A Vibration-Powered Bluetooth Wireless Sensor Node with Running PFC Power Conditioning

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***Abstract*—The kinetic energy harvesting technologies have attracted extensive research interests with the purpose to enable more distributed and wearable electronics to be powered by their surrounding mechanical vibrations or motions. The power conditioning circuit is of importance for harvesting more energy from the vibration source and better managing the energy storage and power users. This paper introduces the design and implementation of a vibration-powered Bluetooth wireless sensor node, whose power is acquired by a low-cost piezoelectric transducer and processed by a self-powered synchronized switch power conditioning circuit. Given the capacitive feature of the piezoelectric transducers and the irregular feature of most vibration sources, the power conditioning circuit realizes the running power factor correction (PFC), making the piezoelectric voltage in phase with the equivalent current source at every current zero-crossing. As a result, it can significantly enhance the energy harvesting capability. Detailed analysis on the power consumption shows the feasibility of this design.**

I. Introduction

Owning to the advances of pervasive computing, wireless communication, etc., the wireless sensor networks (WSNs) and wearable electronics have experienced a rapid development during the last decade. These devices are usually dispersively distributed and cooperate through wireless connection. Nowadays, as most of them are power by batteries, whose storage capacity is limited and energy density has experienced relative slow improvement [1], the power supply has become the biggest constraint for the massive deployment and maintenance of these devices [2]. Different solutions have been proposed regarding the power supply problem. Besides cutting down the power consumption for longer battery life [3], some researchers present a more ultimate solution by enabling the distributed devices to feed themselves by scavenging the energy from their ambience [4]. The ambient energy usually exists in different physical forms, such as luminous, mechanical, thermal energies, etc. The transducers are key components for transforming these ambient energy into electricity.

For harvesting the kinetic energy from mechanical vibrations, three sorts of electromechanical transducers are mostly used: the electromagnetic [4], electrostatic [5], and piezoelectric [6], [7] transducers. Among the energy harvesting systems constructed by these transducers, the piezoelectric ones have relative simple mechanical structure and easy-to-process output voltage. The output ac power from a piezoelectric transducer can be easily converted into usable dc power by using a full-wave bridge rectifier, which sets the baseline for power evaluation and, therefore, is regarded as the standard energy harvest (SEH) circuit. On the other hand, given the capacitive output impedance of piezoelectric transducers, various circuits have been designed to compensate the capacitive reactance, such that to reduce the reactive power. Yet, different from the power factor correction (PFC) solutions in conventional power electronics, where the waves are discussed under a specific harmonic case, vibration sources in the real world are features as broadband, sporadic, or even stochastic. To reduce the reactive power in piezoelectric energy harvesting (PEH), some running PFC solutions were proposed. The most extensively investigated one is called synchronized switch harvesting on inductor (SSHI) [7]. In these running PFC circuits, the power conditioning is not based on frequency-domain characteristics, but refer to every time-domain current zero-crossings.

This paper introduces the design of a Bluetooth wireless sensor node with an emphasis on its running PFC power conditioning. The acceleration record of a vibrating bridge from an open date repository is used to excite the piezoelectric harvester. The benefit of the SSHI circuit, as a kind of running PFC solutions, as well as the power analysis for the entire system are discussed in detail.

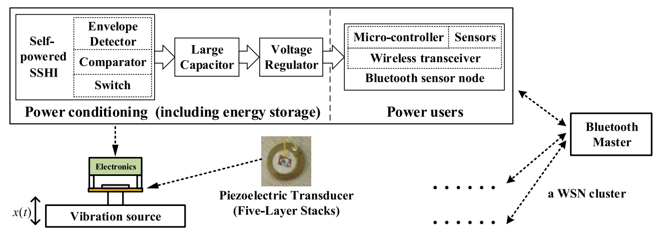
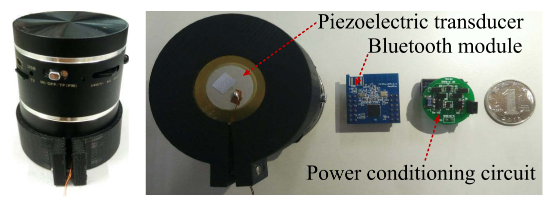


Fig. 1. Configuration of the proposed Bluetooth WSN node.



