Dual-stage Electrode Design of Rotational Electret Energy Harvester for Efficient Self-powered SSHI

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Abstract. This paper presents a dual-stage electrode design for electret-based rotational energy harvester (EH) to improve efficiency of synchronized switch harvesting on inductor (SSHI) technique. With the aid of the present parallel SSHI circuit, output power of the rotational electret EH developed in our group becomes 4.2 times higher if compared with the conventional full-bridge rectifier.

1. Introduction

Electret-based energy harvesters are promising to generate higher output power at a low ambient frequency range [1]. However, the output power of electret EHs suffers from parasitic capacitance, which, even in pF range, leads to substantial power loss due to its shunting effect [2]. Synchronized switch harvesting on inductor (SSHI) is often proposed to increase harvested power for piezoelectric EHs by weakening the shunting effect of its clamped capacitance [3]. Therefore, it is interesting to apply SSHI to electret EHs to enhance their output power.

Compared with piezoelectric EHs, electret EHs [4] exhibit much higher output voltage and much lower current [5], making the electret EHs sensitive to the leakage current and parasitic capacitance introduced by the SSHI circuit itself. In our preliminary study, we experimentally demonstrated that SSHI is effective for in-plane electret EH in a self-powered way [5]. However, the power harvested with the SSHI case was only 21% higher than that in the standard case. This unfavorable result lies on the use of a resistive voltage divider, which is lossy under high output voltage up to 100V. The objective of this study is to propose an improved electrode design of rotational electret EH (Fig. 1a) to achieve a more efficient self-powered SSHI interface circuit.

![Figure 1](image)

Figure 1. (a) Schematic of rotational electret EH [4], (b) Model of in-plane electret EH.
2. Self-powered SSHI interface circuit design

2.1. Modelling

Based on one-dimensional model [1], the relationship between the output current \( I \) and output voltage \( V \) of in-plane electret EH is expressed as

\[
I = \frac{C_{IE} V_s \frac{dx^*}{dt}}{C_{IE} - C_{IC}} - \left( C_{IE} - C_{IC} \right) \frac{dx^*}{dt} V - \left[ C_{IE} x^* + C_{IG}(1 - x^*) \right] \frac{dV}{dt}
\]

where \( C_{IE} \) is the internal capacitance between positive electrode and base electrode when electret is fully overlapped, \( V_s \) is the surface potential of electret, \( x^* = \frac{x}{w} \) is the normalized relative displacement of positive electrode, and \( C_{ig} \) is the internal capacitance when electret is not poled.

The terms on the RHS of Eq. (1) can be viewed as, 1) the induced current \( I = C_{IE} V_s \frac{dx^*}{dt} \), which corresponds to the change of induced charges on the positive electrode, 2) the “ohmic” current through an effective resistor \( \frac{1}{R_e} = \frac{C_{IE} - C_{IG}}{C_{IE}} \frac{dx^*}{dt} \), which corresponds to the charges that are not delivered to the external load due to the capacitance change, and 3) the charging current of the internal capacitor \( C_i = C_{IE} x^* + C_{IG}(1 - x^*) \). In this way, a circuit model is derived and validated [5]. Since \( C_i \) is usually smaller than the parasitic capacitance \( C_p \), electret EHs are susceptible to \( C_p \) and the matched impedance is determined in \( C_0 = C_i + C_p \). In our electret EH, electret material is coated on the whole surface with the same thickness both on the based and guard electrodes, hence \( C_{IG} = C_{IE} \). Then, Eq. (1) reduces to

\[
I = \frac{C_{IE} V_s \frac{dx^*}{dt}}{C_{IE} - C_{IE}} - \frac{dx^*}{dt} V - \left[ C_{IE} x^* + C_{IG}(1 - x^*) \right] \frac{dV}{dt}
\]

(2)

On the other hand, the change of electrical energy \( E_{elec} \) equals the work done by electrical restoring force \( F_e \), namely \( \dot{E}_{elec} = F_e \ddot{u} \). \( E_{elec} \) is the sum of internal electrostatic energy \( E_{in} \) and the external energy \( E_{ex} \) lost in \( C_p \) and consumed in the external load \( R \), i.e.

\[
E_{elec} = E_{in} + E_{ex} = \sum_{k=1}^{s} \frac{C_{ik}}{2} V_k^2 + \int \frac{V^2}{R} dt + \frac{1}{2} C_p V^2
\]

(3)

where \( C_{ik} \) and \( V_k \) are the capacitances and voltages across the dielectric layers corresponding to electric field \( E_i \) to \( E_s \), respectively. Then \( F_e \) is derived as

\[
F_e = \frac{C_{IE} V_s}{w} \frac{dx^*}{dt}
\]

(4)

By comparing Eqs. (2) and (4) with piezoelectric equations [3], it is clear that in-plane electret EHs behave like a piezoelectric EH. Consequently, the applicability of SSHI on electret EHs is confirmed. If the rotor rotates at a constant frequency \( f \), the output power \( P_o \) of the rotational electret EH with SSHI is

\[
P_o = n I_o V_{rec} - 2(1 - \gamma) C_0 n_f V_{rec}^2
\]

(5)

where \( I_o = 2C_{IE} V_p nf \), \( n \) is the number of electrode pairs, \( V_{rec} \) is the rectified voltage at DC side, and \( \gamma = \frac{V_{inv}}{V_{rec}} \) is the voltage inversion ratio by SSHI. Note that \( \gamma = 1 \) corresponds to the standard circuit.

