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# Self-Powered Electronics for Piezoelectric Energy Harvesting Devices

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Yuan-Ping Liu and Dejan Vasic

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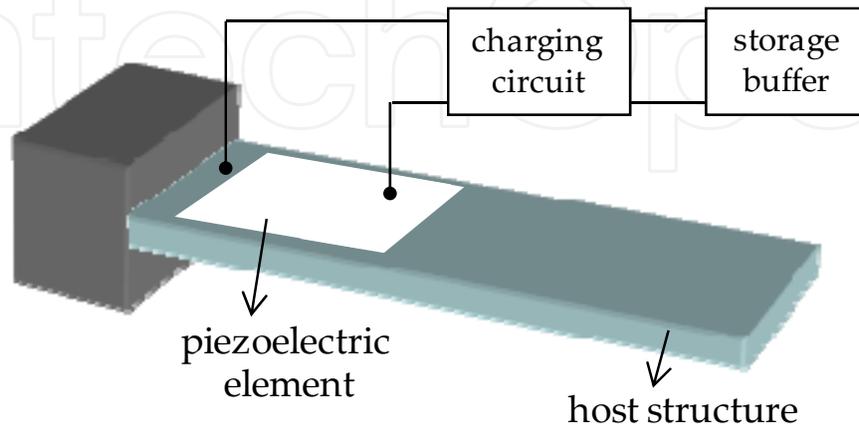
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## 1. Introduction

According to the piezoelectric direct effect, piezoelectric material can generate electrical energy from a mechanical vibration. To collect the energy, a piezoelectric element is attached on a vibrating structure, and an interface circuit is connected to the piezoelectric element to transfer the generated energy to the load. If the collected energy is dissipated by Joule effect in a resistive load, the vibration of the structure will be reduced. This is called structural passive shunt damping [1]. If the collected energy is stored in a capacitor or a battery, an energy recovery system is obtained. Piezoelectric energy harvesters (PEH) have emerged as a prominent theme of researchers whose interest is growing. The advances in low-power components or design methodology have reduced the power consumption of mobile devices, and therefore allow the feasibility of self-powered autonomous electronic devices. This opens the possibility for completely self-powered devices, and the notion of small generators producing enough power for low-consumption devices, like wireless sensor network (WSN). Ambient vibrations are presented in many different environments such as automobiles, buildings, structures (bridges, railways), industrial machinery, etc. Since 2002, numerous studies have been published on the topic of the energy harvesting. Tang et al. [2] and Khaligh et al. [3] made a long synthesis and developed a state of the art for vibration piezoelectric energy harvester. It demonstrates the interest of researchers in this topic. Moreover, piezoelectric materials have high power density [4]. The power density of the piezoelectric generator harvested the energy from vibrations is about  $250 \mu\text{W}/\text{cm}^3$ . In comparison, the power density of the electrostatic generator that harvested energy from vibrations is only about  $50 \mu\text{W}/\text{cm}^3$ . The vibration-to-electricity convertor can be also performed by electromagnetic transducers [5, 6], but the power density cannot be high as the piezoelectric generator. Piezoelectric technologies have received much attention, as they have high electromechanical coupling and no requirement of the external voltage source.

Figure 1 shows the configuration of piezoelectric energy harvesting system. A piezoelectric element is attached on a host structure and a charging circuit is connected to the piezoelectric elements. The piezoelectric elements convert the vibration energy of the host structure into electrical energy, and then the generated electrical energy is stored in a storage buffer. The voltage generated across the piezoelectric element is an AC voltage, so the basic charging circuit is an AC/DC converter or said a rectifier.



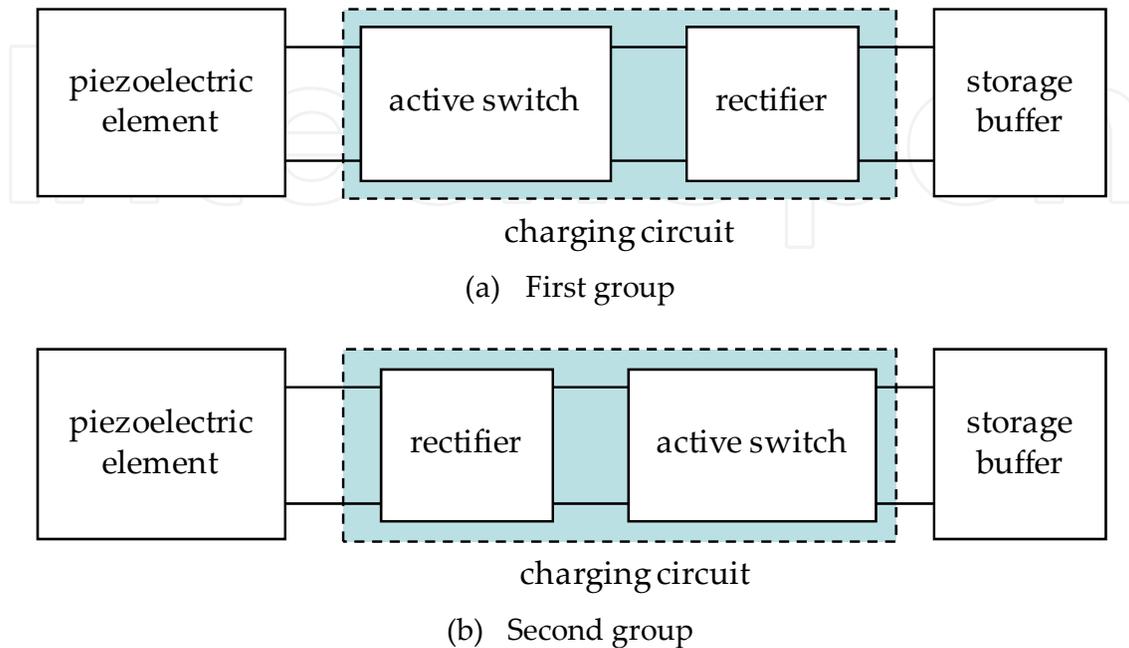
**Figure 1.** Configuration of piezoelectric energy harvester

Since the piezoelectric element has large clamped capacitance, an impedance matching circuit is required to maximize the generated power. It was known that an inductor can be added to compensate the contribution of the piezoelectric clamped capacitor, but it cannot be adaptive to the environmental variations and the value of the inductance is too large in a low frequency range. To overcome this drawback, switching-type charging circuits were proposed and popularly used in recent years. In the switching circuits, the switches are operated synchronously with the vibration of the host structure in order to optimize the power flow.

