Performance Evaluation and Comparison of Developed ULP Energy Harvester in Active Technique with Conventional Circuits in Passive Technique

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Abstract: This paper presents the performance evaluation and comparison of developed Ultra-Low-Power (ULP) energy harvester in active technique with conventional circuits in passive technique. One of the most widely used energy harvesting techniques for micro-power applications uses piezoelectric materials. The materials convert vibrational energy to electrical energy. The interface circuits between the piezoelectric device and micro power devices play an important role in the energy harvesting process. Most of the previous techniques are mainly passive-based energy harvesting circuits. Generally, the power harvesting capability of the passive technique is very low. To increase the harvested energy, we have chosen the active technique and its components such as MOSFET, thyristor and transistor to design our proposed energy harvester system. In this paper, we have simulated both the conventional in passive circuit, and developed ULP energy harvester in active technique. The developed ULP circuits consisting of piezoelectric element with input source of vibration, AC-DC MOSFET bridge full-wave rectifier circuit, voltage regulator and DC-DC step-up (boost-up) converter using thyristor with storage device. In our development circuits, it is noted that we have chosen the components MOSFET instead of mainly diode available in conventional circuits. Because the forward voltage potential (0.7V) is higher than the incoming input voltage (0.3V). We have also designed voltage regulator circuit using MOSFET and op amp components to stabilise the rectified DC voltage. Finally, we have designed and simulated the complete energy harvester using PSPICE software. Our proposed circuits in PSPICE generate the boost-up DC voltage up to 1.67V. In the hardware implementation using breadboard, we obtained similar results as predicted by PSPICE. It is also able to give the maximum voltage of 1.50 V and current of 15uA for input voltage of 0.3V. The tested and verified conventional circuits in PSPICE software give the boost-up DC voltage up to 9.5V for input voltage of 4.5V. The overall efficiency of the developed circuit is 85%, followed by the software simulation, which is greater than conventional circuit efficiency of 20% in performance evaluator. It is concluded that our developed circuit output voltage can be used to operate for the applications in micro-devices.

Keywords: Energy harvester, Low voltage, AC-DC rectifier, DC-DC converter, Micro-devices

Introduction:
In the past researchers have surveyed several ambient sources for energy reclamation and converting into usable electrical energy [1]. Micro energy harvesters are small electromechanical devices, which harvest ambient energy and then convert it into electrical energy, as shown in Table 1. Macro v. Micro energy harvesting comparison is shown in Table 2. The choice of the source depends primarily on the specification of the power requirement for an application and design feasibility [2, 3, 4]. The most common sources for energy harvesting systems are vibration energy, thermal energy, wind energy, solar energy and radio frequency energy harvesting which are described in below.

The available semiconductor rectifiers fall short of ideal behaviour in several respects; the most serious shortcoming in the application of energy harvesting, where the AC frequency is low, is the drop in voltage across the device when conducting in the forward direction. This subtracts from the voltage generated by the harvester and it is therefore desirable to use a device having the lowest forward drop. Discounting germanium devices, (forward drop ~ 0.25V) which are not widely available with an appropriate current rating, silicon or Schottky diodes could be used. Schottky diodes need a forward voltage of 0.4 instead of 0.7V to operate within a circuit. In the bridge configuration, two diodes conduct at any one time hence even with Schottky diodes of a substantial amount of the harvester output voltage can be dropped over the diode, with the consequent losses. This problem is not so prevalent in piezoelectric based harvesters since the output voltage is typically much higher [5].

The process of extracting unused energy from the ambient environment and converting it into a usable form of electrical energy is known as Energy Harvesting. With recent growth in the development of low-power electronic devices such as microelectronics and wireless sensor nodes, as well as the global interest in the concept of “piezoelectric”, the topic of energy harvesting has received much attention in the past decade. Conventional low-power electronics, such as wireless sensor nodes, depend on batteries to provide power to the device. Piezoelectric materials have received the most attention for obtaining electric
energy from the surrounding environment for their ability to directly convert vibrations into electrical energy [6]. Among the various modes of energy harvesting, vibration energy harvesting is the most versatile technique developed in the literature [7]. Three main mechanisms of vibration-to-electrical energy conversion exist including electrostatic, electromagnetic, and piezoelectric transducer. Review articles highlighting work performed on all of the transducer mechanisms are given by [8]. Among the three modes of vibration harvesting, piezoelectric energy harvesting has received the most attention, with three review articles dedicated to recent research on piezoelectric transducer [9, 10]. Piezoelectric vibration harvesting is attractive mainly due to the simplicity of piezoelectric transducer and the relative ease of implementation of piezoelectric systems in a wide variety of applications as compared to electrostatic or electromagnetic methods [11, 12]. The transducer is the key component of the energy harvesting technology.

