The Effect of Switch Triggering Offset and Switch on-time Duration on Harvested Power in Synchronized Switch Harvesting on Inductor

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Abstract

Through SPICE simulation, different piezoelectric harvester interface circuits are demonstrated and compared. In synchronized switch harvesting on inductor interface, the inductor's quality factors are very important on calculating the harvested power so that the power from SSHIs depending on the inductor's Q is calculated. Especially, parallel SSHI shows the optimal output voltage to harvest the maximum power varies according to the Q severely. Switch triggering offset and switch on time duration are very interest in calculating the power in SSHI. So, the simulations of the effect of these factors on SSHI's power are performed. It is conformed that switch triggering offset has more impact on the s-SSHI than p-SSHI. The switch on-time duration is more important in case of the p-SSHI. p-SSHI shows when the on-time duration becomes more than 1.3 times or less than 0.7 times of exact duration time, the harvested power gets zero. s-SSHI reveals the characteristics that when less than 1.5 times exact on-time duration, the harvested power varies significantly with the on-time duration, however larger than 1.5 times exact on-time duration has scarcely influenced on the harvested power.

Keywords: *Piezoelectric, Harvest, SSHI*

1. Introduction

There has been a lot of attention on ubiquitous sensing, computing and perception in the research areas. Wireless sensor networks are representative and are to allow real-time industrial process monitoring, machine health monitoring, environment monitoring, healthcare applications, and traffic control. The recent development of ultra-low power applications demands low cost, long lifetime, small volume and light weight and especially eliminating the battery. Some ubiquitous applications can down the average power consumption to the level of tens to hundreds of microwatts, which results in energy harvested from environments to be used as an alternative power source to provide a virtually infinite lifetime [1, 2].

Sustainable power generation may be achieved in converting ambient energy into electrical energy. Some possible ambient energy sources are, for instance, thermal energy, light energy

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or mechanical energy. Mechanical energy conversion is one of the common sources for these energy harvesting applications and exists almost everywhere. It is estimated that mechanical vibrations inherent in the environment can provide a power density of tens to hundreds of microwatt per cm3, which is sufficient to sustain operations of a sensor node [3]. In this field, electromagnetic and electrostatic generators have been developed [4, 5], however, piezoelectric generators are of major interest due to their solid state nature facilitating their integration and different approaches of energy harvesting using piezoelectric materials have been developed [6, 7].

Conventional power supplies and batteries typically have very low internal impedance, however, internal impedance of the piezoelectric generators is relatively high. This high internal impedance restricts the amount of output current driven by the piezoelectric source to the micro-amp range. The relatively low output voltage of the piezoelectric device is another unique challenge of this power source. This low output voltage poses a difficult on developing efficient rectifier circuits since many half wave or full wave diode rectifiers require nonzero turn-on voltages to operate [8]. One of the challenges in a power generator is the design and construction of an efficient power conversion circuit to harvest the energy from the piezoelectric elements.

The piezoelectric element subjected to a vibration generates the alternating voltage, however most of the electronic sensor nodes and circuits need the DC voltage. Accordingly, there are needs the interfaces between the piezoelectric element and the load or storage devices. So called the standard interface has been widely used, where the interface consists of full-bridge rectifier and storage element. Some techniques to increase significantly the amount of energy by piezoelectric harvesters have been proposed, which are derived from called "synchronized switching damping (SSD) [9]". The SSD technique is based on a non-linear processing on the voltage delivered by the piezoelectric element. This process increases the electrically converted energy resulting from the piezoelectric mechanical loading cycle. From SSD, parallel [9, 10] and serial [9] synchronized switching harvesting on inductor (SSHI) have been proposed. The techniques have increased the harvested power several times more than the standard technique. The nonlinear processing of SSHI consists in inductor and a switch in series and then needs the strict switching action of the switch.

In this paper, different harvesting interface circuits including standard interface, standard interface with a switch, parallel SSHI, and serial SSHI are simulated and compared with LT-SPICE® [11]. The voltage and current waveforms helps the comprehension of the interfaces. And then effect of the switching time of SSHI on the harvested power is examined through simulation. Especially, it is also studied how the switch on time offset and on-time duration deviation have an effect on the power harvested from SSHIs.