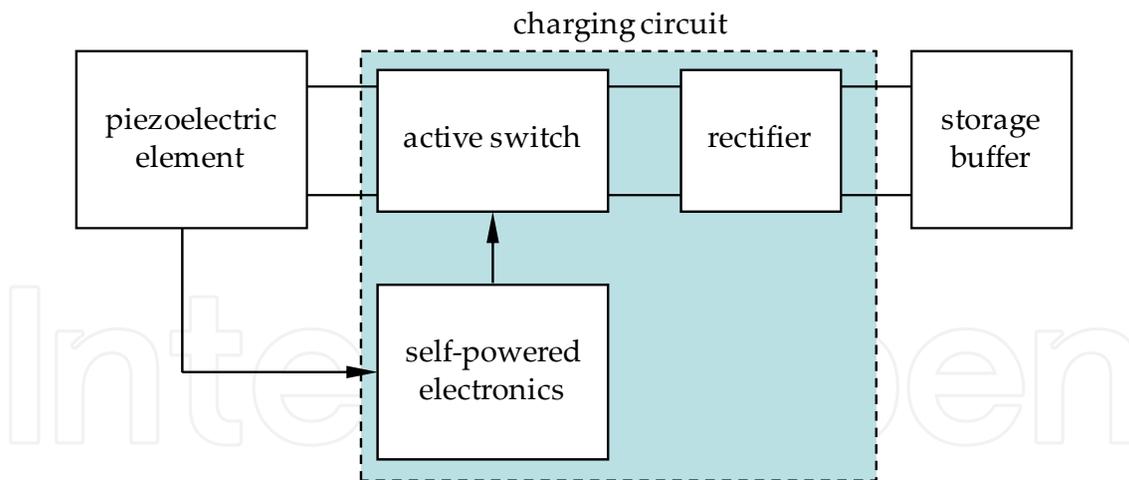
Several synchronized switching circuit topologies and corresponding switching laws were proposed. They can be classified into two groups according to the placement of the rectifier and the active switches, as shown in Fig. 2. The first group of the switching circuits places the switches between piezoelectric element and the rectifier, such as parallel-SSHI (Synchronized Switching Harvesting on an Inductor) and series-SSHI [7-17]. This group of techniques is used to modify the waveform of the piezoelectric voltage, *i.e.* the voltage across the piezoelectric element, in order to increase the collected power in the weakly coupled structure. The second group places the switches between the rectifier and the storage buffer, such as SSDCI [18]. This group of the techniques is used to modify the charging current flowing into the storage buffer in order to fasten the charging speed [19] and to make a load adaptation.

Although the synchronized switch techniques can increase the collected energy or charging speed, they also require energy to supply active components. Therefore, it is of interest to achieve totally self-powered interfaces. In fact, in all switching techniques, the operation principles of the active switches are similar. In most of the time, the switches are cut-off. The

switches only conduct at the local extreme values of the displacement or at the zero-crossing values of the velocity. In other words, there should be a control loop to measure vibration and then control the switching action. Figure 3 shows this control loop with the self-powered electronics.



**Figure 2.** Two groups of charging circuits



**Figure 3.** Piezoelectric energy harvester with self-powered synchronized switching techniques

In energy harvesting device, there are four parts that influence the performances, including 1) piezoelectric material properties, 2) configuration of the host structures, 3) charging circuit topologies and 4) storage buffers. In this chapter, we will only focus on the design of the charging circuit, especially on the self-powered electronics. The SSHI techniques will be used as a targeted circuit to add the self-powered function since it is easy to implement and owns high efficiency. We will neglect the massy theory of synchronize switching techniques, but focus on the operation principle of the self-powered charging circuit.

## 2. Synchronized interface circuit of piezoelectric harvester

### 2.1. Equivalent circuit of piezoelectric harvester

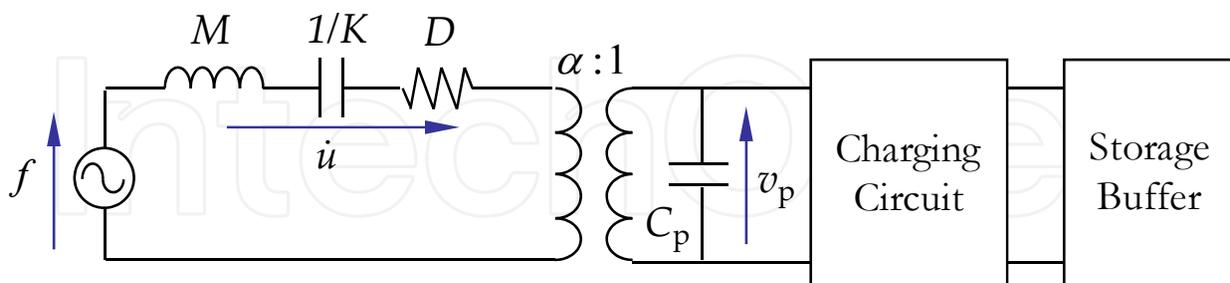
The piezoelectric energy harvester (PEH) consists of a piezoelectric elements bounded on a host structure. A mechanical model based on a spring–mass system gives a good description of the vibration behavior near the resonance of the host structure. Therefore, for simplicity, this system can be modeled as a one degree-of-freedom system of a mass  $M$ , a spring  $K$  and a damper  $D$ . Assuming the system is operated in the linear region, the differential governing equation of this electromechanical system can be expressed as equations (1) and (2):

$$M\ddot{u} + D\dot{u} + Ku + \alpha v_p = f \quad (1)$$

$$\dot{i}_p = \alpha\dot{u} - C_p\dot{v}_p \quad (2)$$

where  $f$  is external force exerted on the host structure,  $i_p$  is outgoing current generated from the piezoelectric element,  $\alpha$  is force-voltage coupling factor,  $C_p$  is the clamped capacitance of the piezoelectric element,  $v_p$  is piezoelectric voltage, *i.e.* the voltage across the piezoelectric element and  $u$  is the displacement of the host structure. The piezoelectric element generates AC voltage from the vibration. To store the energy in the DC form, a rectifier, *i.e.* AC/DC converter is required to connect the storage buffer at the piezoelectric element. Equations (1) and (2) are linear equations, but the rectifier is a non-linear circuit and it is not easy to analyze. To make the analysis more intuitive, we adopt the concept of equivalent circuit in this chapter.

According to equations (1) and (2), the equivalent circuit of the PEH can be illustrated in Fig. 4. It should be noted that force  $f$  and velocity  $u$  are equivalent to a voltage source and a flowing current in the mechanical impedance respectively.



**Figure 4.** Equivalent circuit of the piezoelectric energy harvesting system

To calculate the generated power, the analysis is simplified by two basic assumptions:

1. The piezoelectric element and host structure are given, so the transformation ratio  $\alpha$  is a constant;
2. The displacement  $u$  is sinusoidal at the specific frequency.

