

Buck-Boost Converter Based Power Conditioning Circuit for Low Excitation Vibrational Energy Harvesting

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Abstract - A method of harvesting low excitation vibrational energy using a buck-boost dc-dc converter to power active RFID tags is presented. Using the discontinuous conduction mode (DCM), the impedance of the converter is designed to match that of the piezoelectric transducer, thereby allowing maximum power transfer. It is shown that using multiple transducers in a parallel configuration is the optimum method for harvesting energy by increasing the available power, and reducing the transducer's effective impedance.

I. Introduction

Wireless applications are an integral part of our lives, and are only growing as technology enables smaller, lower power and more capable devices. One of the areas that is popular today and is finding new applications is wireless sensor networks (WSNs). The widespread need for WSNs is evident from the proliferation of short-range wireless standards such as Bluetooth, ZigBee, Wi-Fi, and RFID [1]. Sensor nodes for wireless personal area network (WPAN) that utilize smart mesh network protocols are traditionally designed to be optimized for low cost and low power. Each wireless node is intended for deployment in large quantities at remote locations to sense critical data and relay its measurements to other network nodes for monitoring and control purposes. In this new era of high security and vigilance, wireless sensors are being deployed at major events so as to predict catastrophes such as acts of terrorism [2]. Another application combines the data from vehicular sensors, such as wheel hub-odometers, tire pressure sensors, and asset tags to improve safety, reliability, and reduce fleet maintenance costs. As these types of applications proliferate, it will become necessary to deploy sensor nodes in hard to reach places. Once thousands of low-cost RF sensors are deployed for any given application, replacing batteries will become an impractical task. Therefore, self-sufficient devices that can operate for an indefinite period of time will be required.

Energy harvesting (EH) from solar, wind, vibrations, thermal, etc. to power wireless devices has been attracting considerable interest in the past few years [3]. While solar energy provides relatively higher energy density outdoors, its efficiency under indoor conditions is considerably lower. Similarly, vibrational EH using piezoelectric bimorphs, and electromagnetic and electrostatic generators require high

excitation energy to provide reasonable power levels (of the order of a few mWs). However, many practical applications produce only low excitations (e.g. 0.05 - 0.5 g_{peak}) at low frequencies (e.g. 20 - 200 Hz). Consequently, off-the-shelf DC-DC converters and rectifiers, when coupled with off-the-shelf piezoelectric bimorphs, do not yield optimum results.

This paper focuses on the design of high efficiency power electronics for such vibrational EH systems. The specific application involves powering active vehicle RFID tags, from Axxess International Inc. [4], that are installed on the windshield of automobiles and front of truck trailers. The tags operate at 3 V_{DC} and draw about 6 - 10 μ A during sleep mode and about 15 - 20 mA for short periods of 20 msec when operational. This indicates average power consumption of about 18 - 30 μ W per day. Experimental data shows that a majority of the vibrations for this application lie in the 10 - 30 Hz frequency range with low excitation levels of about 0.05 - 0.3 g_{peak} [1].

The paper is organized as follows: Section II describes the system and the equivalent electrical model. The details of each unit are presented in Sections III and IV. Simulation results are discussed in Section V along with experimental data. Finally, Section VI concludes the paper.

II. Energy Harvesting Circuit and Electrical Model

A. System Overview

A typical EH system for a wireless sensor consists of a transducer, AC-DC conversion (in certain cases), a DC-DC converter, and a battery charging and power management module as shown in Fig.1.

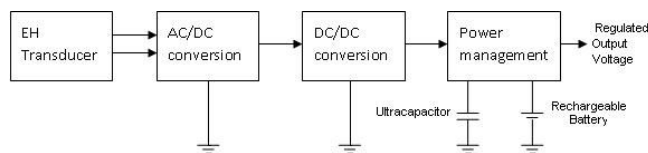


Fig. 1. EH block diagram.

