Analysis of the Power Conversion Efficiency on Energy Scavenging Interface Circuits

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Abstract

In this paper, we report a comprehensive survey on power conversion efficiency of energy scavenging interface circuits. A realistic energy input model for vibrational systems was used and theoretical analysis provided. The realistic energy provided by energy scavenging system can be modeled with a sinusoidal current source in parallel with a capacitor and resistor whereas the magnitude and sinusoidal frequency of the current relate to vibrational magnitude and vibration frequency, respectively. We analyzed and designed different interface circuits used in the energy scavenging system which includes a full-wave, voltage multiplier, and half-wave rectifier. Simulations were performed using IBM’s 130 nm CMOS technology under the Cadence design platform. Each interface circuit was characterized to demonstrate their output power and efficiency. Optimizations of individual topologies were performed to yield maximum efficiency for different loads. We believe this comprehensive analysis will provide a good starting point to circuit designers in the energy scavenging society.

1. Introduction

The need for compact, portable, long-lasting, wireless technology is increasing with time for many applications such as wireless sensor networks, biomedical implants, or other circuit systems requiring microwatts of power\(^1\). These parameters are the force compelling technologies to develop smaller, more efficient designs. The reduction in size and power consumption of these technologies creates a unique opportunity to develop ultra-low power systems capable of batteryless function. This function is essential in the development of self-sustaining wireless technologies. Applications of this self-sustaining technology include ultra-low power systems such as micro-sensor networks and biomedical implants where battery replacement is extremely difficult or impossible\(^2\). Ambient energy is available in many different forms which provide an excellent source of power with absolutely no cost. Sources of ambient energy are geothermal/thermal changes, vibration, solar, and wind power\(^3-5\). Sources of energy to power electronics can also come from unexpected places such as the friction from clothes rubbing together or the vibration in the sole of a shoe when walking.

Self-sustaining wireless and green technologies are the driving force for energy scavenging systems. Energy harvesting for low-power circuits is possible using many different techniques. The most effective method in powering wireless micro-sensor networks is through vibrational energy scavenging. Efficient vibrational energy transducer methods include electrostatic (capacitive) and piezoelectric energy scavenging\(^6\). Other approaches such as electromagnetic transducers are options as well\(^2\). These methods, however, rely on forms of ambient energy that may not occur in large
enough magnitude or frequency for some applications. An example of such situation might include a solar powered interface circuit in an enclosed indoor environment. The same applies for any energy scavenging method but, vibrational energy harvesting is especially attractive because the resonant frequency of the circuit can be manipulated using adaptive circuitry.

Understanding the different approaches in energy scavenging methods is essential to create efficient, optimized systems capable of self-sustainability. Not only is it possible to energize ultra-low power circuits but, with enough research, larger devices will become self-powered as well. For low-vibration commercial settings, the most common method for energy harvesting uses piezoelectric materials.

Several interface methods are developed in order to extract power from the piezoelectric material which includes bias-flip, full-bridge, and voltage doubler rectifiers. A Realistic energy model for vibrational energy can be realized when piezoelectric materials are implemented using a sinusoidal current source in parallel with a capacitor and resistor whereas the magnitude and sinusoidal frequency of the current relate to vibrational magnitude and vibration frequency, respectively.

We theoretically studied and simulated different interface circuits used in the energy scavenging system which includes a full-wave, doubler, and half-wave rectifier. We performed the simulations of each interface circuit using the Cadence design platform. Each circuit was simulated in order to characterize its properties and exhibit its power and efficiency. The interface circuits were then analyzed to optimize performance and provide the most scavenged ambient power. We provide an analysis of different load resistances to demonstrate a maximum efficiency. We believe this analysis of common interface circuits will benefit circuit designers seeking to design new energy harvesting systems.

2. Equivalent circuit of energy harvester

A common source of ambient energy is vibration and an effective method of extracting this energy is using piezoelectric materials. Vibrational energy can vary in both magnitude and frequency. Energy harvesters have an intrinsic resonance frequency in which maximum power is obtained from the ambient source. This poses a challenge because vibrations are uncontrollable and the resonant frequency is rarely created. Ambient energy from vibration is unique because it can be modeled using mechanical mass spring system when harvested by piezoelectric materials.

A Realistic energy model for vibrational energy can be realized using a sinusoidal current source in parallel with a capacitor and resistor whereas the magnitude and sinusoidal frequency of the current relate to vibrational magnitude and vibration frequency, respectively. This model is particularly useful for running computer simulations in a software program such as Cadence.