Therefore, the displacement  $u$  and velocity  $\dot{u}$  can be represented as:

$$u = U_M \sin \omega t \quad (3)$$

$$\dot{u} = \omega U_M \cos \omega t \quad (4)$$

where  $u$  is the velocity of the host structure,  $U_M$  is the amplitude of the displacement,  $\omega$  is the angular frequency of the host structure, and  $t$  represents time parameter. Considering the simple case when the shunt circuit is only composed of passive components first, *i.e.* resistors, capacitors and inductors, the voltage across the piezoelectric element  $v_p$  will be also sinusoidal as shown in equation (5).

$$v_p = V_p \cos(\omega t - \theta) \quad (5)$$

where  $V_p$  is the amplitude of the piezoelectric voltage  $v_p$  and  $\theta$  is the phase difference between the velocity  $u$  and the piezoelectric voltage  $v_p$ . The generated power can be obtained by multiplying piezoelectric voltage  $v_p$  and vibration velocity  $u$ . Applying the equations (4) and (5), the average power  $P_m$  generated from the piezoelectric element can be expressed as:

$$P_m = \frac{\alpha \omega U_M V_p}{2} \cos(\theta) \quad (6)$$

Equation (6) obviously shows the factor which can influence the generated power. In the case of constant velocity, *i.e.*  $\omega U_M$  is a constant, the power is determined by the amplitude of the piezoelectric voltage  $V_p$  and the phase angle  $\theta$ . Actually, the amplitude of the piezoelectric voltage  $V_p$  and the phase difference  $\theta$  are determined by the characteristics of the connected circuit. When the impedance of the connected circuit is zero (short circuit), the piezoelectric voltage is zero. There is no power flow out of the piezoelectric element. When the impedance of the connected circuit is infinite (open circuit), the velocity and the piezoelectric voltage have  $90^\circ$  phase difference due to the capacitor  $C_p$ . There is no power flow out of the piezoelectric element as well. These two critical cases both cannot output any power from the piezoelectric element but the fundamental reasons are not the same. Actually, if the phase difference is not zero, the power generated from piezoelectric material may not only flow from the piezoelectric material to the connected circuit, but may also flow in the opposite direction. To obtain the largest power from the piezoelectric element, high piezoelectric voltage  $V_p$  and zero phase difference ( $\theta = 0$ ) are both required [19].

It should be noted that above analysis is based on the assumption that vibration velocity  $u$  is a constant value. However, the vibration velocity is not independent of the piezoelectric voltage. According to the equivalent circuit in Fig. 4, the velocity can be expressed as:

$$\dot{u} = \frac{f - \alpha v_p}{Z_L} \quad (7)$$

where  $Z_L$  is the mechanical impedance, *i.e.*

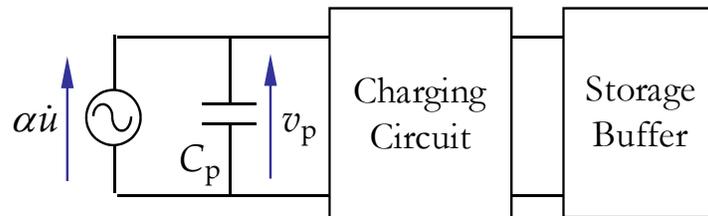
$$Z_L = \sqrt{(K - M\omega^2)^2 + (D\omega)^2} \quad (8)$$

It can be seen that the vibration velocity may decrease with increasing voltage in Eq. (7). We would like to connect an impedance matching circuit to collect more electrical energy, but the vibration energy may be suppressed. Finally, we may not collect more power from the piezoelectric element. Hagood et al. [1] used this effect to increase the structural damping, which was called piezoelectric shunt damping. However, it is not desired case in the piezoelectric energy harvester.

To avoid the influence of the piezoelectric voltage on the vibration, the force coupling factor  $\alpha$  should be sufficient small. With this condition, equation (7) can be re-written as:

$$\dot{u} = \frac{f}{Z_L} \quad (9)$$

Accordingly, the piezoelectric voltage is independent of the vibration velocity. This means that the energy extraction from the piezoelectric element does not disturb the vibration behavior of the structure and the magnitude of the velocity can be viewed as a constant value. Therefore, with the weakly coupling assumption, the equivalent circuit can be further simplified as shown in Fig. 5, where the velocity magnitude  $\omega U_M$  is a constant.



**Figure 5.** Equivalent circuit of the low-coupled piezoelectric energy harvester

The weakly coupling assumption is reasonable when the strain energy of the host structure is much larger than that of the piezoelectric element. Shu et al. [21] gave a more clear definition of the weakly coupled structure, that:

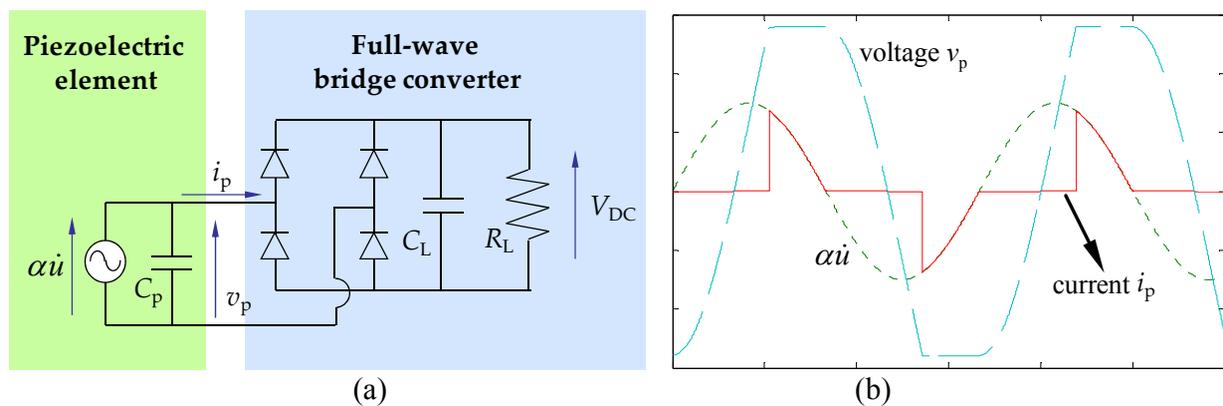
$$\frac{k^2}{\zeta} = \frac{\omega_0^2 - \omega_s^2}{\zeta \omega_s^2} \ll 1 \quad (10)$$

where  $\zeta$  is the damping ratio of the host structure and  $k$  is the electromechanical coupling factor.  $\omega_0$  and  $\omega_s$  are open-circuit resonant frequency and short-circuit resonant frequency of the host structure respectively. Piezoelectric microstructure is weakly coupled since the product of the thickness of piezoelectric element and its Young's modulus is very small compared to the base material. Actually, only a small amount of mechanical energy is taken from the structure and converted into electricity in the low-coupled structure. The synchronized switching techniques increase the piezoelectric voltage and also put piezoelectric voltage in phase with the constant velocity. This is the underlying reason that

the power out of the piezoelectric element can be increased in synchronized switching techniques. In another viewpoint, synchronized switching techniques are also equivalent to increase the coupling factor of the weakly coupled structure.