2. Standard Interface Circuits for Piezoelectric Harvesters

An input vibration applied on to a piezoelectric material cause of mechanical strain to develop in the device which is converted to electrical charge. The piezoelectric material works as a generator to transform the mechanical energy into electrical energy for micro-power generation. At or near resonance, the piezoelectric element can be modeled in electrical domain. When excited by sinusoidal vibrations, as in Figure 1, the piezoelectric element can be expressed as a sinusoidal current source in parallel with a blocking capacitance C_0 which represents the plate capacitance of the piezoelectric material. The amplitude I_0 of current source depends on a displacement and frequency of the vibration.

$$i_S = I_0 \sin \omega_0 t \qquad \textbf{(1)}$$

where $\omega_0 = 2\pi f_0$ and f_0 is the frequency with which the piezoelectric harvester is excited. Because the power output by the piezoelectric harvester is not in a form which is directly usable by load circuits, the voltage and current output by the harvester needs to be conditioned and converted to a form usable by the load circuits. The power conditioning and converting circuits should also be able to extract the maximum power available out of the piezoelectric energy harvester.

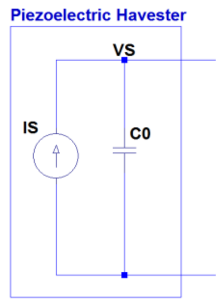
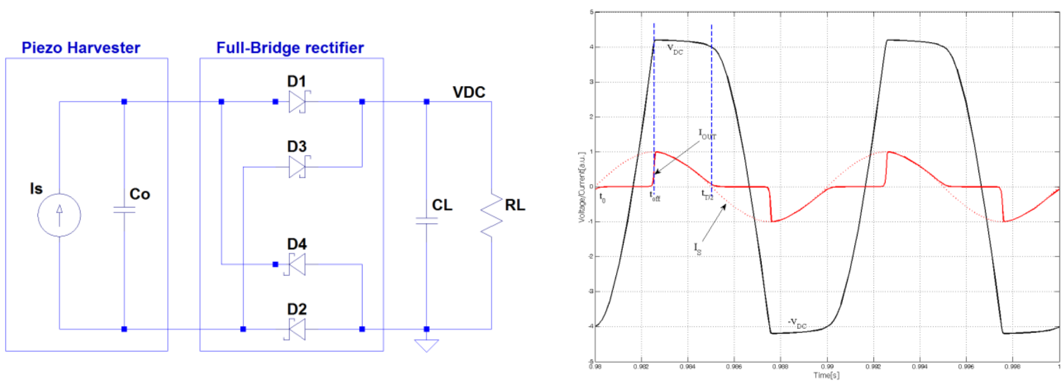
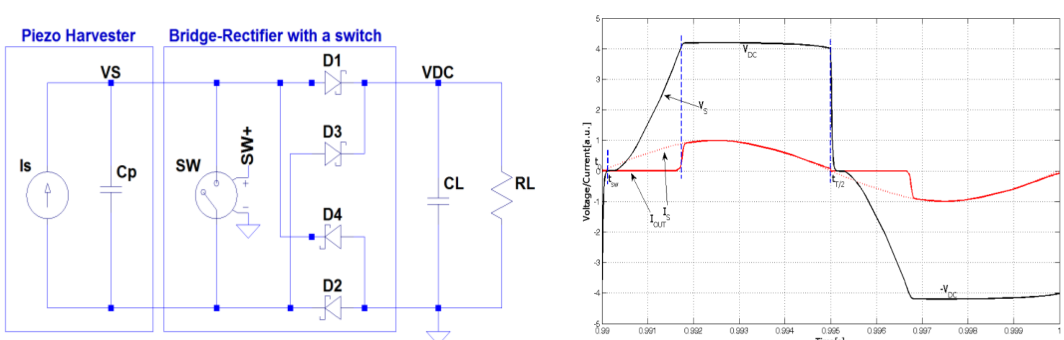


Figure 1. Equivalent circuit of a piezoelectric energy harvester



(a) (b)

