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Designing a Battery-Less Piezoelectric based Energy Harvesting Interface Circuit with 300 mV Startup Voltage

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Abstract. This paper presents a designing a battery-less piezoelectric based energy harvesting interface circuits with 300mV step-up voltage. A technique (i.e., DC-DC Step-Up converter) has chosen for designing the startup voltage with low voltage energy (i.e., 300mV). The proposed method consumes very little power, and is especially suitable for the ambient environmental source, where energy harvested power is very low. The energy harvesting interface circuit consists of MOSFET bridge ac-dc rectifier, voltage regulator, dc-dc step-up converter and an energy storage device with capacitor at the output terminal, replacing this by external battery. This paper will study results these important issues regarding the efficiencies of the energy harvesting power conversion interface circuits considering the storage device low voltage. The achievement of our development circuit is able to boost up minimum 1.67 V for input DC voltage of 300mV. The overall circuit efficiency is greater than 80 % following the simulation results. This research has focused on the application of Wireless Sensor Network (WSN) and bio-medical device can be operated without battery.

1. Introduction
Using of piezoelectric elements from ambient vibrations to harvest energy of great interest over the past few years. One of the most widely used power harvesting techniques for micro-power applications uses piezoelectric materials to convert any type of energy to electrical energy. Micro Energy Harvesters are small electromechanical devices, which harvest ambient energy and then convert it into electrical energy, as shown in Table-1 [1]. Table [2] shows a block diagram of ambient energy harvesting system. The choice of the source depends primarily on the specification of the power requirement for an application and design feasibility [2, 3]. 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. 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.
Piezoelectric materials can be used as a means of transforming ambient vibrations into electrical energy that can be stored and used to power other devices. Usually, energy harvesting systems based on piezoelectric devices can be summarized to have three core components: piezoelectric devices, electric energy storage, and power electronic interface. Different power harvesting methods, one example is Wireless Sensor Network (WSN), which has potential to be used in many areas health monitoring [4, 5, 6], piezoelectric conversion systems [7, 8]. Traditional electrochemical batteries are usually used in powering the WSNs. But replacing batteries, due to their limited lifetime, is not very convenient. The labor and cost associated with changing hundreds or thousands of batteries would be troublesome and expensive in maintaining the networks. Moreover, in many cases, the WSNs are installed in remote areas; therefore, it is difficult to retrieve for battery replacement. Without replacing batteries, the WSNs will stop working as soon as the power runs out. Therefore, it is desired that the WSNs can acquire energy from the ambient environment to have a continuous power supply [9, 10]. A complete WSN node in signal processing and communication area will normally have a power budget of 100 µW. Achieving this requires good application knowledge and well designed energy harvester to enable an optimal balance between power and resolution. The ultimate goal of this research work is to design a micro-power module (i.e., Low voltage circuit) that can be integrated into bio-medical device. Therefore, in this research work, we have a way to develop a low voltage energy harvester system for Ultra Low Power (ULP) Bio-medical application that energy harvester to integrate with WSN node. In this paper, we present the development of a low voltage energy harvesting circuit (based on simulation) using piezoelectric elements. The paper is also organized as follows: Section II describes the modeling of piezoelectric based Energy Harvesting system, such as piezoelectric element, AC-DC rectifier, temporary storage devices, DC-DC Converter (Step-Up). Section III describes the simulation results in PSPICE. Finally, conclusion is given at section IV in the paper.

| Energy Source            | Harvested Power |
|--------------------------|-----------------|
| Vibration/ Motion        | 4 µW/cm²        |
| Human                    | 100 µW/cm²      |
| Industry                 | 1–10 mW/cm²     |
| Temperature Difference   |                 |
| Human                    | 25 µW/cm²       |
| Industry                 | 1–10 mW/cm²     |
| Light                    |                 |
| Indoor                   | 10 µW/cm²       |
| Outdoor                  | 10 mW/cm²       |
| RF                       |                 |
| GSM                      | 0.1 µW/cm²      |
| WiFi                     | 0.001 µW/cm²    |
Table 2. Ambient Energy system [9]