## 2.2. Operation principle of synchronized switching techniques

The standard interface circuit of the PEH is a full-wave bridge rectifier. It converts AC voltage to DC voltage for storage buffers, such as batteries. The schematic diagram of the full-wave bridge rectifier is shown in Figure 6(a). Figure 6(b) shows the waveforms of standard DC approach. When the absolute value of the piezoelectric voltage  $v_p$  is less than load voltage  $V_{DC}$ , the diode bridge is in the open-circuit state and the clamped capacitor  $C_p$  is charged or discharged. Once the absolute value of the piezoelectric voltage  $v_p$  reaches load voltage  $V_{DC}$ , the diodes conduct and piezoelectric elements charge the storage buffer. Accordingly, the current  $i_p$  is flowing to the load discontinuously and the velocity  $\dot{u}$  is not in phase with the piezoelectric voltage  $v_p$ , so the full-wave bridge rectifier is not an efficient solution for the PEHs.



**Figure 6.** (a) Equivalent circuit and (b) waveforms of the piezoelectric element connected to full-wave bridge rectifier

To improve the efficiency of the energy conversion, Guyomar et al. proposed the SSHI techniques (synchronized switching harvesting on an inductor) [9, 11]. Figure 7 shows two types of SSHI techniques: series-SSHI and parallel-SSHI. Figure 8 shows the corresponding key waveforms. In SSHI techniques, a bi-directional switch  $Q$  and an inductor  $L$  are added in series or in parallel with the piezoelectric element. In most of the time, the switch  $Q$  is in open circuit state. When the local extreme displacements or zero vibration velocities occur, the switch is conducted in a very short period. In this short period, the clamped capacitor  $C_p$  makes the resonance with the inductor  $L$  and the piezoelectric voltage  $v_p$  inverses. Accordingly, the SSHI circuit increases the magnitude of the piezoelectric voltage and puts piezoelectric voltage  $v_p$  in phase with the vibration velocity, which indicates that more energy is extracted from the vibration source. The results also show that the energy stored in the clamped capacitor  $C_p$  is extracted by the LC resonance circuit and thus the piezoelectric voltage can be increased [22, 23]. The SSHI technique is equivalent to enlarge the coupling factor in the weakly coupled structure [21]. There are several synchronized switching

techniques derived from SSHI techniques, such as DSSH [24]. These derived techniques still need a pulse signal which is synchronized with the vibration to drive the switches. However, obtaining this synchronized signal consumes the energy. In some cases, the energy used in the synchronized circuit may be larger than the increasing energy by the SSHI technique. So, it is of interest to design an efficiently self-powered synchronized circuit.

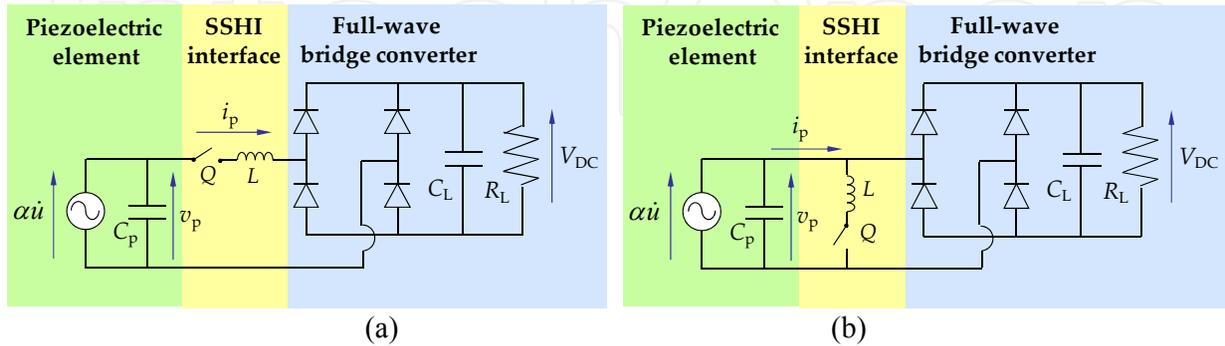


Figure 7. Equivalent circuit of (a) series-SSHI converter and (b) parallel-SSHI converter

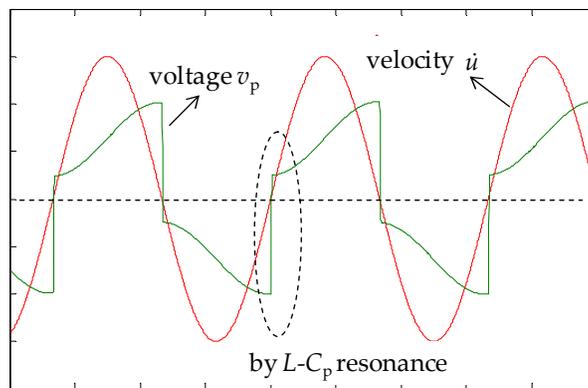


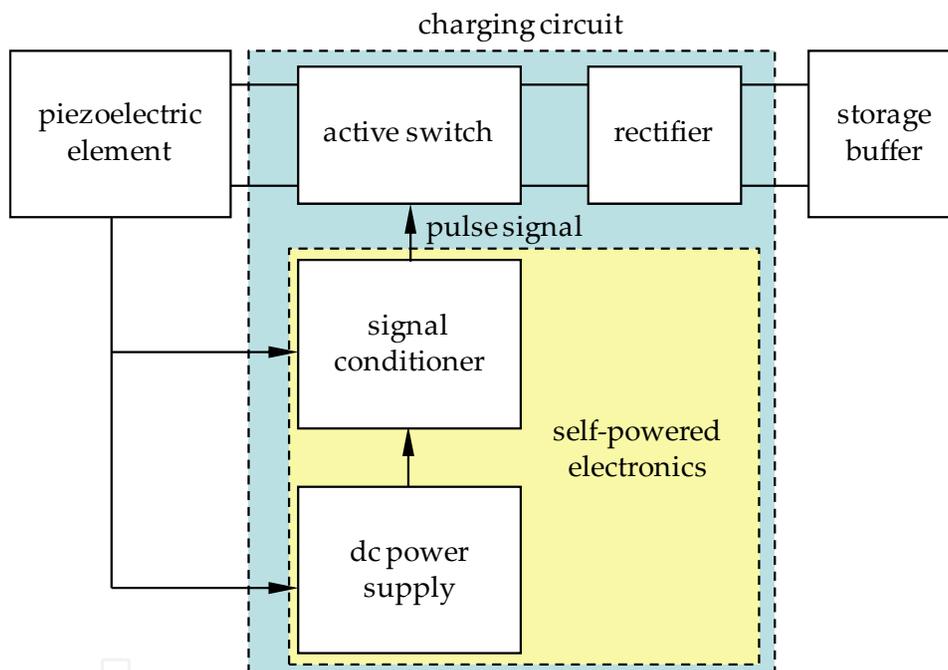
Figure 8. Key waveforms of SSHI converters

Both series-SSHI and parallel-SSHI techniques are efficient and easy to implement, but they are different from the viewpoint of the self-powering. The main difference is the magnitude of the outgoing current, *i.e.*  $i_p$  in Fig. 7. In the series-SSHI converter, the current  $i_p$  is mostly equal to zero since the switch  $Q$  is cut-off. The current  $i_p$  is only flowing when the switch  $Q$  is conducted at the local extreme displacements. On the contrary, in the parallel-SSHI converter, the switch  $Q$  is not in the current path between the piezoelectric element and the rectifier, so the outgoing current  $i_p$  flows to the load in most of the time. This basic characteristic will influence the self-powered loop design in the following section.