Figure 2. Standard interface: (a) circuit schematic and (b) waveforms



(a) (b)

Figure 3. Standard interface with a switch: (a) circuit schematic and (b) waveforms

Figure 2 shows the standard interface using full-bridge rectifier and the simulated voltage and current of the piezoelectric harvester. For the sake of this analysis, assume that the value of C_L is so large compared to C_0 that the voltage at the output of the rectifier (V_{DC}) is essentially constant. During the interval from t_0 to t_{off}, the piezoelectric current source is charging its capacitor C_0 to the V_{DC} and all diodes in the bridge rectifier are reverse-biased. And then, in the interval between t_{off} and $t_{T/2}$, the bridge rectifier will be on, the piezoelectric source provides the current to the load. We can know the reduction in the duration for charging the C_0 can allows the power delivered to the load to be maximized.

Figure 3 shows one of the methods to reduce the duration of discharging the capacitor C_0. This circuit has the switch SW paralleled with the bridge rectifier [8], which is turned on for a brief time at every zero-crossing of the piezoelectric current I_S. When the switch is on, it discharges the capacitor   immediately to ground. Once C_0 has been discharged, *SW* is turned *OFF*. So, this circuit needs only the time interval to charge C_0 from *0* to V_{DC} and accordingly more current can be provided to the load than the standard interface.

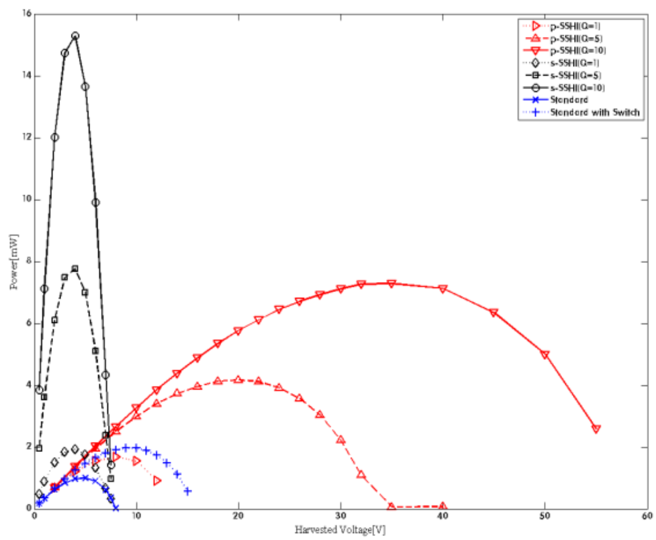
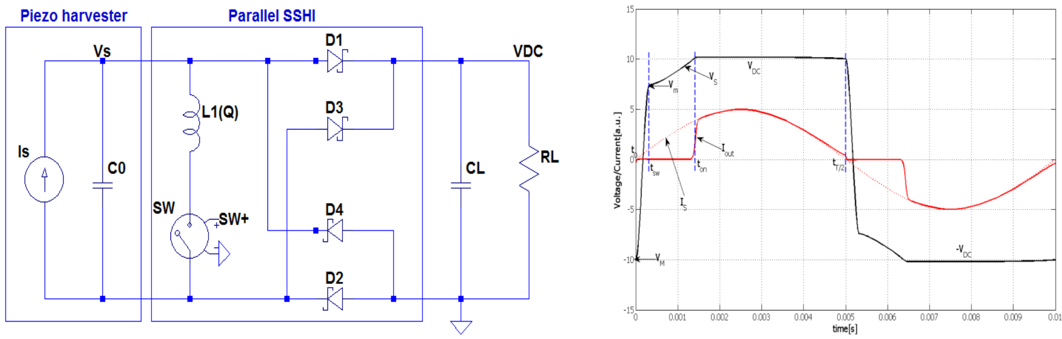


Figure 4. The comparison of power harvested by different interface circuits

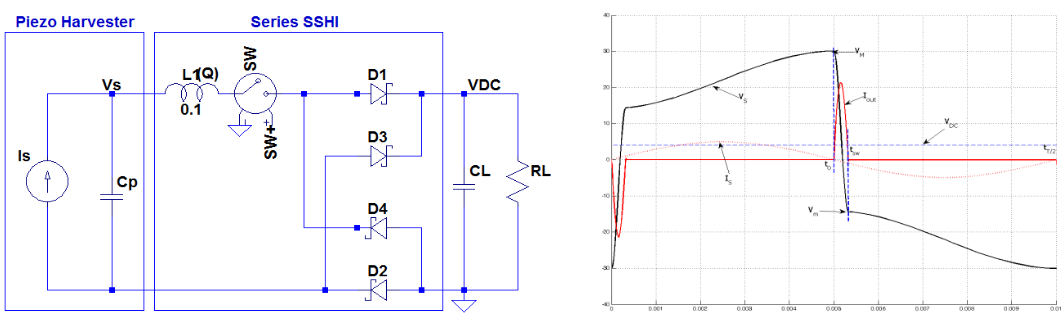
Figure 4 shows the simulated power harvested from different interface circuits. In the figure, solid line with mark x is the power harvested from the standard circuit, and the dotted line with symbol + is the harvested power of the standard circuit with a switch. It shows the power of the standard interface with a switch can gain two times more than that of the standard interface.



(a) (b)

Figure 5. Parallel synchronized switch harvesting on inductor interface

To increase the power from the piezoelectric harvester, several interfaces have been proposed. Synchronized switching harvesting on inductor (SSHI) consists of a non-linear processing circuit. There are two types of SSHI, one is parallel-SSHI (p-SSHI) where the non-linear processing circuit is connected across the piezoelectric harvester and a full-bridge rectifier, and the other is series-SSHI(s-SSHI) where the non-linear processing circuit is connected between the piezoelectric harvester and a full-bridge rectifier in series. The non-linear processing circuit is composed of an inductor and a switch in series. This interface utilizes the synchronous charge extraction principle which consists in removing periodically the electric charge accumulated on the blocking capacitor C0 of the piezoelectric element, and to transfer the corresponding amount of electrical energy to the load or to the energy storage element. Figure 5 and Figure 6 show the two interface circuits and the voltage and current waveforms in them.



(a) (b)

Figure 6. Parallel synchronized switch harvesting on inductor interface

As shown in Figure 6, in p-SSHI interface, the current source is charging the blocking capacitor C_0 only from V_m to V_{DC} and then almost entire current is delivered to the load. The electronic switch is briefly turned on when the current source of the piezoelectric elements crosses zero. This moment is when the mechanical displacement reaches maxima. At these triggering times, an oscillating electrical circuit L-C_0 is established, where the electrical oscillation period is chosen much smaller than the mechanical vibration period T. The switch is turned off after a half electrical oscillating period, resulting in a quasi-instantaneous inversion of the voltage V. The time interval, t_{SW} during the switch is on is expressed as:

$$t_{sw} = \pi\sqrt{LC_0} \tag{2}$$

The voltage relation between before the switch is on and after the switch is off depends on the quality factor Q of inductor.

$$V_m = -V_M e^{-\pi/2Q} \text{ for p-SSHI} \tag{3}$$

$$(V_m + V_{DC}) = -(V_M - V_{DC})e^{-\pi/2Q} \text{ for s-SSHI} \tag{4}$$

where V_m is the voltage after the switch is off, V_M is the voltage right before the switch is on and Q is the quality factor of inductor.

Figure 4 shows the harvested power from SSHI interfaces depending on different inductor's Q_s. The p-SSHI can harvest four times more power than the standard interface does when Q is high and also s-SSHI can get two times more power than p-SSHI. However, it can be known that the harvested power is very dependent on Q_s. In the p-SSHI, the optimum voltage at the maximum power achieved is increased when Q becomes high. Also, in the case of low $Q(Q=1)$, p-SSHI interface provides the power lower power than the standard interface with a switch.

3. The Effect of Switching Time on Harvested Power of SSHI

In SSHI interfaces, the operation of the switch is very important. The switch has to turn on exactly when the displacement reaches maxima and then has to stay on only very short duration, a half period of L-C_0 oscillation period. The switch triggering offset which is the switch on time deviation from the ideal on time and the on-time duration deviation have an important effect on the harvested power.

