

Energy Harvesting Circuits with Piezoelectric Material: Design, Integration, and Optimization

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Abstract

Piezoelectric energy harvesters (PHE) have drawn significant interest as a method of harvesting environment energy to power because of its compatibility and high energy density. Integrating piezoelectric energy harvesters into wireless sensor networks, Internet of Things (IoT) devices, and wearable electronics enhances their functionality and also increases sustainability. This integration can lead to the development of self-powered devices that can operate continuously without the need for external power sources. The problem occurs while using PEH are the low level of harvested power and extraction of maximum power. The extracted output power need rectification and the output voltage need to be regulated. To overcome these problems piezoelectric energy harvester or transducer cannot be used alone to harvest mechanical energy. To increase the output voltage and power it is necessary to choose a piezoelectric material, piezoelectric transducer as well as an electric circuit. In this paper, we discuss different circuits such as Switch only rectifier circuit, Voltage multiplier based energy harvesting circuit, Synchronised Switch Harvesting on Inductor (SSHI) and Synchronous Electrical Charge Extraction (SECE) to harvest piezoelectric energy. The design and optimization of the circuits were done by using Multisim software. Physically, a stack transducer is developed by using PZT materials and integrated into the electrical circuit. The output voltage of 1.2 V to 1.9 V is recorded by using the human thumb impression to piezoelectric element and this voltage is sufficient to glow an LED bulb.

Keywords: Energy harvesting, piezoelectric material, PZT, transducer, electric circuit

INTRODUCTION

Energy harvesting involves extracting energy from external sources to either power machines directly or capture and store the energy for later use. It can be categorized into: Macro Energy Harvesting which utilize renewable energy sources such as solar, wind, tidal, and geothermal. This method aims to decrease dependency on oil and other non-renewable resources and provides an effective energy management solution. The second one is Micro Energy Harvesting where the sources are small-scale sources like vibrations, motion, and heat [1]. This approach is designed to power low-energy-consuming devices, offering ultra-low-power solutions. Micro energy harvesting is ideal for applications such as smart buildings, portable electronics, and sensors located in remote areas or within the human body. This includes devices like retinal prostheses, intraocular pressure monitors, cochlear implants, subcutaneous glucose monitors, and micro-oxygenators [2]. Recently, there has been considerable interest in vibration energy harvesting to create small-scale power sources. Mechanical-to-electrical energy conversion can be accomplished through different methods, yet studies indicate that

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piezoelectric materials are better on scales ranging from meso to micro energy harvesting [3]. Piezoelectric energy harvesting comes under the vibrational energy harvesting category that provides a micro-scale solution for applications requiring low-power electronics and sustainable electrical power, particularly in scenarios where replacing batteries or performing maintenance may be difficult or impractical.

In recent year 2023, U.S. Energy Information Administration (EIA) reported that the residential sector consumes 23% of global energy. This makes it the third-largest energy-consuming sector, following industry at 37% and transportation at 28% [4]. As working from home becomes more common and accepted by employers after the COVID-19 crisis, it is anticipated that energy consumption in residential buildings will significantly rise in the future. So it is necessary to increase the dependency on renewable resources or clean energy harvesting. Compared to electromagnetic and electrostatic methods, energy harvesting using piezoelectric materials offers higher energy density and greater flexibility for system integration, making it the most extensively researched approach.

Piezoelectric materials can be classified based on their structural characteristics into ceramics, single crystals, polymers, and composites (which combine piezoelectric ceramics or single crystals with polymers). The materials which have high piezoelectric coefficient (d_{33}) and high piezoelectric voltage coefficient (g_{33}) are used for piezoelectric energy harvesting. As the output power of the energy harvester depend on the transduction rate ($d_{33} \times g_{33}$). For energy harvesting PZT (lead zirconate titanate) and PMN-PT (a solid solution of lead magnesium niobate and lead titanate), are used. Below their Curie temperature, these materials exhibit spontaneous dipoles and possessed excellent piezoelectric properties [5]. The most powerful material is PMN-PT crystal which has large piezoelectric properties but the formation of large size crystal is expensive and tedious process.