There is a common block diagram of the piezoelectric circuit divided basically into three parts: the energy source, the interface circuit, and the storage device as shown in Fig. 1. The ambient energy (i.e., environmental energy) was considered as a voltage source. The wind and solar energy were not chosen because this research work is at a micro level. That is why, wind is not suitable for indoor based application. The ambient source energy always generates the AC voltage. At first, we have tested and verified the individual conventional energy harvester interface circuits in PSPICE software before developing our propose energy harvester for micro-devices.

**Table 1: Energy Harvesting Estimates [13]**

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Harvested Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vibration/Motion</td>
<td></td>
</tr>
<tr>
<td>Human</td>
<td>4 μW/cm²</td>
</tr>
<tr>
<td>Industry</td>
<td>100 μW/cm²</td>
</tr>
<tr>
<td>Temperature Difference</td>
<td></td>
</tr>
<tr>
<td>Human</td>
<td>25 μW/cm²</td>
</tr>
<tr>
<td>Industry</td>
<td>1–10 mW/cm²</td>
</tr>
<tr>
<td>Light</td>
<td></td>
</tr>
<tr>
<td>Indoor</td>
<td>10 μW/cm²</td>
</tr>
<tr>
<td>Outdoor</td>
<td>10 mW/cm²</td>
</tr>
<tr>
<td>RF</td>
<td></td>
</tr>
<tr>
<td>GSM</td>
<td>0.1 μW/cm²</td>
</tr>
<tr>
<td>WiFi</td>
<td>0.001 μW/cm²</td>
</tr>
</tbody>
</table>

**Table 2 Macro v. Micro energy harvesting comparison [13]**

<table>
<thead>
<tr>
<th>Macro vs. Micro</th>
<th>Energy Source</th>
<th>Solutions</th>
<th>Ultimate Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Macro</td>
<td>Renewable energy (e.g., solar, wind)</td>
<td>Energy management solutions</td>
<td>Reducing oil dependency</td>
</tr>
<tr>
<td>Micro</td>
<td>Energy from the environment (e.g., vibration body heat)</td>
<td>Ultra-low-power solutions</td>
<td>Perpetual devices</td>
</tr>
</tbody>
</table>

2. Design of conventional energy harvesting interface circuits:

2.1. Conventional piezoelectric energy harvesting circuit:

There is a common block diagram of the piezoelectric based energy harvesting circuit divided basically into three parts: the energy source, the interface circuit, and the storage device as shown in Figure 1. The ambient voltage (V_{ac}) harvest the energy for maximum power. The optimal rectifier voltage (V_{rect,opt}) is one-half of the peak open-circuit voltage V_{ac} using by Eq. (1).

\[ V_{rect_{,opt}} = \frac{V_{ac}}{2} = \frac{i_p}{2 \omega C_p} \]  

However, since the diode-bridge rectifier circuit can also follow a resistive load, while the internal impedance of a piezoelectric device is essentially capacitive, the impedance matching condition cannot be satisfied, and so generally, the power harvesting ability of the passive technique is very low.

The conventional full-wave diode bridge AC-DC rectifier circuit is shown in Figure 2. Usually, the conventional full wave bridge rectifier is a four diode bridge rectifier. In operation, the sinusoidal (V1) voltage source is used as an input. The bridge rectifier used the four diodes and considered the first half-cycle, when the source voltage polarity is positive on top and negative on bottom. At this time, only the diodes (D2) and (D4) are conducting. The load shows the first half of the sine wave, positive on top and negative on bottom. During the next half-cycle, the AC polarity reverses. Now, the other diodes (D1) and (D4), the half of the transformer's secondary winding carry voltage while the portions of the circuit formerly carrying voltage during the last half-cycle. The AC-DC full wave diode bridge rectifier circuit in PSPICE...
platform has been simulated and its schematic diagram is shown in Figure 2.