| Ambient Energy Source & Energy Harvesting System |
|-------------------------------------------------|
| Electromagnetic Energy Harvesting                |
| Piezoelectric Energy Harvesting                  |
| Electrostatic (Capacitive) Energy Harvesting     |
| Thermoelectric (Thermal Gradients)               |
| Solar Energy Harvesting                          |
| Waste Energy (Generator)                         |
| Waste Mechanical Energy (PZT based materials)    |
| Initially Charged Varactor (Variable Capacitor)  |
| Thermopiles (-n and –p Types)                    |
| Photovoltaic Cells (Cells Consisted of Reverse-biased P+ + Junction) |
| Converters                                       |
| By Straining Deforming, and Vibrations of Piezoelectric Materials |
| Vibrations Separate Varactor’s Plates            |
| Temperature Differentials between Opposite Segments (Materials Joined at High Temperature Junction Establishes Voltage Differences between Base Electrodes) |
| Light Interfaces with Heavily Doped narrow n+ region (Electric Field Accumulates Electrons and Holes in the n+ and p- Regions) |

2. Development of piezoelectric based low voltage Energy Harvesting interface circuit

This section provides the modeling on piezoelectric based energy harvesting system considering of piezoelectric element, AC-DC rectifier, voltage regulator, DC-DC converter (step-up) and Temporary storage device. Here we mention all these characteristics are illustrated through selective block diagram. A simple produce is step-by-step presented to design the modeling of piezoelectric based energy harvesting system, as shown in Figure 2. To do the development of energy harvesting system, the PSPICE software has been performed on the proposed system. With the recent flow of micro scale
devices, piezoelectric power generation can provide a convenient alternative to traditional power sources used to operate certain types of sensors/actuators. Piezoelectric materials can be used as a means of transforming ambient vibrations into electrical that can be stored and used to power other devices.

![Proposed Energy harvesting modules (Experimental sub-blocks)](image)

**Figure 2.** Propose Energy harvesting modules (Experimental sub-blocks).

### 2.1 Piezoelectric element
Piezo Element is a Piezo Buzzer and also called Piezo Diaphragms and Piezo Benders. Many mechanical vibration-based energy harvesting systems use a piezoelectric transducer as an AC power source, whose output voltage must first be rectified before being delivered to a load. This piezoelectric vibration based transducer very low voltage (300mV) which can be applied to the full-wave rectifier circuit that consist of DC voltage without any voltage lose.

### 2.2 AC-DC rectifier circuit
The first stage of our developed ULP energy harvesting circuit is AC-DC rectifier. The rectifier circuit posed the problem of having very low input at which most devices (diodes) do not work for our case i.e., the forward voltage potential is higher than the input. To eliminate this problem, MOSFET or thyristor needs to be used. In our research, we used MOSFET to design the AC-DC full-wave rectifier circuit to get suitable DC voltage without loss voltage. Figure 3 shown is the proposed block diagram of the AC-DC rectifier.
2.3 **Voltage Regulator**

Voltage regulator is another part in power conversion sequence. As the rectified voltage of the AC-DC converter (on the load resistor) has strong dependency on the distance from the source and amplitude of the input signal, therefore the need of a voltage regulator that converts an input voltage to a fixed output voltage level. It also minimizes any variation by fluctuations in the input voltage or the load voltage is essential. However, due to limitation on available power, the regulator must be efficient and work with low voltage level.

2.4 **DC-DC step-up converter**

The third block of the energy harvesting interface circuit is the DC-DC step-up converter and its schematic diagram shown in Figure 4. The corresponding block diagram is shown in Figure 2 and results shown in section 3. The development of DC-DC converter provides a boost-up output while input voltage is too low. The minimum start-up voltage is 1.67V of the development of DC-DC converter outputs while the input voltage range approximately 300 mV DC after rectified. The development of DC-DC converter used the DC input (V\text{in}) = 0.3V. When switch control (M1) MOSFET is closed for time t\text{1}, the inductor (L1) current rises and energy is stored in the inductor and if the switch is opened for time t\text{2}, the energy stored in the inductor is transferred to load through thyristor (X1) and the inductor current falls. We had faced similar problems during to design DC-DC converter circuit were found, the (low input DC voltage 200mV). We used thyristor in the place of a diode to design this circuit. This is our new modified in our development DC-DC step up converter. The advantage of our modified new development DC-DC boost converter that it is able to increase the voltage using very low input source. We used MOSFET (M1) transistor and pulse (V5) is V1=0V, TD=1m, TR= 0u, TF=0u, PW=7ms, PER=10ms as a switching purpose for open and close. If a large capacitor (C1) is connected across the load as the output voltage is continuous and V\text{out} becomes the average value that the voltage across the load can be stepped up by varying the duty cycle and the minimum output voltage is V\text{in} when duty cycle = 0. We used inductor (L1) is 4.7uH for storage the current, Resistor (R1) is 10k\text{\Omega} used for the better output, we used capacitor (C1) is 100uF for store voltage and filtering of the output voltage to reduce ripple. Finally we are able to achieved the output voltage V\text{out} (1.67V) after using the DC-DC converter (Step-up).