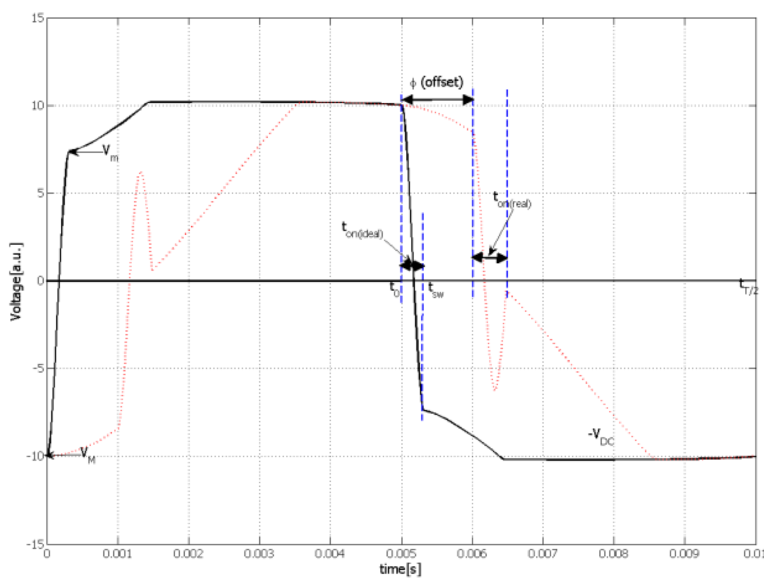


Figure 7. The definition of switch triggering offset and on-time deviation: p-SSHI

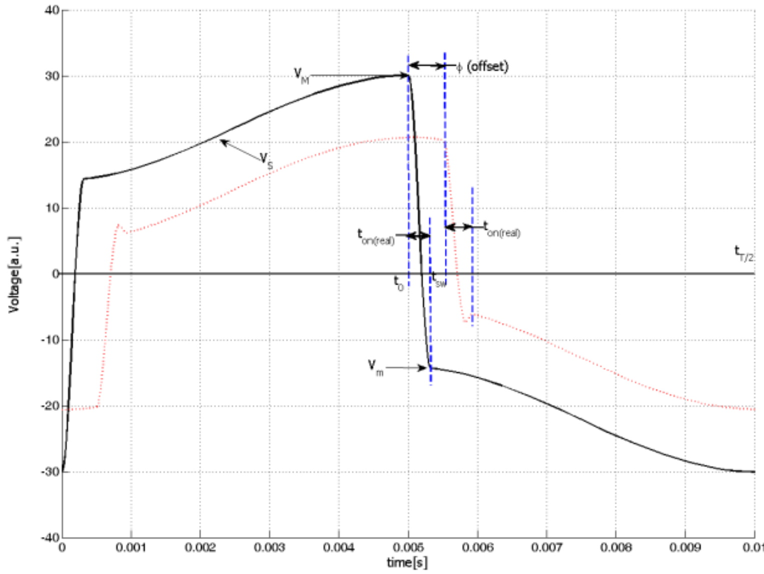


Figure 8. The definition of switch triggering offset and on-time deviation: s-SSHI

Figure 7 And Figure 8 show the definitions of the switching offset and the on-time duration deviation: p-SSHI and s-SSHI. In Figure 9, the effect of the switch triggering offset on harvested power is shown. This figure shows s-SSHI is more dependent on the triggering time than p-SSHI.