Electric Power can be generated from piezoelectric modules either by hitting or vibrating. The hitting method produces more power than the vibrating method since it involves direct energy transfer to the piezoelectric modules. However, it can easily damage the modules. Vibrational energy can be harnessed using methods like inductive or capacitive harvesting, but these methods require an external voltage source [6].

The piezoelectric energy harvester consists of two parts i.e., mechanical module which generate electrical energy and electrical module which made up of an electrical circuit that convert and rectify the generated voltage [7]. Therefore, the efficiency of the energy harvester depends upon the piezoelectric material, harvester design (transducer) and also its incorporation into the electrical circuit.

In this paper, the different technologies used for piezoelectric energy harvesting are discussed and the pros and cons of various types of transducers used in piezoelectric modules are analysed. The design and optimisation of the different electrical circuits were done by using Multisim software. We have physically developed an electrical circuit using PZT stacks which gives higher output voltage of around 2 Volts which is sufficient to glow an LED bulb.

TYPES OF TRANSDUCERS

Depending Upon the Different Shape, The Piezoelectric Transducers Are Different Types

Cantilever Beam

The cantilever beam structure consists of a thin piezoelectric layer and a non-piezoelectric layer (typically a conductive metallic layer) anchored at one end which is designed to operate in its flexural mode. It is used widely because of its simple geometry and ability to generate maximum strain [8]. When a single piezoelectric layer is bonded to the metallic layer, the configuration is referred to as a 'unimorph.' In contrast, when two piezoelectric layers are bonded to a metallic layer on top and bottom side that setup is known as a 'bimorph' depicted in Figure 1(a). Out of both configurations generally bimorph structures are preferred in piezoelectric energy harvesting devices because they effectively double the electrical energy output without significantly altering the device volume [9]. Runday et al.

[10] manufacture 17.5 mm of PZT bimorphs cantilever to capture energy from low vibrations. The harvester's inherent frequency was set at 100 Hz and a proof mass was affixed to the cantilever's tip to decrease the frequency at resonance. This adjustment enabled the generation of power around 60 micro watts. Here the output power is proportional to the proof mass. However, a drawback of this cantilever beam harvester is its inability to withstand high impact forces.

Circular Diaphragm

The circular diaphragm structure illustrated in Figure 1(b), features a thin, disk-shaped piezoelectric layer affixed to a metal shim that is secured around the edges of a clamping ring. A proof mass is attached at the centre of the diaphragm to enhance performance at low frequencies and boost power output [9, 11, 12]. It is stiffer than a cantilever of the same size and demands higher resonance frequencies which are the disadvantage of this structure.

Cymbal Type

The cymbal transducer depicted in Figure 1(c), features a piezoelectric layer positioned between two metal end caps on either side. Axial stress is applied to the transducer, which is then converted into radial stress. This radial stress leads to an elevated piezoelectric coefficient (d_{33}) and also enhanced charge generation from this energy harvester. These structures are beneficial for applications involving greater impact forces generally in orthopaedic surgical device and gave higher output power [13, 14]. It is restricted to applications that require high-magnitude vibration sources.

Stack Type

It is made up of several piezoelectric layers stacked on top of each other (as shown in Figure 1(d)), with the alignment of the poling direction in each layer needing to match the direction of the applied force [9]. This structure can endure high mechanical loads, making it suitable for pressure mode operation, and it provides a higher output in d_{33} mode. These types of transducers are utilized in applications that require high pressure [15-17]. But the drawback of this type structure is its high stiffness.

Each of the four types of transducer has individual pros and cons. In our study we have used stack-type transducer due to its ability to endure high mechanical loads, its suitability for pressure mode operation, and its elevated output in d_{33} mode.