In this paper, piezoelectric cantilever beams are used as the EH transducer. There are different types of piezoelectric materials used to harvest vibrational energy (PVDF, PZT-5, etc.) and each produces maximum power when excited in a certain fashion. The chosen material is a Macro Fiber Composite (MFC) consisting of multiple PZT-5A ceramic rods as a flexible patch [5]. Each patch is mounted on an aluminum beam in a cantilever type set up to allow d_{31} mode of operation [3]. Since the output from a piezoelectric vibrational source is an AC voltage, an AC-DC converter is required. A full wave bridge rectifier has a relatively higher efficiency, and is ideal for AC-DC conversion. In addition, a DC-DC converter is necessary to convert the rectified DC voltage to levels acceptable to recharge an energy storage device (e.g. secondary battery). The rectified DC voltage is conditioned to enable maximum power transfer by carefully designing the DC-DC converter.

B. Simulation Model

In order to simulate a piezoelectric vibrational transducer, an equivalent electrical model is first used. The piezoelectric cantilever is modeled for resonance operation with an appropriate AC voltage source and a series capacitance in PSpice [6]. Fig.2 shows the electrical model.

The model was found to closely match experimental results. The values of components in the simulation model can be modified to represent multiple cantilevers in series or parallel.

III. AC-DC Conversion and Impedance Matching

Different types of rectifiers such as half-wave, full-wave, voltage doublers, etc. can be used to convert the AC transducer voltage to DC voltage. Power efficiency is an important criterion while choosing the rectifier topology. A full wave bridge rectifier has a relatively high efficiency and therefore, was chosen for the harvester (refer Fig.2). The challenges with such a rectifier however, are the minimum voltage requirements due to the forward voltage drop of two diodes in series and the leakage current when the diodes are reverse biased. For example, each silicon diode requires a 0.6 - 0.7 V_{DC} voltage drop to be overcome before conduction begins. This forward voltage drop causes power loss during conduction and consequently, lower efficiency. Alternatively, germanium diodes have a relatively lower 0.3 V_{DC} forward voltage drop. But this is still fairly large when input power flow from the piezoelectric cantilever structure is of the order of only hundreds of $\mu W/cm^3$. It is therefore very important to choose diodes that have a low leakage current and a small turn-on voltage. To meet these specifications, low forward voltage (0.2 V_{DC}) Schottky diodes which have a

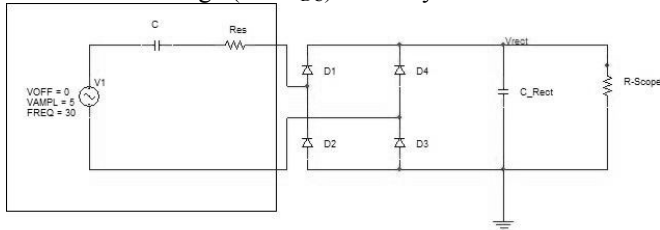


Fig. 2. Equivalent electrical model with rectifier circuit for a piezoelectric cantilever beam vibrating at its resonant frequency.

leakage of 200 nA are chosen. Also, synchronous rectifiers can be used instead of Schottky diodes to improve efficiency. Here, the body diode of a MOSFET is used instead of a discrete pn junction diode. The transistor is turned on when the body diode begins conduction. Due to the extremely low $R_{ds(on)}$ (few mohms) specifications of MOSFETs, the voltage drop across the body diode during conduction is negligible, consequently yielding very low power loss and high efficiency [6].

In order to obtain maximum power transfer, the impedance of the load should match that of the source. It is observed that the impedance of the transducer can be computed to be

$$Z_0 = \frac{1}{2\pi f_R C} \quad (1)$$

where: f_R is the resonant frequency of the cantilever structure and C is the series transducer capacitance. Therefore, as the frequency decreases, the impedance increases.