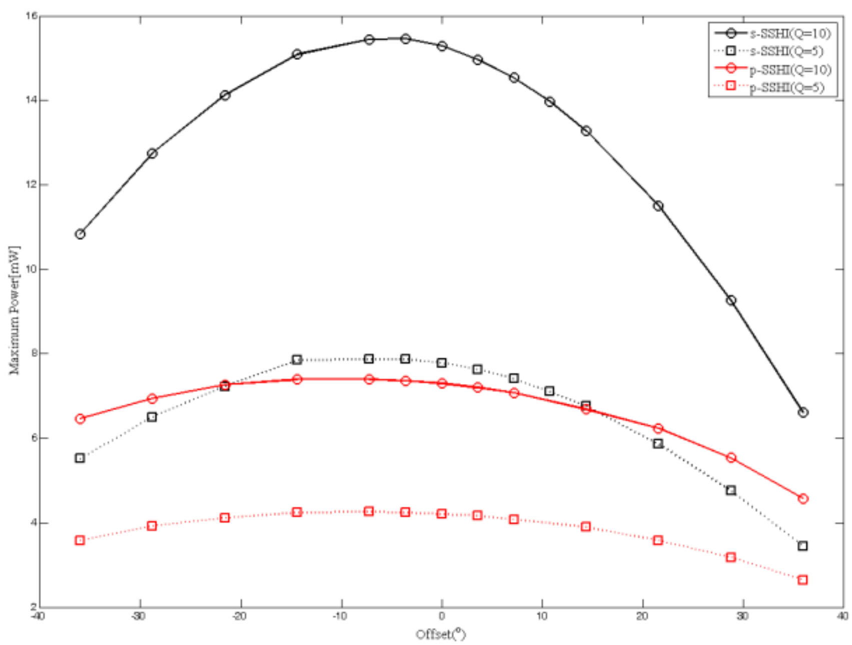


Figure 9. The harvested power as a function of the switch triggering offset

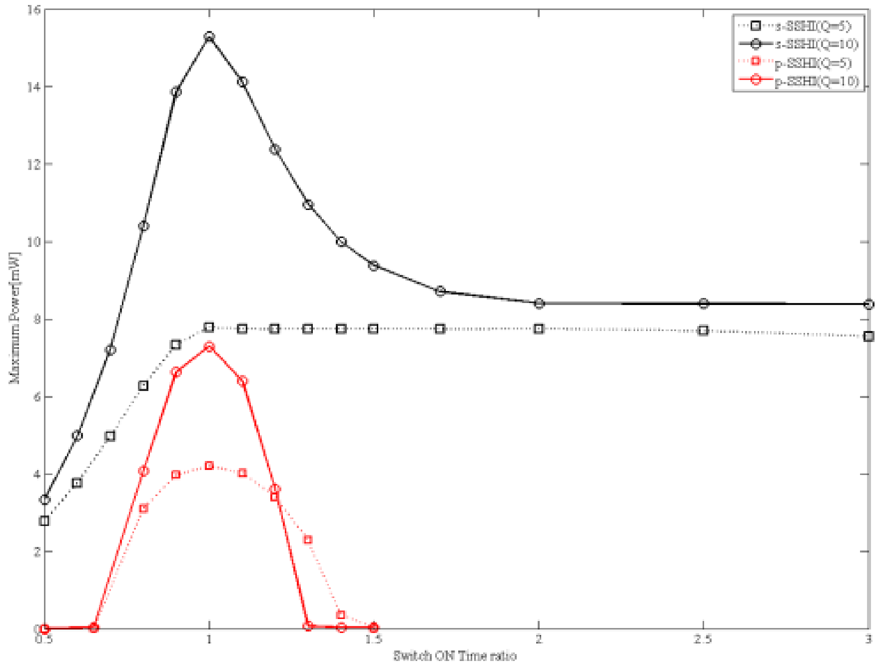


Figure 10. Harvested power as a function of the switch on time duration deviation

Figure 9 shows the harvested power depending on the switching on-time duration. In this figure, switching on time duration ratio is the ratio of the real on-time duration and exact on-time duration as Equation 2. The power harvested in p-SSHI interface is very dependent on the on-time duration deviation, where when the on-time duration becomes over 1.3 times of exact on-time duration expressed by Equation 2, the harvested power goes zero. However, s-SSHI shows when the deviation gets larger, the harvested power does not depend on the on-time duration. In s-SSHI, on-time duration gets larger, piezoelectric voltage gets smaller, however when on-time duration becomes over two times of exact duration, the voltage waveform does not change.

