_1. In the $C_p - L_p$ circuit, the resonant angular frequency is given by

$$\omega_1 = \sqrt{\frac{(L_P - nM)D_1^4T_1^2 - L_P^2C_p}{(L_P - nM)^2D_1^4T_1^2C_p}} \tag{5}$$

3.3 Secondary Stage of Energy Transferring

The $L_s - C_{int}$ resonant circuit is shown in Fig. 5. The R_{2n} is the resistance of the secondary coils in the transformer.

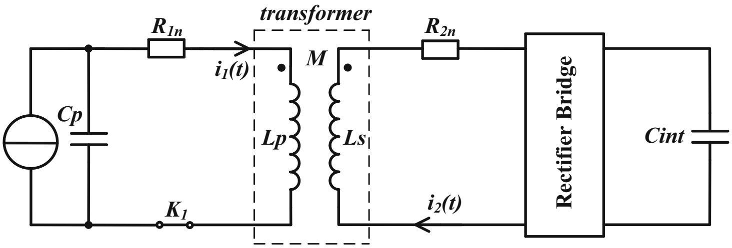

Fig. 5. Energy transfers into the intermediate capacitor.

In the $L_s - C_{int}$ resonant circuit, the output power of the piezoelectric generator transfers from the inductor L_s to the capacitor C_{int} when the voltage reach the break-over voltage of the rectifier bridge.

In the one period time ($t_0 - t_2$), the voltage of the capacitor L_S can be expressed as:

$$V_{Ls}(t) = \begin{cases} I_{1P}L_Pe^{-\beta_1(t-t_0)} \sin[\omega_1(t - t_0) + \alpha]/n\sqrt{\omega_1^2 + \beta_2^2} & t_0 \le t \le t_1 \\ I_{2P}L_Se^{-\beta_2(t-t_1)} \sin[\omega_2(t - t_1) + \gamma]/\sqrt{\omega_2^2 + \beta_2^2} & t_1 \le t \le t_2 \end{cases} \tag{6}$$

Where $i_2(t)$ and ω_2 are the current and resonant angular frequency in the $L_s - C_{int}$ resonant circuit, respectively. I_{2P} and β_2 are the maximum current and the damping coefficient of the $L_s - C_{int}$ resonant circuit, respectively.

In order to get the maximum output power from the piezoelectric generator, the resonant frequency in the $C_p - L_p$ resonant circuit is the same as the $L_s - C_{int}$ resonant circuit ($\omega_1 = \omega_2$), the inductance L_P needs to meet the following equation.

$$f_0 = 1/2\pi\sqrt{L_PC_p} \tag{7}$$

According to the Eq. (7), the frequency of the piezoelectric generator output signal is f_0. Normally, the equivalent internal capacitance is very small (nano-faradas), in order to achieve impedance matching, the inductance L_P need to be thousands of Henry, it is very difficult to find and manufacture so large inductance. This problem can be solved by the frequency conversion circuit. Assuming that f_1 and f_2 are the resonant frequency of the $C_p - L_p$ and $L_s - C_{int}$ circuit, respectively,

In one period time of the switch K_1, the voltage across the capacitor L_S exhibits underdamping attenuation oscillation, assuming that f_1 and f_2 are the resonant frequency of the $C_p - L_p$ and $L_s - C_{int}$ circuit, respectively, it can be expressed as:

$$f_1 = f_2 = \sqrt{\frac{(L_P - nM)D_1^4 T_1^2 - L_P^2 C_P}{4\pi^2 (L_P - nM)^2 D_1^4 T_1^2}} \tag{8}$$

From (8), the resonance frequency is related to the duty ratio of the switch K_1, a new high resonant frequency f_1 and f_2 are generated.

The maximum charging power of the intermediate capacitor C_{int} can be expressed as:

$$P_{C_{\text{int}}(\max)} = \frac{\omega_2^3 C_{\text{int}}^3 L_P^2 V_{oc}^4 (1 + e^{-\frac{\beta_2}{\omega_2 \pi}})}{16 T_1^2 [1 + (\frac{\beta_2}{\omega_2})^2]^2} \tag{9}$$

From (9), the maximum charging power $P_{cint(max)}$ can be obtained under the duty cycle $D_{1(opt)}$, expressed as:

$$D_{1(opt)} = \frac{\omega_2 C_{\text{int}} L_P}{T_1} \tag{10}$$

3.4 Secondary Stage of Energy Transferring

A buck-boost DC-DC circuit (as show in Fig. 6) is designed in the management circuit, which is composed of a switch K_2, an inductor L_1, a diode *Dio* and a storage capacitor C_{st}. $i_3(t)$ and R_{3n} are the current and equivalent resistance of the DC-DC circuit, respectively. When the voltage of the capacitor C_{int} reaches $V_{Cint(opt)}$, the switch K_2 turns on, the energy transfers form the C_{int} to the inductor L_1.

The last energy transferring process is transfer the energy stored in the inductor L_1 to the storage capacitor C_{st} as shown in Fig. 7. At this stage, switch K_2 turns off and diode *dio* turns on.