ELECTRICAL CIRCUITS

When mechanical force is applied to a piezoelectric transducer, it generates an electric potential difference through a process known as direct piezoelectric effect. However, the output of these transducer depends on both the speed and magnitude of the applied force. Consequently, piezoelectric transducers are mainly effective for measuring input force unless the force is mechanically controlled, which necessitates external power. Thus, stand-alone transducers are not used in piezoelectric energy harvesting applications. Instead, the output must be rectified and stored to harness the generated energy for use with external sensors and transmitters [18]. To achieve this objective, various electronic circuits are available i.e.,

- i. AC-DC piezoelectric energy harvesting circuit
- ii. Two stage piezoelectric energy harvesting circuit
- iii. SSHI technique and (iv) SECE technique

AC-DC Piezoelectric Energy Harvesting Circuit

To convert the alternating current (AC) generated by the piezoelectric transducers into a usable form (DC), an AC-DC energy conditioning circuit must be installed between the transducer and the energy storage device [19]. Various electrical configurations are employed to achieve optimal energy conversion efficiency. Among these, the predominantly utilized circuit involves a bridge rectifier, which converts the both polarities of output voltage into a unified polarity. In this circuit, a capacitor (C_L) is charged to a desired voltage and subsequently, a switch (S) is closed to connect the capacitor to the load resistance (R_L) as illustrated in Figure 2.

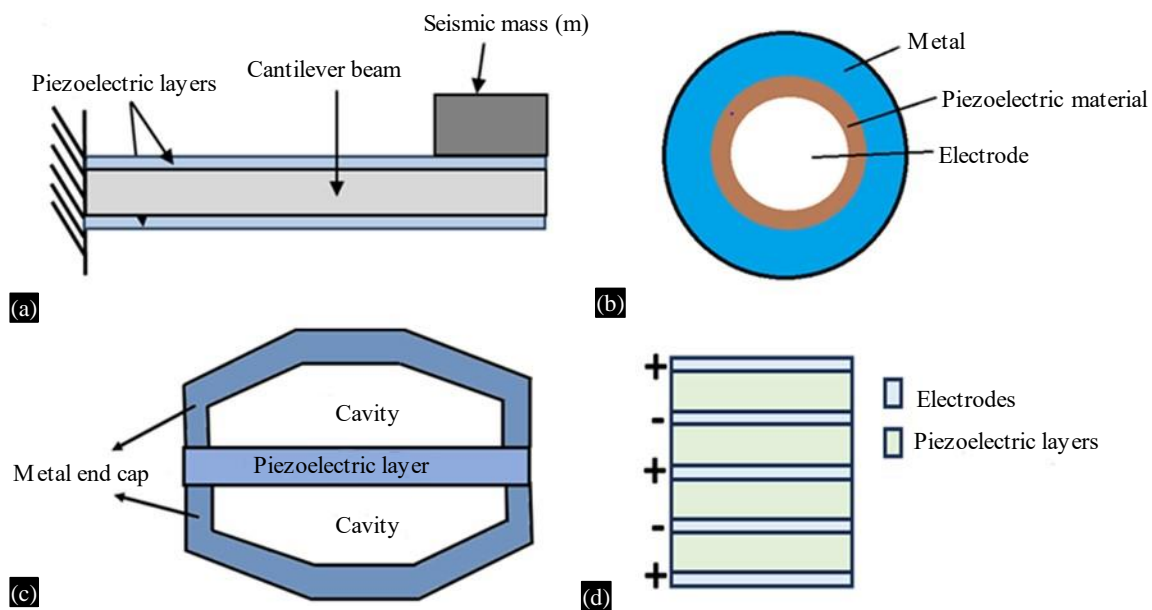


Figure 1. Different types of transducers (a) cantilever beam transducer, (b) circular diaphragm transducer, (c) cymbal transducer.