### 3. Self-powered electronics for synchronized switching

In fact, the standard full-wave bridge rectifier is a passive design, so it can be viewed as fully self-powered interface. However, the full-wave rectifier is not efficient in the

weakly-coupled structure, and the synchronized switching circuits are usually used in PEH. These switching circuits require a switching control signal. In Fig. 3, it was shown that there should be an extra control loops to generate this control signal. Figure 9 shows more detail about configuration of the self-powered PEH. It can be seen that a self-powered charging circuit includes three parts: 1) a main synchronized switching converter, including active switches and a rectifier, 2) a signal conditioner to generate the control signal for the switching circuit, and 3) a DC power supply for the active electronics. The main switching converter in this section is the SSHI converter, which has already mentioned in last section. Therefore, the key point of this section is the signal conditioner and the DC power supply. The signal conditioner should be able to sense the vibration behavior and provide the corresponding real-time signal. In this section, we will start from the sensing signal and then extend it to the design rule of the practical self-powered electronics.

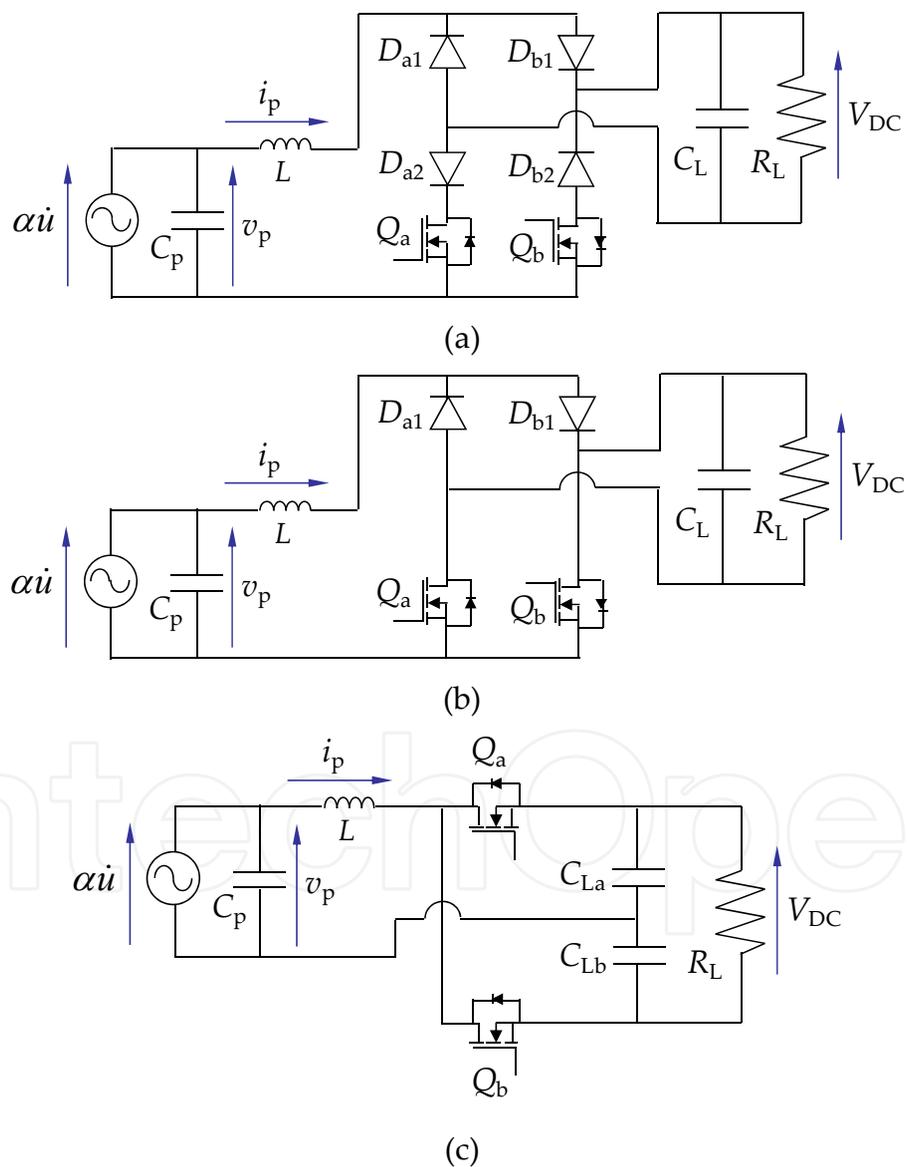


**Figure 9.** Configuration of self-powered electronics

### 3.1. Modified SSHI circuit for Low-voltage drop

Considering the micro-scale PEH, the piezoelectric voltage is typically below 5V [25]. In such a low voltage, the diode voltage drops becomes a series problem. In the original SSHI technique, it owns totally six diodes (Fig. 7) in the implemented circuit, including two diodes in the bi-directional switch and four diodes in bridge rectifier. It means that each current path includes three diode voltage drops. It is a significant voltage drops in the micro-scale PEH. Figure 10(a) shows the modified series-SSHI which owns lower voltage drops. In this design, the bi-directional switch is embedded into the bridge rectifier by using the body diode of the MOSFET. In fact,  $D_{a2}$  and  $D_{b2}$  in Fig. 10(a) are possible be further neglected as shown in Fig. 10(b) and there are only 2 diodes in the SSHI converter

[26]. The operation principles of the modified SSHI converters are similar as the original version. However, in four diodes design, the outgoing current  $i_p$  can be auto switched off by diodes  $D_{a2}$  and  $D_{b2}$  in the end of the SSHI process. It means that the control signal of the switches  $Q_a$  and  $Q_b$  can be a square signal but not a pulse signal, it is easier to generate square signal typically. However, in two diodes design of Fig. 10(b), the switches  $Q_a$  and  $Q_b$  requires the accurate pulse signal. Another modified Series-SSHI is presented Fig. 10(c). Half of the rectifier bridge can be replaced by the switching elements and another half of the rectifier can be replaced by the middle point filtering capacitance, allowing the removal of the diodes [27].