Figure 10 shows the harvested power depending on the switching on time duration. In this figure, switching on time duration ratio is the ratio of the real on-time duration and exact on-time duration as Eq. 2. Two upper curves are the results of s-SSHI (Q=10 and 5) and the lower curves the power from p-SSHI (Q=10 and 5). Especially, the powers harvested in p-SSHI interface are very dependent on the on-time duration deviation, where when the on-time duration becomes over 1.3 times of exact on-time duration expressed by Eq. 2, the harvested power goes zero. However, s-SSHI shows the deviation gets larger, the harvested power does not depend on the on-time duration.

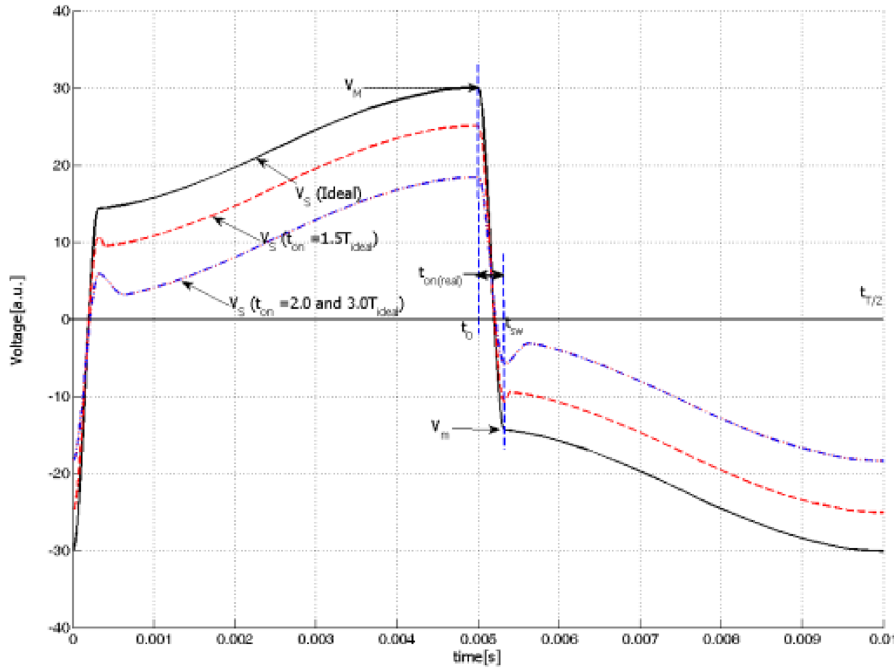


Figure 11. The voltage waveform depending on the on-time duration deviation in s-SSHI

From Figure 11, on-time duration gets larger, piezoelectric voltage gets smaller however on time duration becomes over two times of exact duration, the voltage waveform does not change. It means the harvested power will be constant despite of on-time duration being increased.

4. Conclusion

In this paper, we demonstrate and compare different piezoelectric harvester interface circuits using SPICE simulation. We consider the standard interface, the standard interface with a switch, parallel and serial synchronized switching harvesting on inductor. In SSHI, the inductor's quality factors are very important on calculating the harvested power. So, we calculated the power from SSHIs depending on the inductor's Q. Especially, parallel SSHI shows the optimal output voltage to harvest the maximum power varies according to the Q severely. The low Q makes the power harvesting ability of p-SSHI lower than that of the standard interface with a switch which can be alternate for p-SSHI with low quality inductor.

Switch triggering offset and switch on-time duration are very interest in calculating the power in SSHI. It is conformed that switch triggering offset has more impact on the s-SSHI than p-SSHI. It is recommended that the switch triggering offset is kept smaller than 10% of piezoelectric element vibration period. The switch on-time duration is more important in case of the p-SSHI. p-SSHI shows when the on-time duration becomes more than 1.3 times or less than 0.7 times of exact duration time, the harvested power gets zero. Because on-time duration is very small, careful consideration on the duration will be needed. s-SSHI reveals the characteristics that when less than 1.5 times exact on-time duration, the harvested power varies significantly with the on-time duration, however larger than 1.5 times exact on-time duration has scarcely influenced on the harvested power. Inductor's Q also has contributed on these characteristics.

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