A Switched-Mode Time-Sharing Solution for Piezoelectric Energy Harvesting and Vibration Sensing

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***Abstract*—In piezoelectric energy harvesting (PEH), utilizing the synchronized switch interface circuits can significantly enhance the energy harvesting capability. Vibration sensing and synchronization are necessary functions for carrying out the synchronized switching actions. Those functions were usually implemented with an external displacement sensor in the early designs, which is not friendly for self-contained applications. This paper proposes a compact time-sharing solution for energy harvesting and vibration sensing by making full use of a modified buck-boost design. The circuit works in a strong discontinuous conduction mode (DCM). It is based on the principle that, under DCM operation, the voltage levels of the piezoelectric source side and the storage side are proportional to the actively switch-on and passively freewheeling intervals, respectively. Compared with the other self-powered synchronized switch PEH solutions, which rely on analog peak detectors, this self-sensing solution not only provides synchronized triggering signals for carrying out the switching actions but also tells more information about the driven vibration, such as its frequency and displacement magnitude. With the detailed vibration information, such a time-sharing solution offers more design convenience towards future multi-functional battery-free IoT applications.**

I. Introduction

Piezoelectric materials are widely used in industrial applications such as sensors, actuators, and power generators. In energy harvesting applications, piezoelectric materials are used as transducers that convert kinetic energy into electricity. The bridge rectifier is regarded as the standard energy harvesting (SEH) interface circuit for converting the piezoelectric output ac voltage into usable dc one. As the output impedance of a piezoelectric transducer is capacitive, the reactive component limits the real power harvested by the SEH design. Different types of synchronized switch interface circuits were proposed for enhancing the harvested power by carrying out a running power factor correction (PFC) [1]. The synchronized switch designs can be categorized into two major types: the synchronous electric charge extraction (SECE) and synchronized switch harvesting on inductor (SSHI) [2], [3]. There were many derivatives of SECE and SSHI circuits, such as SC-SECE [4], DSSH [5], SMBF [6], and MCEBF [7] in board-level or integrated circuit (IC) level [8], [9]. No matter what topology is used, the switching actions are usually carried out at voltage peaks. Early solutions used external sensors for offering vibration information on velocity or displacement, which served as a reference for the synchronization purpose. The synchronization function was integrated into the latter board-level and IC level designs with sophisticatedly designed voltage-peak detectors. All of these existing solutions focused on synchronization towards SECE, SSHI, or their derivatives rather than offering a general sensing result. Energy harvesting was the only function that can be realized in these previous designs. In this paper, we developed a new circuit scheme as a derivative of the buck-boost type SECE circuit. The vibration sensing and synchronized switch energy harvesting functions are simultaneously carried out in this switched-mode solution. It provides an unprecedented option for future multi-functional piezoelectric device designs towards integrated IoT applications.

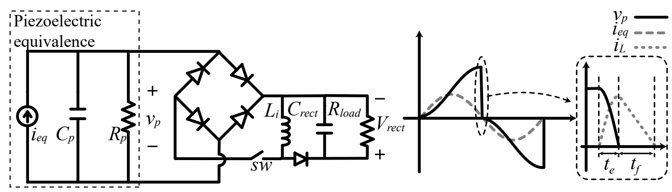

Fig. 1. Conventional SECE circuit topology and waveform.

II. SECE for Piezoelectric Energy Harvesting

When vibrates under a specific magnitude, a piezoelectric structure can be equivalently modeled in the electrical domain as a current source i_{eq} in parallel with the piezoelectric capacitance C_p and dielectric leakage resistance R_p, as shown in Fig. 1. The alternating voltage output should be regulated into dc form for powering digital electronics. The SEH interface circuit offers the most fundamental ac-dc rectification. For achieving higher harvesting capability, synchronized switch interface circuits were designed for improving the power factor [1]. SECE is one of the most extensively investigated interface circuits for making such a purpose. Compared with SSHI, another extensively studied interface circuit family, SECE has an advantage of load independence. The circuit topology and

