

# Optimum Piezoelectric Energy Harvesting with Buck Boost Circuit in Discontinuous Conduction Mode

Darmayuda I Made, Yuan Gao, San Jeow Cheng, Meng Tong Tan, and Minkyu Je

**Abstract**—The amount of energy extracted from a piezoelectric transducer is greatly depend on its load. Optimum load must be connected to the transducer for optimum energy transfer. In practice, it is nearly impossible to always match the circuit load with the optimum load required. Hence, interfacing circuit is essential. This interfacing circuit must be able to provide fix optimum impedance to the transducer regardless the actual circuit load connected. This paper discusses the design of high efficiency piezoelectric energy harvester. The energy harvester is intended to harvest energy from a pushbutton piezoelectric generator powering a battery-less circuit. A buck boost topology is used to provide optimum impedance to the piezoelectric for optimum energy harvesting. The value of impedance seen by the transducer can be adjusted by setting the value of its inductor, clock frequency and duty cycle.

**Index Terms**—Battery-less Buck Boost, energy harvester, piezoelectric, power conditioning.

## I. INTRODUCTION

With the advance of low power IC technology, operating circuit using harvested energy becomes more feasible. Piezoelectric energy harvesting is one of the most common approaches due to its relatively high energy density. Harvesting piezoelectric has its own challenges. Due to its low output current and high output impedance, the piezoelectric must be extracted at its optimum load impedance [1]-[4]. The other challenge is the AC nature of electrical energy generated by the piezoelectric transducer. Hence, a power conditioning is essential to power electronic circuit using piezoelectric transducer.

A high efficiency power conditioning interface circuit based on Buck Boost topology is presented in this paper. The Buck Boost converter, as the backbone of the system, provides optimum load to the piezoelectric transducer. The Buck Boost converter has the capabilities to isolate its input and output impedance when operated in discontinuous conduction mode (DCM). Its input impedance is determined by the switching frequency and duty cycle and also the inductor size. By setting those parameters equal to the transducer's optimum load, optimum power extraction can be achieved. A switch-based rectifier converts polarity of the AC signal generated by the transducer. Compared with the

traditional diode-based rectifier, the switch-based rectifier provides lower voltage drop, hence the efficiency is higher.

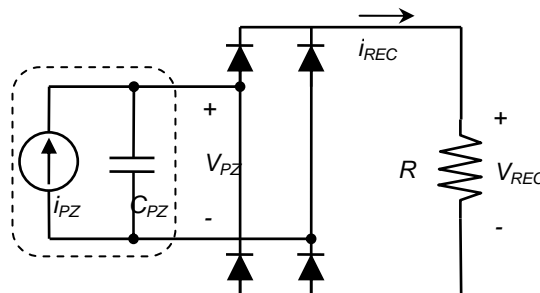


Fig. 1. Harvesting piezoelectric energy with resistive load

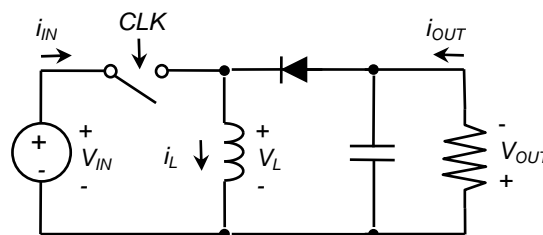


Fig. 2. Buck boost converter

## II. PIEZOELECTRIC HARVESTER WITH RESISTIVE LOAD

When a piezoelectric material is subjected to a mechanical stress, an electric field is generated across the material, creating a voltage gradient and a subsequent current flow, which is called piezoelectric effect [5]. For better understanding of electrical behavior of piezoelectric transducer, it can be modeled as a current source in parallel with a capacitor. Under mechanical excitation, the equivalent current source is proportional to the velocity of the displacement. Maximum power transfer is achieved when the output load match the input impedance. The equation below shows the input impedance of the piezoelectric transducer given in terms of its capacitance and vibration frequency [6]:

$$Z = \frac{1}{2\pi f C_{PZ}} \quad (1)$$

## III. BUCK BOOST CONVERTER

For maximum power harvesting, a power conditioning circuit is needed to provide the optimum load to piezoelectric transducer. This optimum load depends on the electromechanical coupling factor of the piezoelectric transducer. In addition, the power conditioning must be able to provide isolation between load seen by the piezoelectric

Manuscript received June 1, 2012; revised August 26, 2012.

This work was supported by HOME2015II Program, Agency for Science, Technology and Research (A\*STAR), Singapore, under Science and Engineering Research Council (SERC) grant number 082 140 0033.

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transducer and the actual load of the system. The Buck Boost converter, shown in fig. 2, satisfies these requirements [7-9].