(a) (b)

Fig. 2. Prototype of the vibration-powered Bluetooth WSN node. (a) The resonant speaker simulating the bridge vibration. (b) The piezoelectric transducer, power conditioning circuit, and Bluetooth module.

II. System Overview

Fig. 1 shows the configuration of the proposed Bluetooth wireless sensor node, while Fig. 2 shows its prototype. The piezoelectric transducer is made of five stacked low-cost piezoelectric buzzers. The center of the buzzers is bonded on the vibration source for receiving the mechanical excitation, while its periphery supports the electrical parts of the system, which, at the same time, also acts as the proof mass. In this study, the vibration is produced by a resonant speaker, which simulates the vibration of a real bridge. The excitation signal is downloaded from the EH Network Data Repository [8].

Under the aforementioned excitation, the piezoelectric transducer outputs an irregular fluctuating voltage, common ac-to-dc rectifier can be connected for converting the voltage into dc, in order to power the digital electronics. In the commercialized LTC3588-1 (Linear Technology Co.), which is an IC specified for the energy harvesting application, a bridge rectifier is utilized to make the rectification. In this design, a self-contained SSHI interface circuit is adopted before the rectifier. It makes the output voltage in phase with the piezoelectric internal current source, which is similar to realize the running PFC function over a wide range of excitation fluctuation. The harvested energy is stored in a large capacitor, regulated to 3.3 V CMOS voltage, such that to power the microprocessor control unit (MCU), Bluetooth transceiver, and sensors.

III. Power Conditioning

The piezoelectricity can be mathematically described by two constitutive equations linking the mechanical and electrical parameters [6], i.e.,

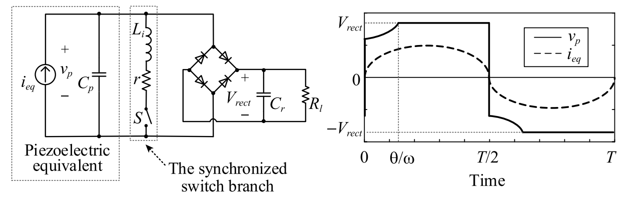
$$f = Kx + \alpha_e v_p \,, \tag{1}$$

$$i_p = \alpha_e \dot{x} - C_p \dot{v}_p \,, \tag{2}$$

where f, x, v_p, and i_p denote the force, displacement, voltage, and current of the piezoelectric transducer; $\dot{x}$ and $\dot{v}_p$ are the derivatives of x and v_p; K, α_e, and C_p donate the short circuit stiffness, force-voltage coupling factor, and clamped capacitance, respectively. Eq. (1) describes the inverse piezoelectric effect, i.e., the introduction of an additional mechanical force resulting from the applied voltage across its electrodes; (2) describes the direct piezoelectric effect, i.e., the generation of an equivalent current because of the mechanical movement. The equivalent current is usually denoted as follows

$$i_{eq} = \alpha_e \dot{x} \,. \tag{3}$$

When neglecting the backward mechanical effect caused by the connected circuit, (2) and (3) lead to the simplified piezoelectric equivalent, which is commonly used for circuit designers. The equivalent model is composed of an equivalent current source i_{eq} in parallel with the piezoelectric capacitance C_p, as shown in Fig. 3(a). Given the capacitive output impedance of the piezoelectric transducer, reactive power is observed when bridge rectifier is used for rectification [6]. PFC is necessary for enhancing the power conversion efficiency in the PEH system.



(a) (b)

Fig. 3. The parallel-SSHI power conditioning circuit. (a) Topology. (b) The voltage and current waveforms under harmonic excitation.