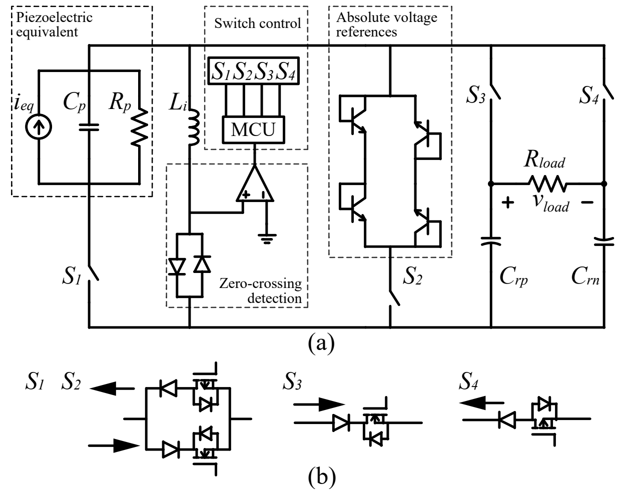

Fig. 2. Self-sensing SECE proposed in this paper. (a) Circuit topology. (b) Switch implementations.

operating waveform of SECE are shown in Fig. 1. The switch sw is off in most of a period. It turns on for a short interval to transfer all energy stored at C_p to the series-connected inductor L_i, whenever a peak voltage is detected. Such a process is called *synchronous charge extraction*. These synchronized switch actions keep the output voltage v_p and current i_{eq} in the same polarity throughout a vibration period. Therefore, it increases the harvesting capability compared with the SEH design.

III. Operation Principle

In conventional SECE, the switching actions are carried out at the synchronized voltage peak instants, which are found out with an external displacement/velocity sensor or additional electronic voltage peak detectors. At every synchronized instant, the charge stored at C_p is fully extracted after a quarter of the L_iC_p cycle. Such an action only transfers the energy but generates no information about the stored charge.

In a general dc-dc buck-boost converter, the increasing or decreasing slopes of inductor current are proportional to the charge extraction or freewheeling voltages respectively. Given this principle, by properly making good use of this feature, not only the energy but also the information of piezoelectric and storage voltages can be extracted with the switching actions.

A. Switched-Mode Sensing

To keep track of the changing trend of the piezoelectric voltage, as well as carry out synchronized switching actions at voltage extremes, the self-sensing SECE solution is proposed and shown in Fig. 2. A zero-crossing detector is added in series with L_i for recording the freewheeling time under DCM operation.

Different from the conventional dc-dc converter design, the buffer capacitances in both sides, in particular, the piezoelectric capacitance, is rather small (usually at the nF level). In order not to induce a strong intervention to the original piezoelectric voltage v_p, the switching time in the sensing phase should be much shorter than that in the charge extraction phase, i.e., $t_{ce} = (8\pi\sqrt{L_iC_p})^{-1}$. Within the short conduction interval for sampling t_{cs}, the piezoelectric transducer can be approximately regarded as a constant voltage source. During the tiny charge extraction step for sensing purpose, the peak inductor current can be expressed as follows

$$i_{L,\text{peak}} = \frac{v_p t_{cs}}{L_i}. \quad (1)$$

After the tiny-step charge extraction, the inductor current freewheels through either of the load capacitor C_{rp} or C_{rn}. The freewheeling time t_{fw} and peak inductor current have the following relation

$$i_{L,\text{peak}} = \frac{v_{load} t_{fw}}{2L_i}. \quad (2)$$

According to (1) and (2), we can easily solve the voltage relationship as follows

$$\frac{v_p}{v_{load}} = \frac{t_{fw}}{2t_{cs}}. \quad (3)$$

In our switched-mode sensing implementation, t_{cs} is actively decided by the program, while t_{fw} is passively measured according to the interrupting instant generated by the zero-crossing detector, as shown in Fig. 2(a). Therefore, the relation between v_p and v_{load} is possible to be obtained along with the switched-mode operation.

According to (3), the relation between piezoelectric and load voltages can be estimated. Relative information is sufficient for generating the synchronized switch command. However, for the sensing purpose, absolute values are also needed for generating useful information. Given this need, two absolute voltage references in positive and negative directions are provided by using four diode-connected transistors, as shown in Fig. 2(a).