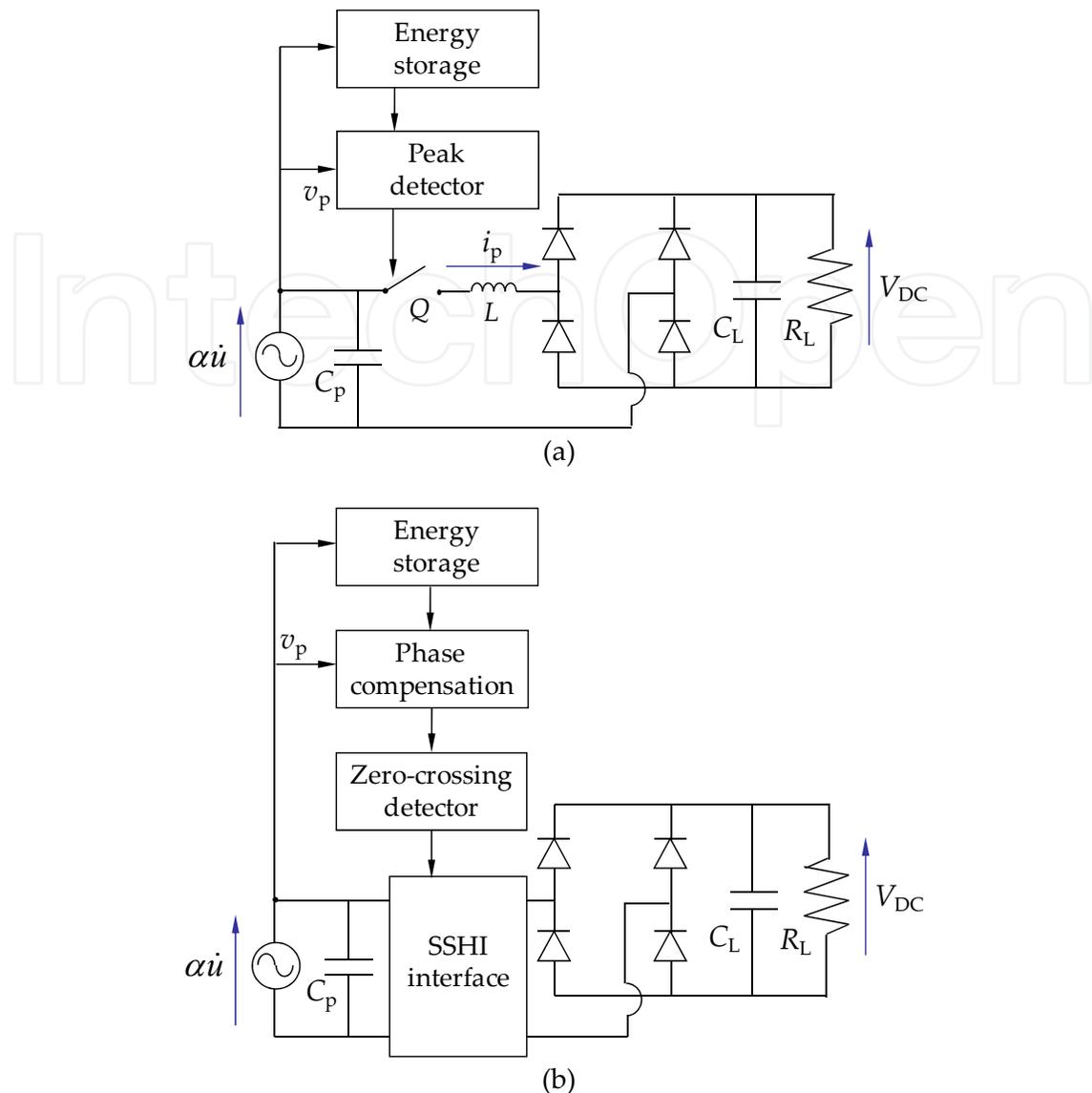
**Figure 10.** Modified series-SSHI converter with low voltage drop: (a) Four diodes design (b) Two diodes design (c) Diode-less series SSHI

### 3.2. Sensing signal

The basic concept of the self-powered issue is how to generate the switching signals synchronously with ultra-low power consumption. The SSHI techniques require the displacement or velocity signals of the host structure to control the switches. In fact, the vibration amplitude is not easily detected by displacement sensor or velocity sensor compactly. The piezoelectric element itself is the best candidate to sense the vibration. However, the piezoelectric voltage or outgoing current may not be proportional to the displacement or velocity. Equation (2) shows the relationship between the piezoelectric voltage and vibration displacement. According to Eq. (2), piezoelectric voltage  $v_p$  is only proportional to the vibration displacement  $u$  when the outgoing current  $i_p$  is equal to zero, *i.e.* the open circuit state of the piezoelectric element. Similarly, the outgoing current is only proportional to the vibration velocity  $\dot{u}$  when the piezoelectric voltage  $v_p$  is equal to zero, *i.e.* the short circuit state of the piezoelectric element. Choosing the displacement or the velocity signals as the control criterion is much different in the practical electronics design. According to the operation principle of SSHI techniques, a peak detector should be used in the displacement signal and a zero-crossing detector should be used in the velocity signal.

In series-SSHI technique, piezoelectric element is mostly in the open-circuit state. The current is only flowing when the switch is conducted. Therefore, the series-SSHI converter is a possible case that we can use the piezoelectric voltage directly to represent the displacement. However, in the parallel-SSHI technique, the current is mostly continuously flowing to the load. The piezoelectric voltage is not proportional to the displacement perfectly. The outgoing current in parallel-SSHI technique is also not proportional to the velocity because piezoelectric element is not in the short circuit state. It means that we cannot use the piezoelectric voltage or the outgoing current directly to synchronize the vibration, and there should be some compensation in the signal conditioner. Since the phase of vibration velocity is 90 degrees lag than that of the displacement, piezoelectric voltage is easier to follow the vibration velocity by the phase compensation of the electrical network.

In brief summary, there are two possible ways to make the control loops of the self-powered function. Figure 11 illustrated these two control loops with different signal conditioners. As shown in Fig. 11(a), the peak detector is more suitable for series-SSHI converter because the piezoelectric voltage is synchronized with the displacement. The peak detector also works with the parallel-SSHI converter, but the phase delay is larger. The concept of the zero-crossing detector is shown in Fig. 11(b). It can be used for both series-SSHI and parallel-SSHI techniques, but a phase compensation is necessary. To avoid the phase compensation, a second piezoelectric patch should be added. Typically, the zero-crossing detector is easier to implement by electronics, but it requires a low-pass filter to avoid the high-frequency noises when the switch of the SSHI converter is active.

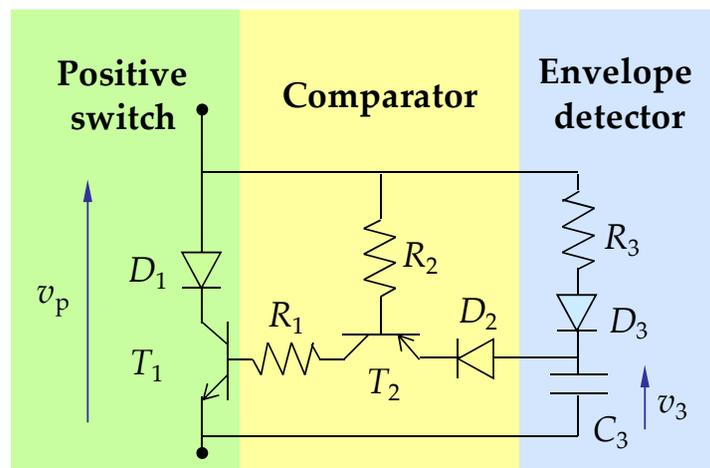


**Figure 11.** Control loops of the self-powered function in SSHI techniques (a) with a peak detector (b) with a zero-crossing detector