Fig.3 shows about 210 μW maximum power obtained from a transducer comprising of one MFC M2814P2 patch mounted on an aluminum beam of adequate thickness and tip mass at 45 Hz f_R and 0.5 g_{peak} acceleration. The electrical model for such a cantilever structure (described in Fig.2) with $C = 26$ nF results in $Z_0 = 136$ k Ω .

Most transducers have such large impedances of the order of 100 k Ω to 1 M Ω . This results in a challenge in designing the DC-DC converter and consequently, harvesting maximum power.

IV. DC-DC Conversion

The overall efficiency of the system depends upon efficiency of the rectifier in conjunction with the DC-DC converter. There are several DC-DC converter topologies to choose from. Typically, non-isolated switch-mode DC-DC converters seem to be the energy conversion device of choice due to relative ease in matching the transducer impedance. The three most basic converter topologies: buck (step-down), boost (step-up), and buck-boost (step-up/step-down) can all be used to achieve impedance matching. Alternatively, charge pumps or switched capacitor converters are also feasible in certain cases due to ease of integration on an integrated circuit (IC). These converters have the advantage of consisting of only capacitors and MOSFETs (no inductor).

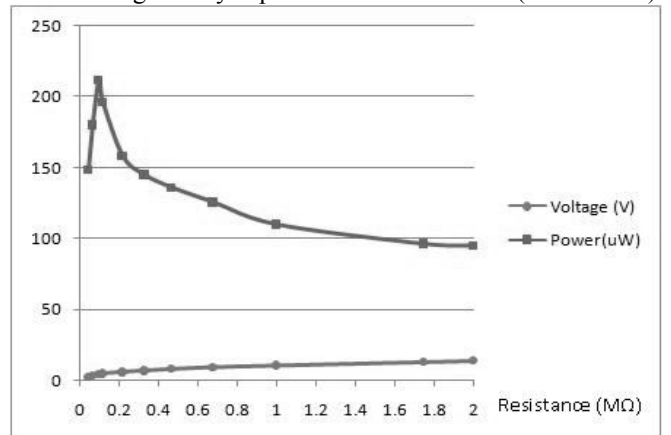


Fig. 3. Power and voltage plots for a single MFC M2814P2 patch based EH transducer.

However, from a maximum power transfer standpoint their input resistance cannot be easily tuned to match the output impedance of the transducer. Low drop out (LDO) regulators are not considered as candidates since they suffer from poor efficiency and can only step down the voltage (no step-up possible).

A buck-boost converter is observed to be most suitable for low excitation levels, and high efficiency requirements [1]. The buck-boost converter circuit is shown in Fig.4. Buck converters are not very efficient at low excitation levels. It has been shown that these converters require at least 35 V_{DC} open circuit rectifier voltage to obtain 60 - 70% efficiency [7]. Moreover, buck-boost converters effectively work at input voltages above or below its output voltage (V_{bat}). Both these converters must operate in discontinuous conduction mode (DCM) for higher efficiency [7,8].

For a buck-boost converter operating in DCM, it has been noted that the average input resistance (R_{in}) is given by [7]

$$R_{in} = \frac{2Lf_{sw}}{D^2} \quad (2)$$

where: L= inductance, f_{sw} = switching frequency, and D = duty cycle.

Therefore, for a given f_{sw} and D, R_{in} scales linearly with L. For large values of R_{in}, a larger L is necessary. However, this is not desirable since the losses due to the inductor ESR increase significantly as its value increases.

Condition for DCM operation is given by

$$V_{rect} < \frac{1-D}{D} V_{bat} \quad (3)$$

Note that if this condition is not adhered to, the converter enters continuous conduction mode (CCM) with

$$R_{in} = \left(\frac{1-D}{D} \right)^2 \frac{V_{bat}}{I_{bat}} \quad (4)$$

Here, R_{in} is no longer constant, and the converter will require feedback for adjusting D to obtain constant R_{in}. This is a serious overhead resulting in lower efficiency, and therefore, must be avoided.