![Figure 2: Conventional AC-DC full wave Diode bridge rectifier [14]](image)

2.3. Conventional voltage regulator circuit:
The linear regulator or Low Drop-Out Voltage (LDO) regulator regulates the output voltage by employing a transistor which operates in the linear region [15]. The transistor works like a variable resistor and it can divide the input voltage to a required value to power the load circuits. The schematic of the linear regulator is shown in Figure 3.

![Figure 3: Conventional voltage regulator Circuit [15]](image)

The amplifier would detect the voltage difference between the output voltage (0.2) and the reference voltage (0). The difference will then be feedbacked to control the gate voltage for transistor MP. The channel resistance of the transistor is adjusted, and the output voltage VO is varied accordingly due to the voltage dividing effect of resistance of the MP and the load resistor (RO= 10k). The voltage (VO=0.2V) is thus regulated and the value will approach the (VREF=0).

However, for the linear regulator, the targeted output voltage must be smaller than the input voltage, and the power transfer efficiency is low. Since the circuit regulates the output voltage by tuning the voltage drop over the transistor, the power loss on the transistor is large, and it is not suitable for the targeted energy harvesting systems.

2.4. Conventional DC-DC boost converter circuit:
A converter can be used to step-up a DC voltage and an arrangement for the conventional step-up operation is shown in Figure 4 [14]. When SW is closed for time t1, the inductor current rises and energy is stored in the inductor (L=4.7uH), if the switch is opened for time t2, the energy stored in the inductor is transferred to the load through the diode (D1=D1N4002) and the inductor current falls.

When the transistor is conducting, current is being drawn through the inductor. At this time, energy is being stored in the inductor. When the transistor stops conducting, the inductor voltage flattens back or reverses because the current through the inductor cannot change instantaneously. The voltage across the inductor increases to a value that is higher than the combined voltage across the diode and the output capacitor. When this value is reached, the diode starts conducting and the voltage appears across the output capacitor, is higher than the input voltage.

![Figure 4: Conventional Boost Converters [14]](image)

In many industrial applications, it is required to convert a fixed-voltage DC source into a variable voltage DC source. A DC converter can be considered as DC equivalent to a transformer with a continuously variable turns ratio. Like a transformer, it can be used to step-down or step-up a DC voltage source.

3. Simulation results of conventional circuits in PSPICE:
3.1. Simulation results of conventional AC-DC full wave rectifier:
The simulation results of the AC-DC diode bridge rectifier circuit is shown in Figure 5. From this figure, the output voltage of 585uV corresponding to the input voltage of 0.3V can be observed. This simulation result show the DC voltage with more ripple. From this figure, it can be observed that the voltage increases slowly after every 10 ms.

![Figure 5: Simulation result of the conventional full wave rectifier in Pspice](image)

3.2. Simulation Results of Conventional Voltage Regulator:
The simulation output result of the voltage regulator circuit is shown in Figure 6. The input value of the regulator circuit is 0.3V and simulation results show an unstable ripple output voltage of 0.2V. Finally, from this curve, it can be observed that the
conventional regulator circuit results are not able to achieve the expected stable output voltage.

The input value of the boost converter circuit is 5V and output voltage is 9.5V. Finally, from this curve, it can be observed that the conventional boost converter is able to boost-up the voltage approximately of 5V.

4. Development of the overall energy harvester system in Pspice:
The proposed block diagram is presented (step-by-step) to design the modeling of the piezoelectric based energy harvesting system, as shown in Figure 8. The completed energy harvester system is designed and developed with AC-DC full-wave bridge rectifier, voltage regulator circuit, DC-DC converter (step-up) and other devices. The schematic diagram of energy harvester is also given in Figure 9. The 0.1V~0.3V is chosen as an input voltage in Pspice simulation, instead of a piezoelectric vibration transducer (i.e., as equivalent voltage). It generates AC voltage, so a rectifier circuit is designed to convert the AC to DC. The input voltage of the piezoelectric based vibration transducer is not stable. To stabilize the rectified voltage, a voltage regulator circuit is developed which controlled the rectified voltage. The op amp output is the input of the DC-DC converter, the unity gained in this op amp is used as a buffer to prevent loading effects; and a satisfactory output is obtained. The regulated voltage is very low, so a DC-DC converter circuit is developed to boost-up the voltage level of 1.67V. The capacitor behaves as a battery for the purpose of voltage storage. A stable voltage is needed to run the micro-devices (i.e., bio-medical device and WSN etc).