A. The synchronized switch solution for running PFC

The conventional PFC technology deals with periodic voltage and current. Solutions are usually derived based on the frequency-domain principle. However, periodicity is not the necessary case for most mechanical vibrations in the real world. Given these practical feature, the PFC for the specific PEH application is all realized by taking time-domain maneuvers. Such time-domain operation is possible because, generally speaking, mechanical structures response much slower than electrical circuits. Therefore, manipulation of the piezoelectric voltage v_p can be rapidly carried out at every zero-crossing instant of the equivalent current i_{eq}. To distinguish this PFC like power conditioning from the conventional technology, we call these solutions *running PFC*.

The SSHI interface circuits are the most extensively investigated power conditioning solutions realizing the running PFC. Fig. 3(a) shows the circuit topology of the parallel version SSHI (P-SSHI) and Fig. 3(b) shows the typical operating waveforms under harmonic excitation. By adding an inductive switching branch in parallel to the input of an ordinary bridge rectifier, it is able to change the voltage sign whenever the current crosses zero. The circuit branch is composed of an inductor, whose inductance is L_i and equivalent series resistance (ESR) is r, and a bidirectional switch S. The bidirectional switch S is open most of the time. Only at the zero-crossing instants of the equivalent current i_{eq}, e.g., the 0, $T/2$, and T instants in Fig. 3(b), it closes for half of an LC cycle

$$\Delta t = \pi \sqrt{L_i C_p} \,, \tag{4}$$

such that to activate the transient of the C_p-L_i-r-S loop. After the transient connection, the voltage across the piezoelectric transducer v_p will be changed from the rectified voltage V_{rect} to γV_{rect}, or from $-V_{rect}$ to $-\gamma V_{rect}$, where

$$\gamma = -e^{-\frac{\pi}{2Q}} \tag{5}$$

is a negative number called the *inversion factor*. The inversion factor is only related to the quality factor Q of the under-damped C_p-L_i-r-S circuit. By instantaneously change the sign of v_p along with that of i_{eq}, no matter i_{eq} is a harmonic function or not, their product, i.e., the power extracted from the equivalent current source, is always positive. Moreover, such synchronized switch actions also boost the magnitude of v_p and increase the harvested power [6], [7].

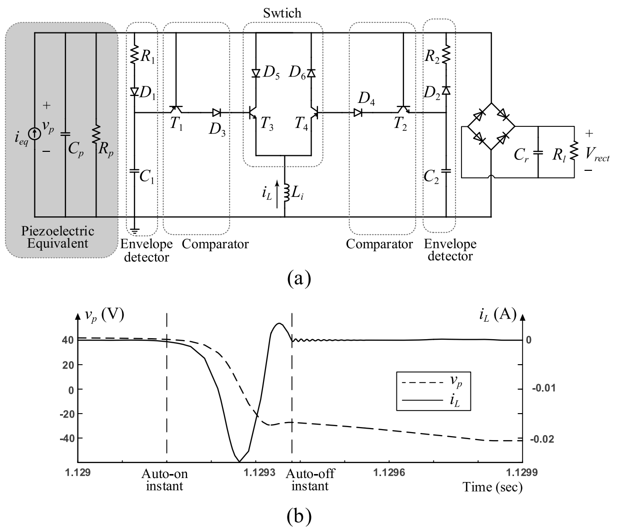


Fig. 4. Self-contained SSHI interface circuit for running PFC. (a) Circuit topology. (b) Simulation waveforms at a voltage inversion instant.

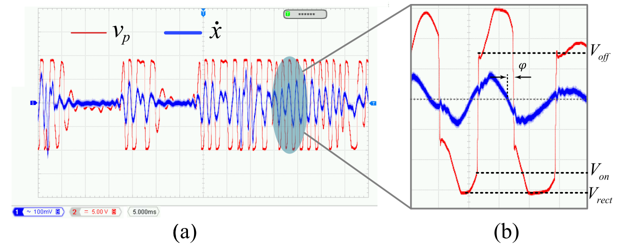


Fig. 5. (a) The voltage v_p and vibration velocity $\dot{x}$ under the simulated vibration. (b) An enlarged snapshot.