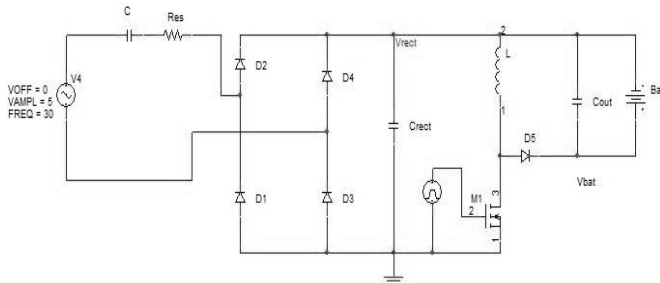


Fig.4. Buck-boost converter for piezoelectric EH.

V. Simulations and Experimental Results

As indicated earlier, the Axxess active vehicle RFID tags were used as the sensor load. These tags operate at 3 V_{DC} and draw about 6 - 10 μA during sleep mode and about 15 - 20 mA for short periods of 20 msec when active. This indicates average power consumption of about 18 - 30 μW over one day. Experimental data shows that a majority of the vibrations for this application lie in the 10 - 30 Hz frequency range with low excitation levels of about 0.05 - 0.3 g_{peak}. Given a constraint that vibrations are only available for four hours in a day, this requires about 108 - 180 μW be available to recharge the battery during that time.

The maximum power that can be harvested using a single cantilever structure with one M2814P2 MFC patch was observed to be about 70 μW at a resonant frequency of 30 Hz, and an excitation of 0.07 g_{peak}. This power is insufficient for the chosen application. Therefore, multiple MFC patches need to be used to achieve the necessary power. While cascading the transducers in series, it is observed that the power achieved scales with the number of transducers if all of them are vibrating in phase with each other. Such a scenario is difficult to obtain practically. Simulations show that the power falls off steeply for even slight variations in phase of individual transducers.

While transducers are connected in parallel, with independent rectifiers, the problem of out of phase inputs can be alleviated, and at the same time the effective impedance reduces. At this low resonant frequency, the impedance of a single transducer is approximately 200 kΩ. When eight such transducers are cascaded, the effective impedance reduces to 25 kΩ while providing 480 μW of maximum power. Fig.5 shows the simulated power comparison for 0.5 g_{peak} at 45 Hz resonant frequency. In this case about 1.6 mW was obtained at 17 kΩ with eight cascaded transducers while only about 200 μW was obtained at a much higher impedance of about 100 kΩ with a single transducer.

Due to hardware and space constraints, experimental results are limited to a maximum of two transducers in parallel.

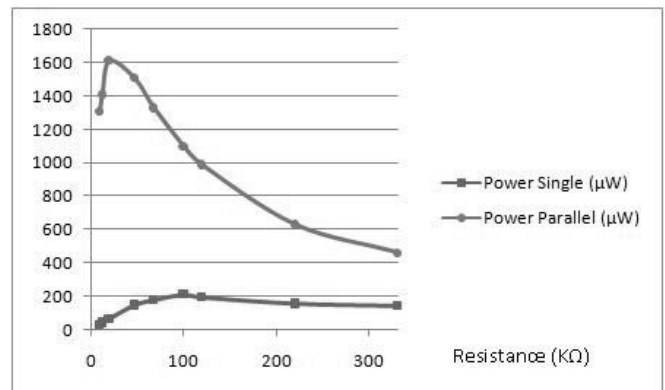


Fig.5. Power comparison for single vs. multiple MFC transducers.

The results from two parallel transducers match equivalent simulations, bringing the effective impedance down to 100 k Ω and providing a maximum rectifier power of 140 μ W at 0.07 g_{peak} acceleration and 30 Hz resonant frequency. This is effectively the input power to the DC-DC converter used for battery trickle charging. The output DC-DC converter power was measured to be 90 μ W which indicates DC-DC converter efficiency of 64%.