Vibrations can be measured in any environment and converted into this equivalent circuit. This configuration can then be used in combination as a power source for different interface circuits in order to extract the ambient energy.
3. Common Interface Circuits

The full-bridge, half-wave, and voltage multiplier rectifier circuits were constructed using the Cadence design platform. The power source of each interface circuit is the piezoelectric model as shown above. This source was used to analyze the characteristics of each rectifier circuit. In order to properly analyze each interface method, the process of calculating power and efficiency is necessary. The values of the load current, internal and source capacitors affect the resonant frequency the circuit.

We designed the piezoelectric model to have a frequency value similar to what a commercial setting might demonstrate. This allowed us to choose capacitances accordingly. Once the values were chosen, the output voltage was simulated and compared to the input voltage. Using parametric analysis, an efficient load current was realized and provided a maximum output voltage.

Once an optimum load current was found, the efficiency of each circuit was then calculated. Efficiency, in this case, is the ratio of the output voltage and the input voltage supplied from the piezoelectric model. This value is calculated by taking the ratio of the average of the output voltage over the average of the input voltage during a specific interval of time. Once the maximum efficiency was found, an analysis of different efficiencies for different load currents is provided.

3.1 Half-Wave Rectifier

The first interface circuit we theoretically studied and simulated was the half-wave rectifier. Using IBM’s 130 nm technology, diodes were created by connecting the gate and drain terminals of the transistors. Then, using these diode elements and capacitors, a half-wave rectifier was created. The source capacitor is necessary because this is the constant voltage source the harvester will provide once the rectifier charges it. Without the source capacitor, a DC voltage source is not replicated and is not useful.
The function of the half-wave rectifier is to create an output voltage that is only the positive component of a sinusoidal input voltage. The half-wave rectifier achieves this function through use of the diode. The diode only conducts current if the anode voltage is greater than the cathode; otherwise the diode is reverse-biased and will not conduct. In a voltage signal with both positive and negative components, the positive portion of the signal will be passed while the negative is blocked because then the cathode is not greater than the anode. This is effective in energy harvesting because the energy signal provided by vibrations have both a positive and negative component in the voltage signal. If the entire signal were used in the interface circuitry, the output voltage of the harvester would be virtually nonexistent.

The realistic energy model is used with the half-wave rectifier to create the energy harvester. From here, different loads may be applied for the harvester and output voltages can be measured. For this energy harvester, we theoretically calculated a maximum output voltage of an efficient load 1.55 V and a maximum efficiency of 45.5%. The most efficient load for this circuit is 574 nA. These two values are demonstrated in Fig. 3 and 4. This is done by conducting a parametric sweep of the load resistance to effectively analyze the most efficient load.

![Figure 2: Schematic representation of half-wave rectifier with diode connected transistor.](image)

![Figure 3: (A) Efficiency of half-wave rectifier implementing parametric sweep of the load current. (B) Output voltage of the half-wave rectifier with efficient load current.](image)
The efficiencies of these circuits are measured by taking the output voltage over the input voltage and are calculated using the following equation in the Cadence Design Platform where \( V_{out} \) is the voltage at the output node and \( V_{in} \) is the input voltage from the piezoelectric model:

\[
\text{average}(\text{clip}\left(\frac{V_{out} \times I_L}{V_{in} \times I_P}\right), 2, 3)
\]

This equation yields the efficiency of the circuit by taking the average of the signals during a clipping period from two to three seconds. This equation produces the efficiency graph when a parametric sweep of the load current is performed.

### 3.2 Voltage Multiplier

The voltage multiplier achieves the same function as the half-wave rectifier in the sense that only the positive portion of the ambient signal is used. A multiplier increases the output voltage achieved by the energy harvester but at the cost of efficiency. The multiplier achieves its function because the first capacitor and diode act just as a half-wave rectifier during the positive portion of the input signal. When the input signal becomes negative, the first diode is then reverse biased and the second is forward allowing the first capacitor to aid in charging the storage capacitor creating a voltage equal to double the input. The actual voltage created is not equal to exactly double because the voltage drop across the diodes need to be accounted for. The most simple voltage multiplier is the voltage doubler, shown below.

![Figure 4: Schematic representation of voltage doubler.](image)

The voltage doubler achieved a peak efficiency of 58% with an output voltage of 1.9 V. The load current which provided the greatest efficiency is 574 nA. These values are demonstrated in Fig. 5.
Figure 5: (A) Efficiency of the X2 voltage multiplier implementing parametric sweep of the load current. (B) Output voltage of the X2 voltage multiplier with efficient load current.