5. Simulation result of the fully developed energy harvester in Pspice:
Figure 10 shows the final output voltage (1.6V) of the fully energy harvester interface circuit in Pspice simulation. The curve shows the horizontal voltage range between 0.1V to 0.3V and the current range between 5uA to 15uA. The times range of the voltage and the current are between 0s to 100ms. From Figure 10, it can be observed that the curve is becoming bent; initially, it takes some time to reach the current; after 5ms, it becomes constant.
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Figure 9: Energy harvester system using the developed piezoelectric transducer, AC-DC rectifier and DC-DC step-up converter with regulator (In working condition)

Figure 10: Input and output simulation voltages of energy harvester system in Pspice

6. Implementation of fully energy harvester system:
The complete developed energy harvester interface circuits consisting of several hardware modules such as AC-DC rectifier, voltage regulator circuit and DC-DC converter circuit using storage device. The snapshot of the fully energy harvester hardware system is shown in Figure 11. The input source (0.3V) of the integrated energy harvesting system has been chosen from Function Generator (i.e., equivalent of ambient sources piezoelectric vibration transducer). It generates AC voltage, so a rectifier circuit is designed for converting the AC to DC voltage. To stabilize the rectified voltage, a voltage regulator circuit is developed which stabilized the rectified voltage. The regulated voltage is also very low, so, a DC-DC converter circuit is developed to boost-up the overall voltage level of 1.5V in hardware implementation for fully energy harvester. The achieved voltage is measured by voltmeter. It is concluded that this voltage can be used for micro-devices application. The comparison results between the conventional, development circuits, and hardware implementation are given in Table 3.

Figure 11: Implementation of completed ULP energy harvester system with overall generated voltage (1.504V) for micro devices
Table 3: Comparison results between conventional, development circuits, and hardware implementation of energy harvesting circuits

<table>
<thead>
<tr>
<th>Different modules of energy harvester</th>
<th>Frequency</th>
<th>(V_{\text{in}}) (Input voltage for conventional simulation in PSPICE)</th>
<th>(V_{\text{out}}) (Input voltage for proposed simulation in PSPICE)</th>
<th>Output voltage of conventional circuits (PSPICE simulation)</th>
<th>Output voltage of development circuits (PSPICE simulation)</th>
<th>Output voltage in Hardware implementation</th>
<th>Application for micro-devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC-DC rectifier circuit</td>
<td>50 Hz</td>
<td>0.3V</td>
<td>0.3V</td>
<td>585uV</td>
<td>0.3V</td>
<td>0.51V</td>
<td>Both voltages of 1.6 V and 1.5V can be used for this micro-device.</td>
</tr>
<tr>
<td>Voltage regulator circuit</td>
<td>50 Hz</td>
<td>0.3V</td>
<td>0.3V</td>
<td>0.2V</td>
<td>0.29V</td>
<td>0.483V</td>
<td></td>
</tr>
<tr>
<td>DC-DC step-up converter circuit</td>
<td>50 Hz</td>
<td>4.5V</td>
<td>0.483V</td>
<td>9.5V</td>
<td>1.67V</td>
<td>1.63V</td>
<td></td>
</tr>
<tr>
<td>Fully energy harvesting circuit</td>
<td>50 Hz</td>
<td>0.3V</td>
<td>0.3V</td>
<td>1.6V</td>
<td>1.6V</td>
<td>1.5V</td>
<td></td>
</tr>
</tbody>
</table>

Conclusion:
The main focus of this paper is the testing and verification of the conventional circuit, development of an energy harvesting interface circuits, and implementation of the developed energy harvester circuit into hardware. The energy harvesting circuits consisting of piezoelectric element, AC-DC rectifier, temporary storage device, and DC-DC converter (Step-Up) have been developed in PSPICE simulation and verified by hardware implementation into breadboard. We have verified, proposed and analyzed our energy harvester system (using an active technique) for micro-devices application. The conventional circuits in PSPICE simulation is generated the maximum voltage of 9.5V for an input voltage 4.5V. The development circuit in PSPICE simulation is 1.67V for an input voltage of 0.3V and also hardware implementation is 1.5V. The overall circuit efficiency is about 85%, following the simulation results of the development circuits. This work have focused on the markets for ULP energy harvesting of vibration to electricity generation technology covering several primary applications – WSN, building automation wireless, battery-less, low-power applications.

References: