An energy extraction enhanced interface circuit for piezoelectric and thermoelectric energy harvesting

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Abstract In this paper, an interface circuit based on parallel-synchronous switch harvesting on inductor (SSHI) is proposed for piezoelectric and thermoelectric energy harvesting. The proposed interface circuit could harvest power from piezoelectric transducers (PZT) and thermoelectric generators (TEG) simultaneously with a single-shared inductor. In addition, the harvester enables cold start without external battery. Simulation results indicate that the proposed circuit has higher power extraction capability by increasing damping force of the PZT, and the overall output power is 15.8% higher than conventional SSHI harvester when the load resistor is 10 KΩ.

Keywords: piezoelectric energy harvesting, thermoelectric energy harvesting, SSHI, inductor shared

1. Introduction

With the growing popularity and applications of the new generation sensor and internet of things (IoT), there is urgent need to extend the battery lifetime of wireless sensor nodes [1]. Since it is an arduous work to personally replace battery especially in a large wireless sensor networks (WSN), such as manufacturing plants, hospitals, and military camps [2, 3, 4]. Thanks to ubiquitous energy in heat, vibration, light and electromagnetic radiation, energy harvesting is an attractive solution of the energy-constrained sensor nodes in WSN to perpetually capture energy from ambient environment and convert to DC supply [5, 6]. Among these energy sources, the outputs of heat energy transducers are directly DC voltages, and vibration energy has high power density [7, 8, 9, 10, 11]. Both of which are convenient for harvesting.

Several energy harvesting interface circuits have been proposed for capturing thermal energy and vibration energy [12, 13, 14, 15]. Thermal energy harvesting usually adopts TEG as the energy transducer. It can be modeled as a voltage source in series with a resistor [16]. The output of the voltage source is related to difference in temperature between two sides of the transducer, generally 50–100 mV/°C [17]. The challenge of thermoelectric energy harvesting is that the DC voltage generated in general environment is too low to be used directly [18]. In addition, under ultra low voltage situation, it usually has difficulty to activate circuits [19].

PZT is suitable for vibration energy harvesting due to its relative high power density and high output voltage. The operating principle of piezoelectric transducers can be explained by a simple piezoelectric cantilever, which is shown in Fig. 1 [20]. As the element bends, the top layer of the element is in tension and bottom layer is in compression or vice versa. Therefore positive and negative electrical charge will generate on each side of the layer respectively, and accumulate through vibration. With charge accumulating, electric field between the two layers will increase, inducing that the electrical damping force against PZT vibration work will increase as well. The more energy can be scavenged during every cycle of vibrations, the more energy extraction capability of transducers can be achieved. If the excitation vibration is sinusoidal, which is true in most cases, PZT can be modeled as a sinusoidal current source in parallel with a resistor and a capacitance [21]. One the other hand, the intrinsic capacitance of PZT

Fig. 1. Structure of piezoelectric cantilever and equivalent circuit of a piezoelectric energy transducer.
is relatively large. Thus, electric charge will accumulate on the parasitic capacitance during every half period, and then neutralize after piezoelectric currents change direction. The charge neutralization will cause energy loss and the total energy efficiency will decrease dramatically as frequency increases [22, 23]. The SSSI and synchronous electric charge extraction (SECE) topologies are designed to enhance energy efficiency by avoiding charge neutralization [24, 25, 26, 27]. Furthermore, for miniaturized PZT, the electromechanical coupling factor is low, consequently, the transducers generate litter power from vibrations.

In order to improve the power extraction capability, energy-investing piezoelectric harvester interface circuits were proposed [28, 29]. The external battery will firstly charge the PZT capacitance to set an initial voltage across the intrinsic capacitance of PZT. Thus, the harvester increases the cantilever’s electrical damping force and induces the transducer to draw more energy. However, these topology can not start when the battery is exhausted. Once the battery is used up, the circuit can not be activated.

To address the challenges mentioned in the previous mentioned topologies, we proposed a novel inductor shared energy harvesting circuit based on parallel-SSSI structure. The proposed topology can efficiently extract the energy from both PZT and TEG simultaneously and is compatible with standard CMOS process. Furthermore, if the initial electromechanical coupling factor is low or the vibration source is strong, which means the damping force that tiny transducers impose on vibrations is hardly noticeable, the energy produced by TEG can be used to improve the energy extraction capability of PZT by increasing the electrostatic force against vibrations, and it doesn’t need external battery to startup the circuit.

The remainder of this paper is structured as follows, section 2 discusses our proposed energy harvester. Section 3 presents the post-layout simulation results of proposed harvester. Finally, the entire work is concluded in section 4.

2. Proposed energy harvesting interface circuit

Our proposed energy harvesting interface circuit is based on SSSI topology. As depicted in Fig. 2, a TEG and a storage capacitor are incorporated compared to parallel-SSSI topology. To decrease the system size, the inductor $L_p$ is shared by TEG and PZT. All the switches are implemented by transmission gates.

The overall timing diagrams are shown in Fig. 3 with the assumption that the corresponding switches are on when the voltages $V_{sw}$ are high, and vice versa. In a half period of $i_{pzt}$, firstly, switches $S_{sw7}$ and $S_{sw8}$ are on. The thermoelectric generator will charge the storage capacitor $C_t$. Before the piezoelectric current crosses zero, switches $S_{sw5}$ and $S_{sw6}$ are on, forming a $C_t - L_p$ resonant circuit. After resonating $\frac{1}{2}$ period, a current on inductor $I_{init}$ is generated, setting for the $L_p - C_{pzt}$ resonance. When $i_{pzt}$ is zero and the direction of $i_{pzt}$ is from positive to negative, $S_{sw1}$ and $S_{sw2}$ are on. When $i_{pzt}$ is zero and the direction of $i_{pzt}$ is from negative to positive, $S_{sw3}$ and $S_{sw4}$ are on. This control scheme can ensure, during the oscillation, the current direction of inductor is always positive. Because of the initial state current $I_{init}$, higher voltage across $C_{pzt}$ can be obtained after $L_p - C_{pzt}$ resonance. When both vibration energy and thermal energy exist around the interface circuit, it not only can harvest vibration energy and thermal energy simultaneously, but benefits from the increment of damping force of PZT to output more power. In addition, the piezoelectric transducer is directly connected to the AC-DC converter and the AC-DC converter is connected to the output through a switch $S_9$ in parallel with a diode $D_1$. In regular working period, $S_9$ is controlled by switch controller. When $V_{out}$ is higher than $V_{buf}$, $S_9$ is on, otherwise $S_9$ is off. It can not only prevent current flows reversely to the AC-DC converter, but also shorten the diode to reduce the voltage drop when output current flows to the load. In the beginning period, this circuit can start up through the diode $D_1$ without external batteries. If TEG energy is absent, this circuit will operate in the same way with parallel-SSSI topology.

To obtain the maximum output power and overall efficiency, the passive elements in the harvester and the conducting time of switches should be carefully chosen. A relatively large inductor is desired to increase the Q factor of $LC$ resonant, which can reduce the energy loss during the initial current generating and voltage flipping. The initial state current $I_{init}$ is given by,

$$I_{init} = \frac{V_{C_t}}{\omega_{d1} L} e^{-\alpha_1 t_{i1}} \sin \omega_{d1} t_{i1}$$

$$\alpha_1 = \frac{R_{para}}{2L}$$

$$\omega_{d1} = \sqrt{\omega^2_p - \omega^2_1}$$

$$\omega_1 = \frac{1}{\sqrt{LC_1}}$$
where $V_C$ is the voltage across the capacitor $C_t$, which approximately equals to $V_T$. $R_{para1}$ is the parasitic resistance in the $C_t - L_p$ resonant loop, and $t_1$ is the conducting time of switches $S_{w5}$ and $S_{w6}$ to obtain a maximal $I_{init}$. The invert voltage after $L_p / C_0$ resonance is,

$$V_{p,inv} = \frac{V_{buf}}{\sin \theta} e^{-\alpha t_2} \sin(\alpha t_2 t_2 + \theta)$$

(5)

$$\theta = \arctan \frac{\alpha t \sin(\alpha t_2 t_2)}{I_{init} + \alpha V_{buf} C_{pzt}}$$

(6)

$$\alpha_1 = \frac{R_{para2} \alpha t_2}{2L}$$

(7)

$$\alpha_2 = \sqrt{\alpha_1^2 - \alpha_2^2}$$

(8)

$$\omega_2 = \frac{1}{\sqrt{LC_{pzt}}}$$

(9)

where $R_{para2}$ is the parasitic resistance in the $L_p - C_{pzt}$ resonant loop, and $t_2$ is the conducting time of switches $S_{w1-4}$. The optimal value of $t_1$ and $t_2$ can be determined by simulation.

3. Post-layout simulation results and discussion

The design prototype of energy harvesting interface circuit is presented in Fig. 4, with total covered area of 1.05 mm$^2$ (including bond pads). The energy harvesting interface circuit is designed with SMIC 0.18 µm CMOS technology. The piezoelectric material we used is PPA-1014 from Mide Technology Corporation [30]. When the transducer vibrates at 400 Hz and 2g acceleration amplitude, it can be modeled as a 400 µA sinusoidal current source in parallel with a 40 nF capacitance and a 8.9 KΩ resistor [31]. TEG is modeled as a 300 mV voltage source in series with a 200 Ω resistor. The load capacitor is 400 nF in order to reduce the fluctuation of the output voltage. To maximize the energy harvested from the TEG, storage capacitor $C_t$ is set to 220 nF. Corresponding to the previous theoretical analysis, a 470 µH off-chip inductor with quality factor of 100 is adopted, under the consideration of overall efficiency and portability. When the load resistor is 10 KΩ, the waveforms including output voltage of proposed circuit with TEG $V_{prop}$ and output voltage of proposed circuit without TEG $V_{conv}$ are presented in Fig. 5. The waveforms illustrate that from $0 < t < 5$ ms, the proposed harvester with TEG operates as a full bridge rectifier to charge the load capacitor. As the load capacitor voltage increases, the control voltage will be generated, fulfilling the cold start function. The overall output power and the total energy from harvested TEG can be represented by following equations.

$$P_{prop} = \int_{T}^{T+\frac{V_{prop}^2}{R_{load}}} P_{TEG} + P_{PZT} = 421.2 \mu W$$

(10)

$$P_{conv} = \int_{T}^{T+\frac{V_{conv}^2}{R_{load}}} P_{PZT} = 363.6 \mu W$$

(11)

$$P_{TEG} = \frac{1}{\eta} C_t V_{TEG}^2 \times 2 f = \eta C_t V_{TEG}^2 f = 7.92 \mu W$$

(12)

$\eta$ is TEG energy conversion efficiency. Supposing that TEG energy conversion efficiency is 1, which is an ideal case. Therefore $P_{PZT}$ can be calculated, which is 413.28 µW. Upon the above analysis, the power extraction ability of PZT in proposed circuit with TEG is 15.8% higher than...
the output power of conventional SSHI harvester. The additional energy is generated from TEG and PZT by increasing damping force of the transducer. The direct contribution of total energy from TEG is 2.17%.

Fig. 6 illustrates simulated output powers of the proposed energy harvesting interface circuits under different loads. Load resistors range from 800 Ω to 1200 Ω. It can be shown that, the proposed technique improves output power by approximately 15%, when the load resistor change from 800 Ω to 1200 Ω.