### 3.3. Peak detector

Figure 12 show a simple peak detector design [26-29]. It includes three parts: a switch, a comparator and an envelope detector. To easily explain the principle of operation, we assume the diodes are ideal first. In the beginning of the positive piezoelectric voltage, the capacitor  $C_3$  is charged by the piezoelectric voltage. The emitter-base polarization of the transistor  $T_2$  is reverse bias, so the transistors  $T_2$  and  $T_1$  are both blocked. The voltage on capacitor  $C_3$  is equal to the piezoelectric voltage  $v_p$  before the peak voltage, if the diode voltage drop is neglected. When the piezoelectric voltage reaches a peak value, it means that the piezoelectric voltage  $v_p$  will start to decrease. However, because there is no discharging current path for the capacitor  $C_3$ , the capacitor voltage  $v_3$  will keep the same voltage value after the peak voltage of  $v_p$ . Therefore, diode  $D_3$  is reverse bias. Once the

voltage difference between the piezoelectric voltage  $v_p$  and the capacitor voltage  $v_3$ , *i.e.* ( $v_3 - v_p$ ), is greater than the threshold voltage of  $T_2$ , the transistor  $T_2$  starts conducting. The capacitor  $C_3$  discharges through the path  $D_2$ - $T_2$ - $R_1$ - $T_1$ , and conduct the transistor  $T_1$ , which is the switch of the SSHI converter. Therefore, the piezoelectric voltage  $v_p$  starts to inverse and the outgoing current  $i_p$  starts to flow. When the outgoing current  $i_p$  reaches zero again by the  $L$ - $C_p$  resonance, the harvesting process is interrupted by the diode  $D_1$ . At the end of the harvesting process, the capacitor  $C_3$  is totally discharged. This peak detector can work both in series-SSHI converter and the parallel-SSHI converter. However, in the parallel-SSHI converter, a small voltage difference is required between the piezoelectric voltage  $v_p$  and capacitor voltage  $v_3$  to turn  $T_2$  on. In this case, the phase delay is larger and it depends on the load value. It should be noted that this peak detector only allows the current flowing in single direction in the SSHI switch. For bi-directional current, two peak detectors must be adopted.



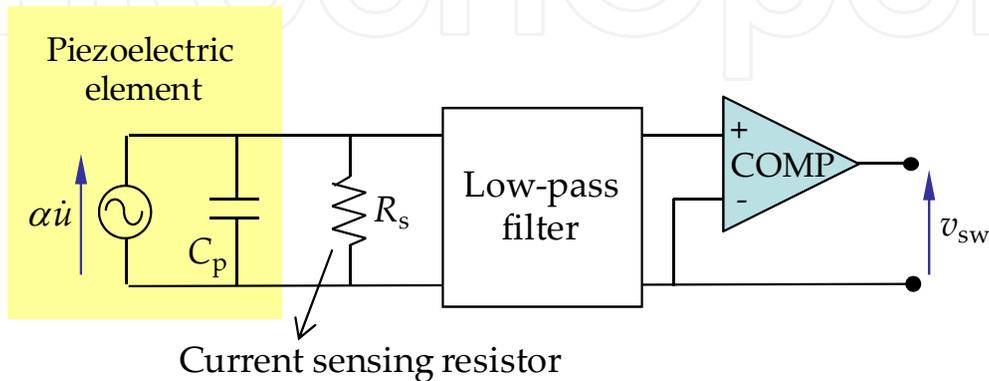
**Figure 12.** Positive peak detector for SSHI technique

### 3.4. Zero-crossing detector

Except the peak detector, another choice of the sensing circuit is the zero-crossing detector. Different from the voltage peak detector, the zero-crossing detector should detect the zero velocity or said zero equivalent current. Figure 10(b) has shown the completed system of the self-powered SSHI based on zero-crossing detector. There are three parts. First, the velocity is sensed through a conditioning circuit. Second, a comparator is required to make a zero-crossing detector in order to obtain the pulse driving signals for the switches. Third, a DC power source is required to supply the active electronics above.

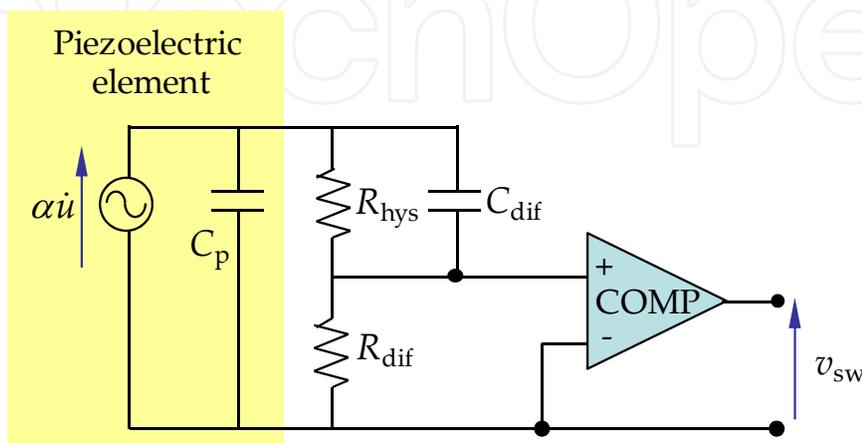
Chen et al. [15, 16] applied the velocity as the switching criterion to self-powered series-SSHI and parallel-SSHI converters, which called V-SSHI. Figure 13 shows the V-SSHI design. In Chen's design, an extra piezoelectric patch was used. A current sensing resistor  $R_s$  is connected in parallel with the piezoelectric patch and a passive low-pass filter is used to reduce the high frequency noise, introduced by the SSHI switching. The high frequency noise of the velocity signal can be very large, so it is impossible to apply the sensing signal to the

comparator directly. The current sensing resistor used herein must be small enough to neglect the effect of the piezoelectric capacitance, *i.e.*  $i_p \approx \alpha \dot{u}$ . The low-pass filter should be carefully designed to guarantee there is no phase lag. It should be mentioned that the output terminal of the comparator is a square signal but not a pulse signal, so it can only drive the SSHI-switch  $Q_a$  and  $Q_b$  in Fig. 10(a). Although the circuit topology in Fig. 10(a) owns an extra diode voltage drop compared to the circuit topology in Fig. 10(b), the peak detector in Fig. 12 also own an extra diode  $D_1$  series with the switch  $T_1$ . Consequently, there are no difference of the voltage diode drops between the peak detector and the zero-crossing detector.