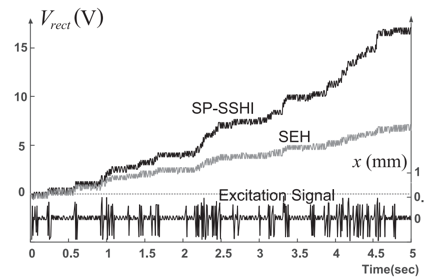


Fig. 6. Comparison of SEH and SP-SSHI interface circuits for charging the same filter capacitor C_r under the same vibration excitation.

B. The self-contained implementation

Three functions are necessary for implementing SSHI, i.e., to sense the equivalent current, compare the current with zero, and control the switch action. In most of the early researches, these functions were realized by using velocity or displacement sensor for sensing, op-amp comparator for signal comparison, and MCU for switch control [7]. These functional blocks usually require extra power supply, which hinder the practical application of SSHI. To overcome such restriction, Lallart and Guyomar proposed the self-powered SSHI (SP-SSHI) [9]; and Liang and Liao improved the circuit and provided a detailed design formula [10].

The self-contained SSHI circuit used in this study is a parallel modification based on the series-SSHI circuit introduced in [10]. The circuit topology is shown in Fig. 4(a). The circuit can be divided into three functional blocks: the envelope detectors, comparators, and switches. Compared with the series version, the parallel one has an independent rectifier branch, which increases the reliability against the switch problem. On the other hand, the parallel version enables larger output voltage across the storage capacitor, which implies a larger amount of backup energy in a long run. The sensing function is realized by the piezoelectric transducer itself. As v_p is proportional to the integral of i_{eq}, the zero-crossing instants of i_{eq} is the same as the maximum or minimum instants of v_p. The v_p extreme values detection is made by using the envelope detectors, which are composed of R_1, D_1, and C_1 for the maximum envelope, and R_2, D_2, and C_2 for the minimum. The transistors T_1 and T_2 act as two comparators comparing the voltage of v_p and its envelope. Once v_p attains its extreme values and begin to turn over its increasing or decreasing trend, the corresponding transistor conducts. The output of the comparator will drive the corresponding transistor switch T_3 or T_4 for turning on the switching path for the inductor L_i, such that to automatically start the voltage inversion process. Fig. 4(b) shows the simulation waveforms in a positive-to-negative voltage inversion. The current flows through L_i, then v_p drops across zero accordingly until it attains its transient minimum. At this point, the current through L_i tends to reverse its flowing direction. But it is blocked by the diode D_5. Then the voltage inversion ends.

The detailed working principle of the SP-SSHI interface circuit can be referred to [10]. The inversion of v_p on its extreme values is not confined for harmonic cases; therefore the SP-SSHI can be used in irregular vibration and realize the running PFC. Fig. 5 shows the v_p and $\dot{x}$ waveforms under the simulating bridge vibration. Since the vibration signal is from a real bridge, which was excited by some moving vehicles, it is sporadic and irregular. From the overview in Fig. 5(a), v_p can follow the sign change of $\dot{x}$, which is proportional to the equivalent current i_{eq},[1] except that there is a small phase lag φ in between the $\dot{x}$ zero-crossing and the inversion instant, as observed in the enlarged snapshot in Fig. 5(b). Such phase lag is inevitably caused by the voltage gap enabling the extreme value detection [10]. It is reduced under higher voltage ouput.

Fig. 6 compares the performances of two circuits SP-SSHI and SEH for charging the same capacitor, as the energy storage, under the same vibration excitation. It shows that the rectified voltage V_{rect} in SP-SSHI after the five-second charge is about 2.5 times of that in SEH, which means the harvested energy is increased by five times by using this running PFC. The average harvested powers of SP-SSHI and SEH are about 289 μW and 49 μW, respectively.

[1] Since i_{eq} is a small current inside the piezoelectric transducer, it is unable to be measured. In experiment, the vibration velocity $\dot{x}$ is measured with a laser vibrometer instead for the evaluation.

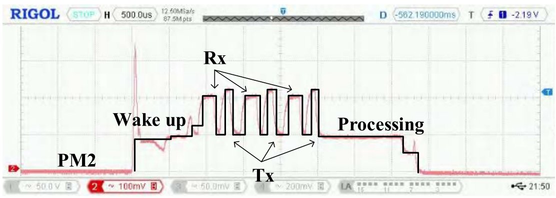


Fig. 7. The current history of the Bluetooth module in a transmission event (sampled by a 10 Ω resistor).

C. Voltage regulator

The SP-SSHI has converted the alternating power output from the piezoelectric transducer into the storable potential energy and keep it in a large filter capacitor C_r. Yet, the rough dc voltage cannot be directly used to power digital modules. A regulator is necessary for stabilizing the output voltage to a specific logic level for driving the user modules. In this design, the power management IC LTC3588-1 is utilized to regulate the output voltage at 3.3 V logic level. LTC3588-1 is specifically designed for the PEH application. It integrates a low-loss bridge rectifier and a high efficiency buck converter. It has a protection to ensure the input voltage to be lower than 20 V, so as to prevent the chip damage.

IV. The Bluetooth and sensing module

A Bluetooth sensor module is connected to the output of LTC3588-1 for fulfilling the wireless temperature sensing. The Bluetooth sensor node has two working stages: the connection and matching stage, and sensing and transmission stage. The digital modules and the voltage regulator are not necessarily to keep active all the time. They are turned off or put into low power mode for cutting down the overall power consumption in between two active stages.

A. Power analysis

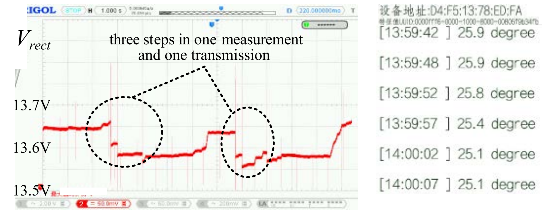
A 10 Ω current sampling resistor is connected in series for evaluating the power consumption. Fig. 7 shows the operating current during a transmission event. The system wakes up from the low power mode (PM2). After performs three-package handshake (Rx and Tx) to ensure the veracity of communication, it processes and transmits the data. The average power consumption in this specific event can be estimated as follows

$$\bar{P} = \frac{V_s \sum_{n=1}^{N} (\bar{i}_n \Delta t_n)}{\sum_{n=1}^{N} \Delta t_n}, \tag{6}$$

where V_s is the supply voltage (3.3 V in this design), Δt_n and $\bar{i}_n$ denote the duration and average current in each interval, respectively. With this formula, the average power in the connection and transmission stages are about 79 μW and 103 μW, respectively. The sleeping period are set to 2 sec and 5 sec for the two stages, in order to reduce the power consumption.

B. Performance

According to the feature of LTC3588-1, the regulator is activated to output a steady 3.3 V voltage when V_{rect} is above 5 V, then the Bluetooth module begins to operate.



(a) (b)

Fig. 8. Operation of the system. (a) The variation of storage voltage V_{rect} in one measurement and transmission. (b) Messages received by the master device.

After the initialization and matching, the MCU measures the temperature and transmits to the master device every five seconds. The waveform of V_{rect} and the received information by the master node are illustrated in Fig. 8. From the figures, the power consumption of the system is estimated at about 121 μW, which approximates to the analysis. In general, the harvested power is enough for implementing the sensing and wireless transceiving functions in this simulated scenario.

V. Conclusion

This paper has introduced the design and implementation of a vibration-powered Bluetooth wireless sensor node, with an emphasis on its running PFC power conditioning, which was realized by the SP-SSHI interface circuit. The self-contained solution has eliminated the reactive power and increased the harvesting capability. Evaluation on the power consumption of the Bluetooth module has proved the feasibility of this design towards batteryless remote sensing applications.

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