4. Conclusion

A novel inductor-shared harvesting interface circuit based on SSHI is presented for piezoelectric and thermoelectric energy with enhanced power extraction capability. The proposed circuit is self-powered without external battery. It can simultaneously harvest piezoelectric and thermoelectric energy. The circuit could achieve high portability by sharing the inductor. Simulation results show that the power extraction capability of the proposed circuit is 15.8% higher than conventional SSHI rectifier, including 2.17% energy contributed by TEG, when the load resistor is 10 KΩ. Therefore it is a potential battery replacement in wireless sensor networks.

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References

[1] C. Knight, et al.: “Energy options for wireless sensor nodes,” Sensors 8 (2008) 8037 (DOI: 10.3390/s8128037).
[2] R. J. M. Vullers, et al.: “Energy harvesting for autonomous wireless sensor networks,” IEEE Solid-State Circuits Mag. 2 (2010) 29 (DOI: 10.1109/MSSC.2010.936667).
[3] S. P. Beeby, et al.: “Energy harvesting vibration sources for microsystems applications,” Meas. Sci. Technol. 17 (2006) R175 (DOI: 10.1088/0957-0233/17/12/R01).
[4] P. D. Mitcheson, et al.: “Energy harvesting from human and machine motion for wireless electronic devices,” Proc. IEEE 96 (2008) 1457 (DOI: 10.1109/JPROC.2008.927494).
[5] R. J. Vullers, et al.: “Micropower energy harvesting,” Solid-State Electron. 53 (2009) 684 (DOI: 10.1016/j.sse.2008.12.011).
[6] K.-S. Yoon, et al.: “A 1452%-power extraction improvement energy harvesting circuit with simultaneous energy extraction from a piezoelectric transducer and a thermoelectric generator,” Symposium on VLSI Circuits (2017) C202 (DOI: 10.23919/VLSC.2017.8008482).
[7] S. Roundy, et al.: “Improving power output for vibration-based energy scavengers,” IEEE Pervasive Comput. 4 (2005) 28 (DOI: 10.1109/MPRV.2005.14).
[8] S. Sudevalayam, et al.: “Energy harvesting sensor nodes: Survey and implications,” IEEE Comm. Surv. and Tutor. 13 (2011) 443 (DOI: 10.1109/SURV.2011.060710.00094).
[9] P. D. Mitcheson, et al.: “Energy harvesting from human and machine motion for wireless electronic devices,” Proc. IEEE 96 (2008) 1457 (DOI: 10.1109/JPROC.2008.927494).
[10] V. Raghunathan, et al.: “Design considerations for solar energy harvesting wireless embedded systems,” International Symposium on Information Processing in Sensor Networks (2005) 457 (DOI: 10.1109/IPSN.2005.1440979).
[11] A. S. Platt, et al.: “On low-frequency electric power generation with PZT ceramics,” IEEE/ASME Trans. Mechatron. 10 (2005) 240 (DOI: 10.1109/TMECH.2005.844704).
[12] Z. Chen, et al.: “A 1.7 mm2 inductorless fully integrated flipping-capacitor rectifier (FCR) for piezoelectric energy harvesting with 483% power-extraction enhancement,” ISSCC Dig. Tech. Papers (2017) 2376 (DOI: 10.1109/ISSCC.2017.7870416).
[13] Y. K. Teh, et al.: “Design of transformer-based boost converter for high internal resistance energy harvesting sources with 21 mV self-startup voltage and 74% power efficiency,” IEEE J. Solid-State Circuits 49 (2014) 2694 (DOI: 10.1109/JSSC.2014.2354645).
[14] D. H. Jung, et al.: “Thermal and solar energy harvesting boost converter with time-multiplexing MPPT algorithm,” IEICE Electron. Express (2016) (DOI: 10.1587/elex.13.20160287).
[15] A. Morel, et al.: “A shock-optimized SECE integrated circuit,” IEEE J. Solid-State Circuits 53 (2018) 3420 (DOI: 10.1109/JSSC.2018.2868299).
[16] J. Katic, et al.: “Dual-output thermoelectric energy harvesting interface with 56.6% peak efficiency at 30 µW and total control power of 160 nW,” IEEE J. Solid-State Circuits 51 (2016) 1928 (DOI: 10.1109/JSSC.2016.2561959).
[17] J. Goeppert, et al.: “Fully integrated startup at 70 nV of boost converters for thermoelectric energy harvesting,” IEEE J. Solid-State Circuits 51 (2016) 1716 (DOI: 10.1109/JSSC.2016.2563782).
[18] E. J. Carlson, et al.: “A 20-nV input boost converter with efficient digital control for thermoelectric energy harvesting,” IEEE J. Solid-State Circuits 45 (2010) 741 (DOI: 10.1109/JSSC.2010.2042251).
[19] Y. K. Ramadass and A. P. Chandrakasan: “A battery-less thermoelectric energy harvesting interface circuit with 35 mV startup voltage,” IEEE J. Solid-State Circuits 46 (2011) 333 (DOI: 10.1109/
[20] Y. K. Ramadass and A. P. Chandrakasan: “An efficient piezoelectric energy harvesting interface circuit using a bias-flip rectifier and shared inductor,” IEEE J. Solid-State Circuits 45 (2010) 189 (DOI: 10.1109/JSSC.2009.2034442).