B. Time-sharing Operation

Owing to its switched-mode sensing capability, a self-sensing SECE (SS-SECE) interface circuit is implemented by using a double-rail buck-boost topology, as shown in Fig. 2(a). The v_p voltage sensing actions are scheduled based on a specific sampling frequency. Whenever the maximum or minimum points are found by comparing the sensed values, a charge extraction action is taken for energy harvesting purpose. Both of these two sorts of actions are carried out by the same switching branch. Therefore, no additional module is needed to implement this SS-SECE. It requires more computing or controlling efforts from the controller. In this study, a microcontroller is used to implement the time-sharing control. Its power is still offered by batteries at this stage. We put an emphasis on interface circuit design first. The zero-crossing detector is implemented with two diodes and one compactor. Four diode-connected transistors work as constant voltage references in the sensing mode. Two switch S_3, S_4 and two storage capacitors C_{rp}, C_{rn} form the harvesting branch. The load voltage v_{load} across the resistor R_{load} is a differential dc voltage across C_{rp} and C_{rn}. Two of those switches, S_1

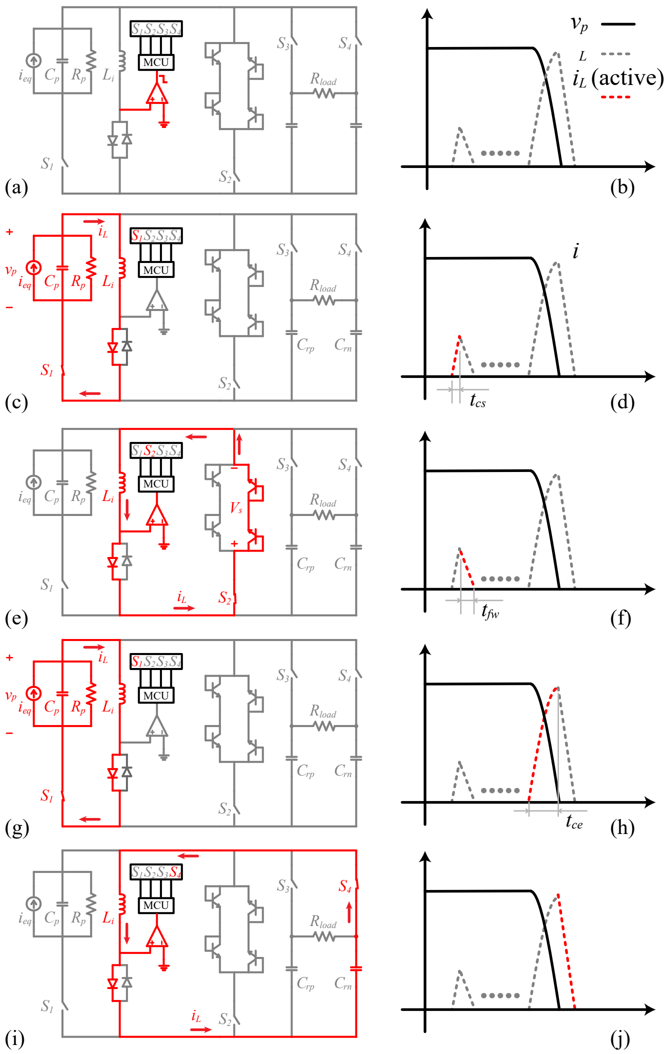

Fig. 3. The working phases and waveform of self-sensing SECE in the positive v_p half cycle. (a) and (b) Open-circuit phase. (c) and (d) Charge extraction phase in sensing mode. (e) and (f) Freewheeling phase in sensing mode. (g) and (h) Charge extraction phase in harvesting mode. (i) and (j) Freewheeling phase in harvesting mode.

and S_2, allow bidirectional current flow at the low side, while the other two S_3 and S_4 only flow unidirectional current at the high side. The switches are implemented with different configurations of series MOSFETs and diodes, as shown in Fig. 2(b).

Fig. 3 shows the detailed working phases and waveform of the SS-SECE design. It works under strong DCM. Like conventional SECE, the circuit is in open-circuit condition during most of a period, as shown in Fig. 3(a) and (b). The sensing actions are carried out with uniform sampling. Each sensing action includes two phases: a charge extraction phase with an S_1 turn-on interval t_{cs}, as shown in Fig. 3(c) and (d), and a following freewheeling phase through the S_2 path, whose duration is measured by a zero-crossing detector, as shown in Fig. 3(e) and (f). Freewheeling through the storage capacitance can reclaim the extracted energy, while freewheeling through the absolute voltage reference can generate absolute voltage information about the piezoelectric transducer. The energy harvesting actions are carried out once the maximum or minimum voltage is found, i.e., according to the interrupt triggering. Each harvesting action also includes two phases: a fully charge extraction phase with an S_1 turn-on interval t_{ce}, whose conducting path is also shown in Fig. 3(g) and (h), and a following freewheeling phase through S_4 and the storage capacitor C_{rn}, as shown in Fig. 3(i) and (j). Those figures in Fig. 3 are only for the positive v_p half cycle. The other conducting paths in the negative v_p half-cycle open the complementary branches for the corresponding sensing and harvesting actions.