For AC-DC rectifier circuit we used four MOSFET bridge rectifier and we got output (300mV) from this circuit without loss any voltage. The main focus is the paper by using DC-DC converter...
(Step-Up) boost up the rectified voltage. Finally we got output (1.67V) after using the DC-DC converter (Step-Up).

![Diagram of DC-DC converter (Step-Up) circuits](image)

**Figure 4.** Development of DC-DC converter (Step-up) circuits.

### 3. Simulation Results in Pspice software

The piezoelectric element used sinusoidal ($V_{in}$) voltage source as an input source. We used voltage source and internal series capacitor, and for voltage source we use capacitor as a series, output as shown in Figure 5 (a). For the AC-DC rectifier circuit we used four MOSFET-bridge rectifiers. We got (300mV) after rectified the piezoelectric voltage output as shown in Figure 5(b). The voltage (rectifier voltage) can be modified by controlling the DC-DC converter (Step-Up) between the two energy voltage the AC-DC rectified voltage and after using the DC-DC converter (Step-Up) circuit output. Using the AC-DC rectifier, and DC-DC converter (Step-Up), the energy storage device with the rectifier voltage output as shown in Figure 5(c) and 5(d).

![Simulation results](image)

**Figure 5(a).** Input voltage of the piezoelectric transducer.
The curve on the Figure 5(a) shows output of the piezoelectric circuit. The curve [A] observe is the input voltage of the piezoelectric transducer maximum 300mV AC voltage, curve [B] observe 200mV AC voltage and curve [C] observe 100mV AC voltage.

The Figure 5(b) is the output of the AC-DC MOSFET-bridge rectifier circuit. Finally, after analysis we are able to get full wave AC-DC rectifier voltage (without loss any voltage and without any ripple). In Figure 4.9(e) shows the final output DC voltage at different inputs AC single (between 100mV to 300mV).

We consider PER values duration between 1m to 9m and observed voltage and current. After analysis we find out suitable value of target voltage. Specify its start value, end value and increment as shown in Figure 5(c). From this Figure it can be observed that the voltage increase and decrease with values of switch. However, beyond 5m switch parameter value the voltage exceed our goal. Therefore, values for 5ms switch are match to achieve our expected results 1.67V.

The Figure 5(d) shown is the final output of the DC-DC converter circuit. There are two curves in the Figure. Here the curve [D] mention is the input of piezoelectric vibration sensor after AC-DC rectifier circuit full DC voltage 300mV, and the curve [E] denoted is the final output of the Step-Up DC-DC converter circuit is (1.67V). From this Figure, it can be observed that the curve is become bending, initially it takes some time to reach the voltage after 30ms it becomes constant. This phenomenon is also clearer from these Figures.
4. Conclusion
The energy harvesting circuits consisting of piezoelectric element, AC-DC rectifier, voltage regulator, DC-DC converter (Step-Up) and temporary storage device have developed by PSPICE simulation. The main focus of the research work is the development of the DC-DC Converter (Step-Up) of 1.67V. The overall circuit efficiency is about 80%, following the simulation results. Research work have focused on the markets for ultra-low power energy harvesting of vibration to electricity generation technology covering several primary applications – WSN, building automation wireless, battery-less, low-power switches, automotives, medical uses such as body area networks; precision agriculture; and consumer electronics. Future work will be focused on the design of the hardware implementation to verify the simulation result etc.

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