![Figure 2](image)
2.2. Dual-stage electrode design

Figure 1a shows the schematic of the rotational electret EH [4], in which the rotor with electret and eccentric mass is supported by a ball bearing unit on the stator. Number of poles is 120, which is patterned on a pair of print circuit boards.

Figures 2ab show the details of new electrode design with dual output stages for efficient SSHI. The large portion of the electrode in the outer part (10 mm < r < 20 mm) is for output power at high voltage \( V_{po} \). On the other hand, the smaller inner part (9 mm < r < 10 mm) is for the control stage of the SSHI circuit with lower output voltage \( V_{ct} \). The source current of the control stage \( I_{ct} \) can be used to accurately detect the zero-crossing point of the current source of the power stage \( I_{po} \) to trigger switch actions, since \( I_{ct} \) is in phase with \( I_{po} \). The values of \( I_{ct} \), \( I_{po} \), \( C_{ct} \) and \( C_{po} \) are calculated based on the proposed model.

In this way, the lossy voltage divider we used previously is removed. The sacrificed power by control stage \( (P_{loss} = I_{ct}V_{rec}) \) is proportional to \( V_{rec} \), whilst the consumed power by voltage divider \( (P_{loss} = V_{rec}^2/R_{eq}) \) is proportional to \( V_{rec}^2 \). Obviously, the sacrificed power by control stage is lower than power consumed by voltage divider at high voltage, hence dual-stage case is more efficient when \( V_{rec} \) is high. Another merit of this design is that the switch control signal \( I_{ct} \) is isolated from the main circuit, so that voltage decrease of \( V_{rec} \), which results from power transfer to load, will not trigger switch action erroneously as it does in the voltage-divider case.

2.3. Self-powered SSHI interface circuit

Figure 3a shows the present SSHI circuit design. Compared with our previous design [5], the lossy voltage divider is removed, and a dual-polarity rectifier is used to simplify the circuit to reduce the power consumption and enhance the SSHI performance. \( V_{ct} \) is connected to a peak detector. The comparator will therefore output positive (resp. negative) voltage \( V_g \) when \( V_{ct} \) is on maximum (resp. minimum) values. At this instant, the NMOS M1 (resp. PMOS M2) transistor will be turned on initiating the inversion process. The latter is stopped when the current tends to reverse, as the diode D1 (resp. D2) stops conducting, thereby inverting \( V_{po} \) synchronously with \( I_{po} \).

Figure 3b shows a self-powering scheme to make the system truly energetically closed. The challenge is to build a dual-polarity low-voltage \( (V_s = \pm 3V) \) power supply for the comparator used in the peak detector. Here, we propose a dual-polarity rectifier to obtain the voltage supply for the comparator. The positive part is a BUCK converter [6], with the conversion efficiency over 50\%. whilst in the negative part, the polarities of D4, D5, D6, and IC2 are reversed.

Figure 3. (a)SSHI interface circuit for dual-stage electrodes, (b) Dual-polarity rectifier.
3. Results and discussion

To manage the high voltage in the main circuit, high-voltage small-signal MOSFETs BSP89 ($V_{DS}=240$ V) and BSP92p ($V_{DS}=-250$ V) are employed. To reduce power dissipation of the control block, the nanopower comparator LTC1540 is employed. Here, the output voltages of electret EH are emulated by power amplifiers. The comparator is externally powered by DC supply, but its power consumption is subtracted from the harvested output power. A full-bridge diode rectifier is connected in parallel to the EH and the SSHI circuit, with resistive load connected subsequently. The output voltage is measured by oscilloscope through a 100:1 probe. By measuring current $I_r$ on load $R$, the output power $P_o$ is calculated by $P_o=I_r^2R$.

Figure 4a shows the measured output voltage $V_{po}$. An inversion ratio of 0.7 is obtained with the current design. Figure 4b shows the output power versus load. With the present SSHI circuit, 641 μW has been obtained for a rectified voltage $V_{rec}=230$ V, which is 4.2 times higher than with the standard full-bridge rectifier where conventional electrode design is employed. Moreover, power harvested in the present dual-stage case is 2.5 times higher than that in the voltage-divider case, indicating a more efficient SSHI by using the present dual-stage strategy.

4. Conclusion

In summary, with the dual-stage electrode design, the performance of self-powered SSHI on electret EH has been much improved, and 4.2 times higher output power is expected compared to the standard full-bridge rectifier interface circuit.

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Figure 4. (a) Experimental waveform of output voltage in the present SSHI, (b) Measured harvested power as a function of rectified voltage.