Peak detection is a necessary function for carrying out the synchronized switch control for SECE interface circuit. In this study, supposing that the the n^{th} measured value of v_p is $\hat{v}_{p,(n)}$, at the v_p peak (minimum and maximum) positions, the following voltage relation holds.

$$\text{sign}[\hat{v}_{p,(n-1)} - \hat{v}_{p,(n-2)}] = -\text{sign}[\hat{v}_{p,(n)} - \hat{v}_{p,(n-1)}]. \quad (4)$$

Voltage sensing actions are carried out at a constant sampling rate f_s, while the harvesting actions only occur at voltage peaks. The time-sharing control ensures the proper operation of this SS-SECE design. Such a control scheme is effective under either regular harmonic or complex vibration conditions. The detailed information sensed by this circuit provides more design possibilities beyond telling the voltage peak positions. Therefore, the time-sharing sensing and harvesting scheme might lead to more degree of freedom for the design of future multi-functional piezoelectric devices.

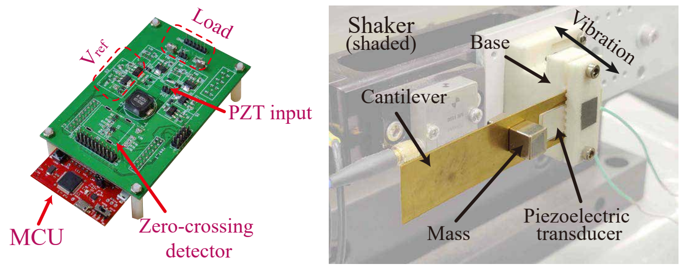

Fig. 4. SS-SECE PCB prototype and piezoelectric structure.

TABLE I
CIRCUIT PARAMETERS AND COMPONENT TYPES.

NMOS	PMOS	L_i	Transistor	Diode
ZVP4424	ZVN4424	120 mH	2SC4083	NSR0240H
MCU	Comparator	f_0	C_p	V_{oc}
TM4C123GXL	TLV3201	47.3 Hz	50 nF	9.5 V

IV. EXPERIMENT

The SS-SECE printed circuit board (PCB) prototype and the piezoelectric structure used in experiment are shown in Fig. 4. The circuit parameters and component types are listed in Table I. From the captured v_p waveform from an oscilloscope, as shown in Fig. 5(b), the SS-SECE circuit functions well.

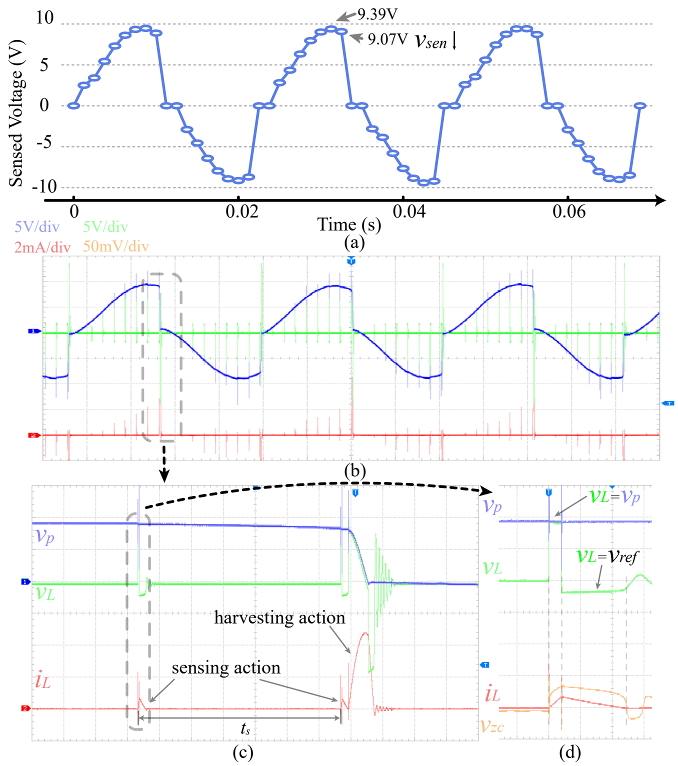

Fig. 5. SS-SECE waveform. (a) The sensed voltage v_p by the self-sensing solution; (b) Oscilloscope waveform. (c) The zoom-in view showing the current and voltage during sensing and harvesting instants. (d) A further zoom-in view of the sensing instants.

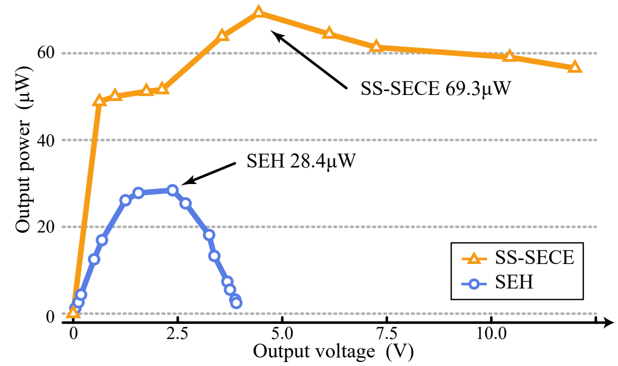

Fig. 6. Harvested power comparison.

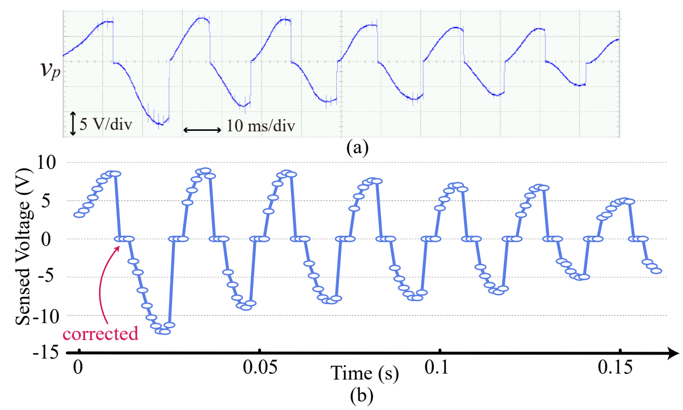

Fig. 7. Operating waveform under a shock vibration. (a) Oscilloscope measurement. (b) Measurement result with SS-SECE.

The switch harvesting actions take place when the voltage just passes the peaks. There is some small delay because of the peak estimation, which inevitably exists in peak detectors. In this experiment, the voltage sampling frequency is $f_s = 800$ Hz. Given that the vibration frequency $f_0 = 47.3$ Hz, there are about 17 voltage samples at each cycle. The maximum switch delay is about 1.5 times of a sampling interval, i.e., 1.9 ms. Fig. 5(a) shows the sensed data from the SS-SECE design. The sensed waveform shows a good agreement with the result from the oscilloscope. This information can be used to identify the voltage peaks and carry out synchronized switch actions. It also carries useful information about the vibration condition.

Fig. 5(c) further illustrates two uniform sensing actions with a sampling interval of $t_s = 1/f_s$, following by a charge extraction harvesting action. Fig. 5(d) shows the further enlarged waveform in each sensing instant. Fig. 6 shows the harvested power under different output voltage levels. From the comparison with SEH, we can observe that SS-SECE can increase the harvested power by 244% in this case. Therefore, it inherits the advantage of conventional SECE, in terms of piezoelectric energy harvesting improvement.

The SS-SECE can also robustly carry out sensing and harvesting actions under irregular vibrations. For example, Fig. 7 shows the results after a shock impact. From the figure, we can observe that the charge extraction actions are carried out in time, regardless of the peak changes. More importantly, the sensed voltage with our switched-mode method looks almost the same as the results obtained from the oscilloscope. The utilization of this sensed information will be further explored in future study.

V. CONCLUSION

A new switched-mode time-sharing solution for piezoelectric energy harvesting and vibration sensing purposes were introduced in this paper. It was extended based on the conventional buck-boost type synchronized electric charge extraction (SECE) interface circuit. The voltage sensing action was realized given the fact that the charging/discharging voltage is proportional to the inductor current slope. Therefore, the voltage values can be related to the conduction intervals of different switching paths. A zero-crossing detector was implemented to determine the freewheeling time. Some diode-connected transistors were utilized for providing absolute voltage references. The time-sharing control was carried out by a micro-controller. Experimental results showed that this SS-SECE design works well under both regular harmonic or irregular vibrations. Compared with the other self-powered SECE driven by voltage peak detectors, this design offers more detailed vibration information, which might benefit future designs towards multi-functional piezoelectric devices.

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