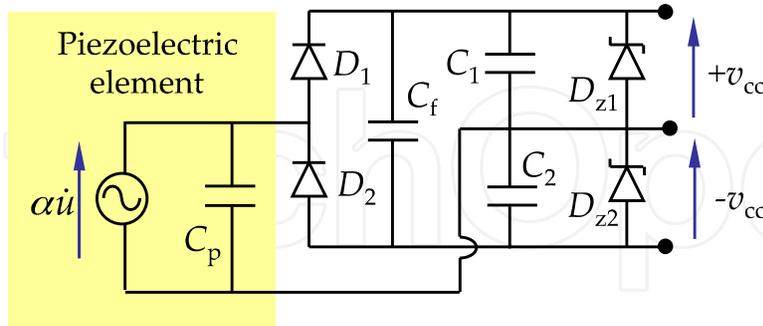
**Figure 13.** Equivalent current (velocity) sensing by a resistor and a passive low-pass filter

On the other hand, Ben-Yaakov and Krihely [30] adopted the zero-crossing detector in the self-powered rectifier for the output terminal of piezoelectric transformers. Their circuit is similar as the parallel-SSHI converter. Figure 14 shows their design of the signal conditioner. The signal conditioner consists of a passive differentiator ( $C_{dif}$  and  $R_{dif}$ ) with a hysteresis resistor ( $R_{hys}$ ) and a comparator. The passive differentiator is used to obtain the velocity signal from the piezoelectric voltage and the hysteresis resistor  $R_{hys}$  prevents undesired triggers. The output terminal of the passive differentiator and the piezoelectric reference terminal are then connected to the negative input and the positive input of the comparator respectively. Different from Chen's design, only one piezoelectric patch is used here and thus the detecting signal of the velocity has larger phase lag.



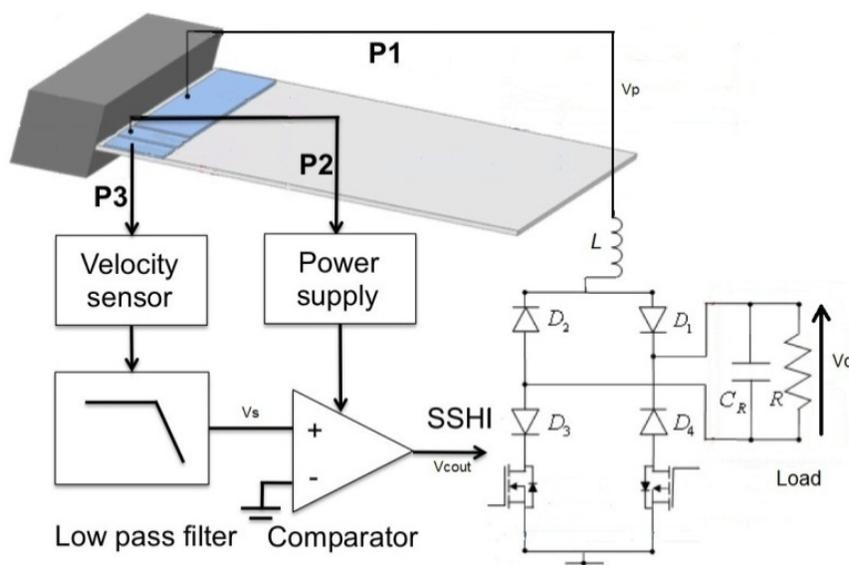
**Figure 14.** Equivalent current (velocity) sensing by a resistor and a passive low-pass filter

It should be noted that the comparator requires a DC power source. The auxiliary DC power source can be obtained from piezoelectric element with the diode rectifier directly. Figure 15 shows this auxiliary DC power supply.



**Figure 15.** Auxiliary power supply for the comparator

Although the zero-crossing detector seems more complex than the peak detector, the zero-crossing detector can have less phase delay than the peak detector [15]. In addition, both the peak detector and zero-crossing designs potentially can be integrated into the ASIC design. Combing the zero-crossing detector, the auxiliary power supply and the SSHI interface, the completed self-powered series-SSHI converter for the piezoelectric energy harvester is shown in Fig. 16. It should be noted that there are three independent piezoelectric elements on the host structure. Since piezoelectric element is mostly in open-circuit state in series-SSHI converter, it is equivalently connect to high impedance. Therefore, adding the small sensing resistance influences the piezoelectric voltage in the SSHI converter. Another independent piezoelectric element is thus required to avoid phase lag of the velocity in the case of zero-crossing detector. However, an additional independent piezoelectric is not necessary in Richard's design, *i.e.* the self-powered peak detectors with the SSHI switch. The comparisons between above three self-powering techniques are summarized in Table 1.



**Figure 16.** Self-powered SSHI converter based on a zero-crossing detector [15]

	Richard et al.	Chen et al.	Ben-Yaakov & Krihely
Signal conditioner	Peak detector	Zero-crossing detector	Zero-crossing detector
Principle			
Waveforms			
Suitable converter	Series-SSHI & parallel -SSHI	Series-SSHI & parallel -SSHI	Series-SSHI & parallel -SSHI
Phase lag	Medium (Series-SSHI), Large (Parallel-SSHI)	Small	Large
Piezoelectric element	Single piezoelectric patch	Require additional piezoelectric patches for sensing	1) Single piezoelectric patch (larger phase lag) 2) Additional patches (small phase lag)
Voltage drops	2 diode drops	2 diode drops	2 diode drops

**Table 1.** The comparison of each design

To summarize the comparison, we can say that the peak detector technique proposed by Richard et al. is an interesting solution as it is reliable and robust and can even use the signal from the piezoelectric transducer itself to operate (*i.e.*, no additional patch is needed). However, the command of the switching signal is not perfectly generated on maximum and minimum displacement values. The phase delay appears because of the voltage gap of discrete components (diodes and transistors) that perform the detection and the switching command, and it depends on the piezoelectric voltage level. Moreover, in the case of the parallel-SSHI converter, this phase delay also depends on the load. The zero crossing technique proposed by Chen et al. is the most accurate solution because the load impedance does not delay the sensing signal. However, the

drawback of this technique is that another independent piezoelectric patch is required with a self-powered supply and that a low-pass filter must be added to avoid the high-frequency noise generated by the SSHI switching. The Ben-Yaakov & Krihely's technique simply used the signal from the single piezoelectric transducer, so their velocity detection is not accurate and is influenced by the load effect. Specifically, in this solution, the switching commands do not perfectly fit the value of the zero velocities and owns poorer performance. In addition, this technique also requires an extra power supply for the comparator.

#### 4. Conclusion

This chapter focused on the charging circuit of the piezoelectric energy harvester. The operation principle of the series-SSHI and parallel-SSHI converter was explained. Both two SSHI techniques can enlarge the collected power efficiently on a weakly coupled structure. Considering the application of the micro-scale energy harvester, the low voltage drop SSHI converter was developed by using the body diodes in MOSFET switches. It can neglect maximum 4 diodes drops, which is a significant value in micro-scale energy harvester. Two kinds of signal conditioners, *i.e.* the peak detector and the zero-crossing detector were demonstrated. The peak detector can have easy topology and high reliability with single piezoelectric patch, but it generates a phase delay especially in the parallel-SSHI converter. Chen's zero-crossing detector has less phase lag and thus the switching command is no difference in the series-SSHI converter and the parallel-SSHI converter, but it is more complex and requires additional piezoelectric patches. Ben-Yaakov's zero-crossing detector adopted the single piezoelectric patch, but it owns large phase lag.

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