The rectifier voltage, rectifier power and hence DC-DC converter output power increases with increased acceleration. It is observed that the rectifier power obtained from two transducers in parallel increases to about 230 μ W for an acceleration of 0.09 g_{peak} . The DC-DC converter output power was measured to be 150 μ W which indicates DC-DC converter efficiency of 65%. The rectifier voltage and DC-DC converter output power and efficiency plots obtained for varying acceleration values are shown in Figs. 6 – 8 respectively.

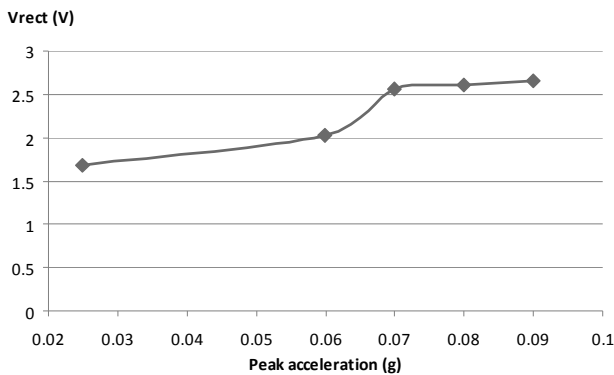


Fig.6. Rectifier voltage vs. acceleration.

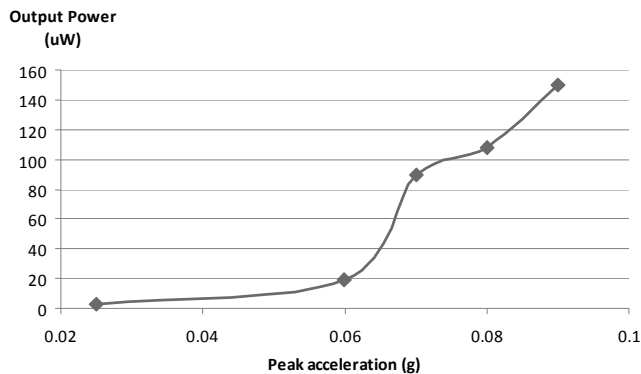


Fig.7. DC-DC converter output power vs. acceleration.

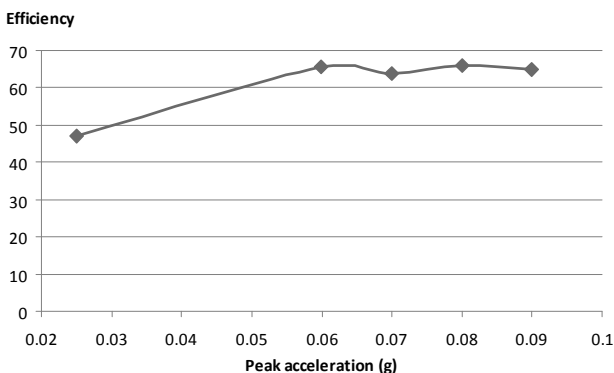


Fig.8. DC-DC converter efficiency vs. acceleration.

Higher values of acceleration resulted in the DC-DC converter entering CCM. This caused excessive loading on the transducer and therefore, poor power transfer. Needless to say, direct battery charging (without DC-DC converter) resulted in extremely poor power output and efficiency values.

VI. Summary and Conclusions

The design of EH circuits for WSN nodes is very important primarily because of the rapid development of this market and secondly, due to the limited life of battery and consequently, replacement. This, in particular, adds cost and limits deployment of these devices to high-value asset and limited life applications. Feasible EH from vibrations can extend battery life and at the bare minimum replenish idle energy consumption which is a dominant factor in battery life reduction. Since off-the-shelf converters do not meet the specifications of transducers at low frequencies and excitation levels, it is essential to have efficient electronics to be able to harvest power in such applications. Further optimization and implementation on a chip could allow more widespread use of such circuits.

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