In DCM the peak current ( $I_{PK}$ ) of the Buck Boost converter is equal to:

$$I_{PK} = \frac{V_{IN}}{L} DT_{SW} \quad (2)$$

$D$  and  $T_{SW}$  are the duty cycle and switching frequency of the clock respectively. Over one switching cycle the average current drawn from input ( $I_{AVE}$ ) is equal to:

$$I_{AVE} = \frac{I_{PK} D}{2} \quad (3)$$

$$I_{AVE} = \frac{V_{IN} D^2 T_{SW}}{2L} \quad (4)$$

By rearranging the above equation, the input impedance is expressed as the following equation:

$$R_{IN} = \frac{V_{IN}}{I_{AVE}} = \frac{2L}{D^2 T_{SW}} \quad (5)$$

From the equation it is clear that the input impedance of the Buck Boost converter in DCM only depends on inductor size and clock parameters.

#### IV. BUCK BOOST HARVESTER WITH ON-CHIP CLOCK GENERATOR

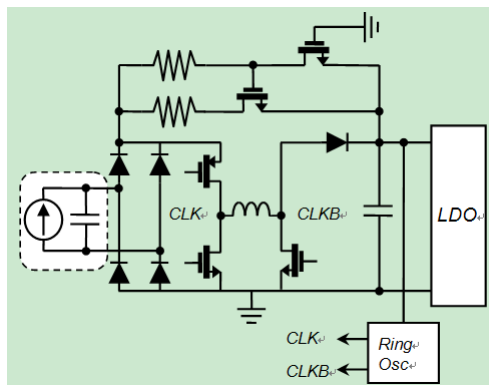


Fig. 3. Buck boost harvester with on-chip clock generator

Fig. 3 above shows the schematic of Buck Boost Piezoelectric Energy Harvester. The system consists of switch-based rectifier, Buck Boost converter and ring oscillator for on-chip clock generator. A direct charging path is added to provide initial power for the ring oscillator. Once the ring oscillator is active, the direct path is then cut-off for high-efficiency energy harvesting.

Three-switches Buck Boost converter is used instead of the conventional one-switch. Although the additional switches incur more power losses, the three-switch Buck Boost converter has single polarity which is crucial in IC implementation. A diode is used as a passive zero-current switch.

The upper switch is implemented using a PMOS while the lower switches using NMOS. When  $CLK$  is low PMOS and right NMOS are turned on. The energy is transferred from the piezoelectric to the inductor. When the  $CLK$  is high, the left NMOS is turned on and the energy is transferred to the storage capacitor.

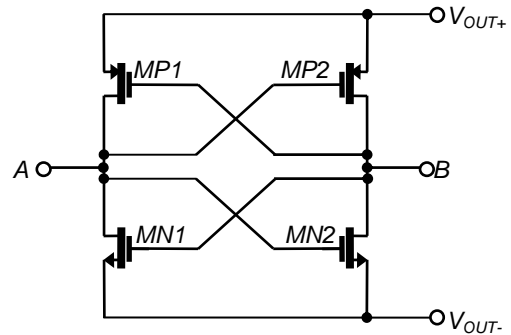


Fig. 4. Switch-based rectifier

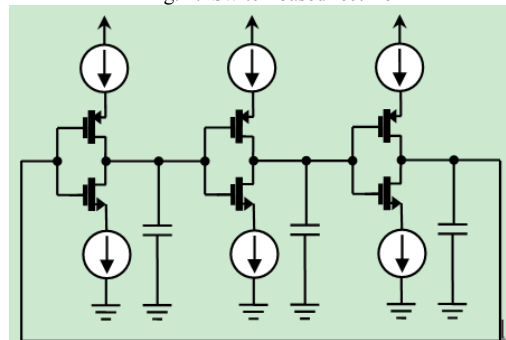


Fig. 5. Current-starved ring oscillator

Due to its AC nature, rectification is crucial in piezoelectric energy harvesting. Fig. 4 shows the switch-based rectifier used in this piezoelectric energy harvester. The switch-based rectifier has only  $2 V_{DS}$  voltage drop which is much lower than the conventional diode-based rectifier. The operation of this rectifier is as the following. When  $A$  is high  $MP1$  and  $MN2$  turn on, current flows from  $A$  to the output via  $MP1$  and returns to  $B$  via  $MN2$ . During the other half cycle,  $MP2$  and  $MN1$  turn on, current flows from  $B$  to the output via  $MP2$  and return to  $A$  via  $MN1$  [10].