The voltage multiplier is capable of creating integer multiples of the input voltage. This is accomplished by cascading voltage multipliers which are known as peak detectors. It should be noted that the storage capacitor is much larger, about 10x’s, than the internal capacitors because it is used as the DC supply voltage for external circuitry. The transistors are in a diode connected formation meaning their gates are connected to their drains forcing them to conduct in saturation mode.

Figure 6: Schematic representation of a plural voltage multiplier.

The X6 voltage multiplier was also analyzed in the same manner as before which yielded an efficiency of 46% with an output voltage of 4.6 V. The most efficient load was 354 nA. These values are demonstrated in Fig. 7.
Figure 7: (A) Efficiency of the X6 voltage multiplier implementing parametric sweep of the load current. (B) Output voltage of the X6 voltage multiplier with efficient load current.

The X10 voltage multiplier was also analyzed in the same manner as before which yielded an efficiency of 42.2% and output voltage of 6.9 V. The most efficient load was 218 nA. These values are demonstrated in Fig. 8.

Figure 8: (A) Efficiency of the X10 voltage multiplier implementing parametric sweep of the load current. (B) Output voltage of the X10 voltage multiplier with efficient load current.

3.3 Full-Wave

The full-wave rectifier is unique because its formation allows the negative portion of the input signal to follow the same current path as when it does during the positive input signal. The full-bridge rectifier consists of diode pairs connected in series. There are two pairs but only one pair is on per half cycle of the sinusoidal input signal. The diode pairs are connected in such a way that the current from the source flows through the load in the same direction during each half cycle. There exists a ripple voltage if a storage capacitor is not implemented. This storage capacitor essentially removes the ripple allowing for a
constant DC voltage to be provided to the external circuitry assuming the ambient vibrational source provides a sufficient power source.

Figure 9: Schematic representation of full-bridge rectifier.

The full-wave rectifier achieved a peak efficiency of 78.2% with an efficient load current of 281 nA. The voltage achieved at the most efficient load is 731 mV. These values are demonstrated in Fig.10.

Figure 10: (A) Efficiency of the full-wave rectifier implementing parametric sweep of the load current. (B) Output voltage of the full-wave rectifier with efficient load current.

In Fig.11, the efficiencies of the common interface circuits are arranged. It should be noted that while the full-wave rectifier was the most efficient, it did not produce the most useful output voltage, in comparison to the other simulated circuits.
Figure 11: Maximum efficiencies of the common interface circuits at most efficient load current.

4. Applications

Applications of systems that only require microwatts of power are perfect candidates for energy harvesting circuits. Specific applications that require ultra low power include wireless sensor micro-sensor networks\(^1\), tire-pressure sensor systems\(^2\), and implantable medical electronics\(^3\).

The application of IBM’s 130nm CMOS technology is best suited for extracting ambient energies on scales less than one volt. This is because the transistor has a smaller channel length and can function with much lower threshold voltages. This property makes this technology a perfect candidate for systems requiring microwatts of power.

Systems that could take advantage of the efficiency of this technology might include wireless micro-sensor networks. This becomes even more intriguing if the devices to be powered are fabricated using IBM’s technology. This would improve the minimum voltages required to power micro-devices. Wireless micro-sensor networks for process monitoring would be an ideal candidate for implementing these piezoelectric energy harvesters. Lead zirconate titanate (PZT) is an effective ceramic in piezoelectric energy harvesting applications and is best suited for low-level vibrations\(^4\). PZT is most effective with low-level vibrations because the material is fragile with relatively high vibration amplitudes and frequencies.
5. Conclusions

Based on the values derived from the simulations using IBM’s 130nm CMOS technology, the multipliers with the highest efficiency produced the best results in terms of extracting the most ambient vibrational energy. The piezoelectric energy model’s values were chosen solely based on values one might encounter in a low-level vibrational facility. Without adding any external circuitry, the power extracted ranges from 10 nano to 20 microwatts of power. In comparison to previous methods which produced power on the order of a few hundred micro watts, the values achieved here are much lower. This is due to the fact that the input signals in other methods are much higher than values used in these simulations. This does not mean that other methods are more efficient. IBM’s 130nm CMOS technology is much smaller than technology from other methods. This enabled the energy harvester interface circuits to yield a higher efficiency.

This technology for energy scavenging is useful in exceptionally low vibration systems. Other methods have larger technology which would require larger input signals from the piezoelectric model. These values include a larger amplitude and frequency. IBM’s technology sidesteps this in creating smaller, more efficient technologies. The channel length of the transistors used in these simulations is 130 nm where previous methods have much longer channel lengths. The smaller technology created by IBM provides an opportunity to create smaller, more efficient devices which takes technology one step closer to complete self-sufficiency and batteryless applications.

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