[21] H. Liu, et al.: “Piezoelectric MEMS energy harvester for low-frequency vibrations with wideband operation range and steadily increased output power,” J. Microelectromech. Syst. 20 (2011) 1131 (DOI: 10.1109/JMEMS.2011.2162488).

[22] D. A. Sanchez, et al.: “A parallel-SSHI rectifier for piezoelectric energy harvesting of periodic and shock excitations,” IEEE J. Solid-State Circuits 51 (2016) 2867 (DOI: 10.1109/JSSC.2016.2615008).

[23] T. Hehn, et al.: “A fully autonomous integrated interface circuit for piezoelectric harvesters,” IEEE J. Solid-State Circuits 47 (2012) 2185 (DOI: 10.1109/JSSC.2012.2200530).

[24] L. Wu, et al.: “A direct AC-DC converter integrated with SSHI circuit for piezoelectric energy harvesting,” IEICE Electron. Express 14 (2017) 20170431 (DOI: 10.1587/elex.14.20170431).

[25] D. Guyomar, et al.: “Toward energy harvesting using active materials and conversion improvement by nonlinear processing,” IEEE Trans. Ultrason. Ferroelectr. Freq. Control 52 (2005) 584 (DOI: 10.1109/TUFFC.2005.1428041).

[26] A. Morel, et al.: “A shock-optimized SECE integrated circuit,” IEEE J. Solid-State Circuits 53 (2018) 3420 (DOI: 10.1109/JSSC.2018.2868299).

[27] A. Quelen, et al.: “A 30 nA quiescent 80 nW to 14 mW power range shock-optimized SECE-based piezoelectric harvesting interface with 420% harvested energy improvement,” ISSCC Dig. Tech. Papers (2018) 150 (DOI: 10.1109/JSSC.2018.8310228).

[28] D. Kwon, et al.: “A single-inductor 0.35 µm CMOS energy-investing piezoelectric harvester,” IEEE J. Solid-State Circuits 49 (2014) 2277 (DOI: 10.1109/JSSC.2014.2342721).

[29] M. Lallart, et al.: “Piezoelectric conversion and energy harvesting enhancement by initial energy injection,” Appl. Phys. Lett. 97 (2010) 014104 (DOI: 10.1063/1.3462304).

[30] Mide Technology Corp.: Vibration energy harvesting with piezoelectrics (2018) https://www.mide.com/collections/vibration-energy-harvesting-with-protected-piezoelectrics.

[31] Mide Technology Corp.: PPA PRODUCTS Datasheet & User Manual.