A current-starved ring oscillator is used for on-chip clock generator, as shown in fig. 5. The current-starved topology limits the current consumption of the ring oscillator. In addition it also helps to minimize the frequency variation over supply variation [11]. The current source of the ring oscillator is design to be imbalance. It is designed that way to have less than 50% duty cycle and to ensure the Buck Boost converter operates in discontinuous conduction mode. Capacitors are added to reduce number of inverters used to generate clock frequency in the range of 1 MHz.

#### V. RESULTS AND DISCUSSION

The input impedance of the Buck Boost circuit can be varied by adjusting the clock parameters and/or inductor value. Fig. 6 shows the comparison of measured and calculated input impedance of the buck boost circuit. The clock frequency inductor value is fixed at 1 MHz and 100  $\mu H$  respectively while the duty cycle is varied between 20% and 30%. It is shown that the measured value indeed very close to

the theoretical calculated value.

The Buck Boost circuit is meant to provide impedance isolation so that the piezoelectric energy can be harvested at its optimum resistive load level regardless the value of the real load. In fig. 7 the input impedance is measured at different output load. The measurement is done by setting the clock frequency and duty cycle to be 1 MHz and 20% respectively, and inductor value of 100  $\mu$ H. The measurement shows that the input impedance relatively constant regardless the output load levels. Hence it proved that the Buck Boost circuit provides impedance isolation.

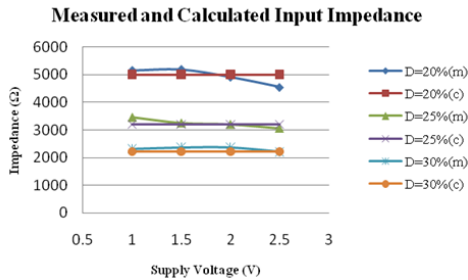


Fig. 6. Measured and calculated buck boost input impedance (D=duty cycle, m=measured, c=calculated)

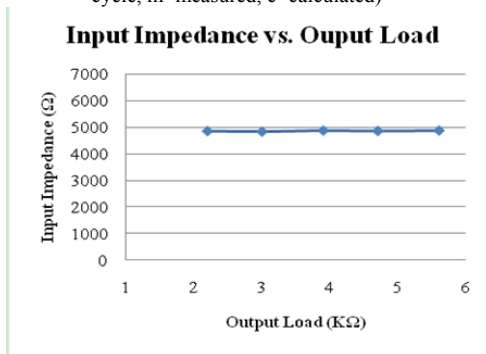


Fig. 7. Buck boost input impedance vs. output load

With 3.3 nF capacitor and 10 KHz frequency, the piezoelectric model has input impedance of approximately 5 K $\Omega$ . In fig. 9 the harvested piezoelectric power is plotted over different load level. It is shown that when the output load is below the input impedance of the piezoelectric, the harvester power is very low. This is because the Buck Boost circuit is in step-down mode. During step down mode, the power loss at the diode will be large hence results in lower output power. Around 5 K $\Omega$  the harvested power is optimum. It is expected that the Buck Boost circuit to have relatively constant output power. However, after 5K $\Omega$  the output power decreases slowly. This might be attributed by increases of output voltage (fig. 8), which caused higher switching losses.

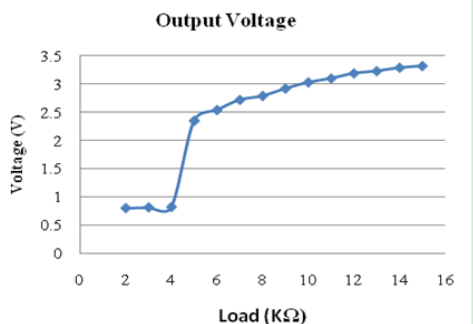


Fig. 8. Output voltage of buck boost harvester

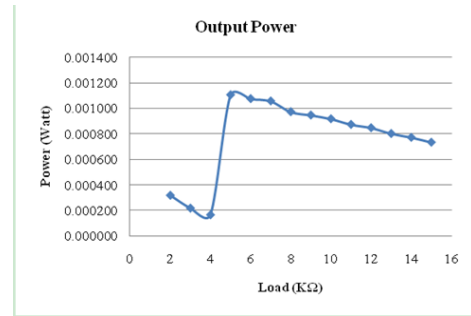


Fig. 9. Output power of buck boost harvester

## VI. CONCLUSION

This paper shows the design of Buck Boost Harvester with on-chip clock for battery-less piezoelectric energy harvesting. It is shown that when operated in DCM mode the Buck Boost input impedance can be set at certain value regardless the output load value. Using Buck Boost as power processing circuit allows optimum piezoelectric energy harvesting based on impedance matching principle. It is also proven that amount of power extracted from piezoelectric is almost constant due to impedance isolation provided by the Buck Boost harvester.

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