The harvested energy for a signal period can be expressed as:

$$E_s = \frac{1}{2} \gamma L_1 C_{\text{int}}^2 V_{C_{\text{int}(opt)}}^2 \omega_3^2 \tag{11}$$

Where γ is the over efficiency of the DC-DC convert which can be expressed as:

$$\gamma = e^{-\xi_3 \pi} \tag{12}$$

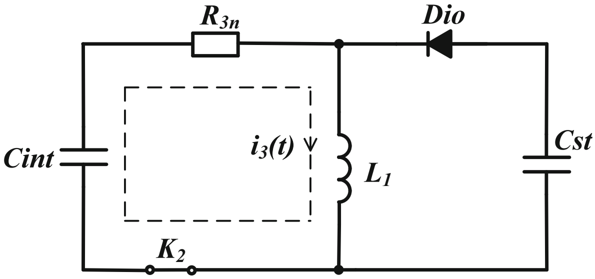

Fig. 6. DC-DC circuit.

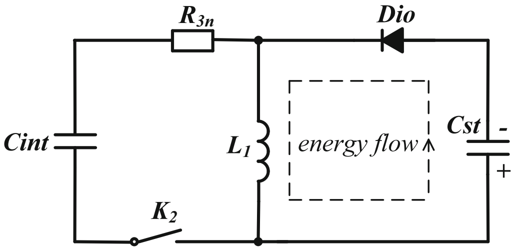

Fig. 7. Last energy transferring.

4 Experiment and Analysis

An experimental platform for energy harvesting is established. The maximum output voltage of the piezoelectric generator is 9 V. Switch K_1 is closed in positive period when the output voltage of the piezoelectric generator reaches maximum. The period of switch K_1 is $T_1 = 44$ ms (46 Hz), the duty cycle of switch K_1 is 9.8%.

The voltage of the inductor L_S is shown in Fig. 8. The frequency of the piezoelectric generator output signal can be transferred from 23 Hz to 2.5 kHz when the switch K_1 closed, thus a new high resonant frequency is generated both in the $C_p - L_p$ resonant circuit and the $L_s - C_{int}$ resonant circuit.

The frequency conversion management circuit is compared with the P-SSHI management circuit. The two management circuits have the same piezoelectric generator. The internal capacitances and frequencies are the same of 50 nF, 23 Hz. The open-circuit voltage is 10 V, and all the storage capacitors have the same capacitance of 0.1 F. In Fig. 9, the voltages across the storage capacitors in the frequency conversion management circuit and the P-SSHI circuit are 1.71 V and 0.29 V respectively.

According to Fig. 9, the harvested energy of the storage capacitor is $C_{st}V_{Cst}^2/2$, hence the frequency conversion management circuit can obtained 411% more energy compared with the P-SSHI circuit. Therefore, the frequency conversion management circuit has higher efficiency of energy harvesting than the P-SSHI management circuit.

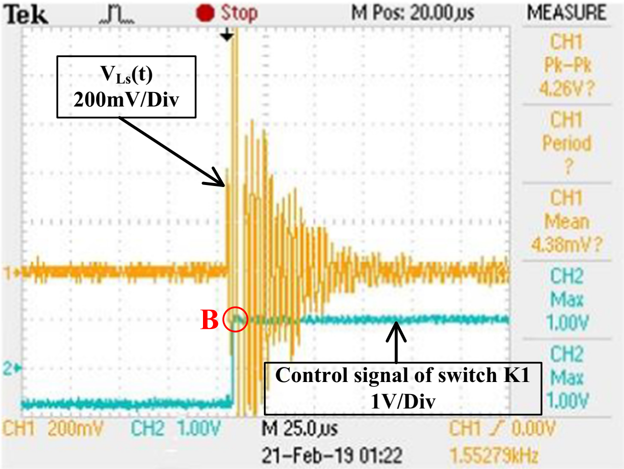

Fig. 8. Voltage waveforms across the intermediate capacitor C_{int}.

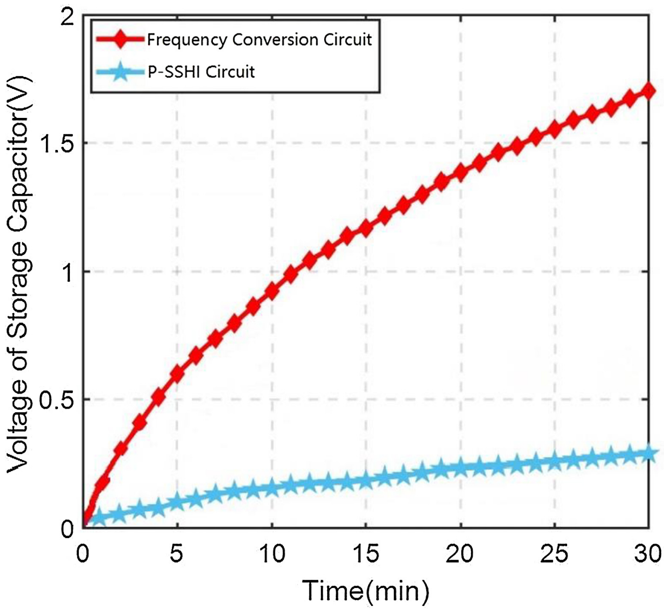

Fig. 9. Charging voltages of the storage capacitor.

5 Conclusion

In this paper, a frequency conversion management circuit has been proposed. A high resonant frequency is produced by using the matching circuit. Therefore, the maximum power can be extracted from the piezoelectric generator and transferred to the storage capacitor. The proposed management circuit also has obvious advantages compared with the P-SSHI circuit, which can be used in other weak low-frequency vibration energy harvesting.

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