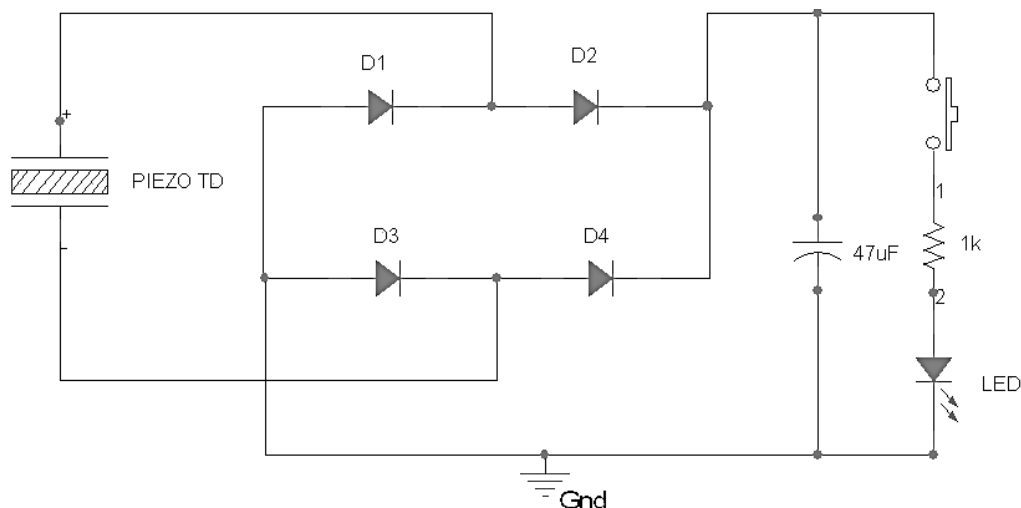


Figure 2. Piezoelectric harvester and switch-only rectifier.

As a result of the low power delivery of switch only rectifier, another inductor was added in the above circuit and named is as bias-flip rectifier circuit. A biased flip rectifier is a type of rectifier circuit that is used in energy harvesting applications. The bias-flip rectifier shown in Figure 3, incorporates an inductor connected in series with the switch. This inductor has the ability to store energy through an external magnetic field, facilitating the reversal of voltage across the piezoelectric element. This eliminates the need for complete discharge of C_p before it can be recharged. The switch operates by turning ON during an alteration in the direction of I_p and turning OFF when the current in the inductor reaches zero [20]. This circuit yields more than four times of the power in comparison to a conventional full-bridge rectifier. The biased flip rectifier efficiently converts the AC voltage produced by the piezoelectric element into DC voltage, while reducing losses from reverse leakage current. However, the output current will depend on both the load resistance and the strength of the mechanical force exerted on the element. The maximum voltage output of a piezoelectric element occurs when it is exposed to a resonance frequency. Therefore, the maximum voltage and current output of a piezoelectric element depend on the resonance frequency of the element and the load resistance of the circuit connected to it.

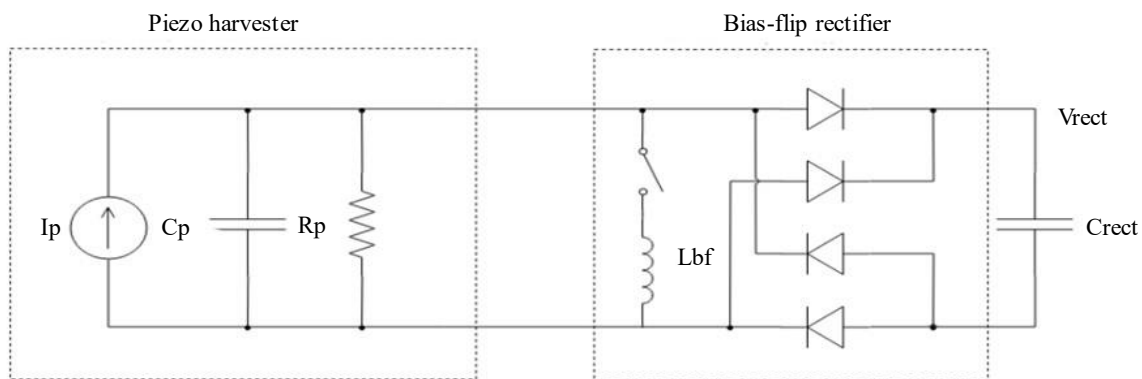


Figure 3. Piezoelectric harvester and bias-flip rectifier.

Another AC-DC converter energy harvesting circuit is Voltage multiplier based energy harvesting circuit as depicted in the Figure 4. When the voltage requirement is higher, a voltage multiplier based circuit can generate a higher voltage across the output. Adding a voltage multiplier to a piezoelectric energy harvesting circuit can increase the complexity of the circuit, which can make it more difficult to design, implement, and troubleshoot. It can introduce additional losses into the energy harvesting system which can reduce the overall efficiency of the system. This is because of the voltage multiplier uses diodes which have a voltage drop and capacitors have leakage currents. While a voltage multiplier can increase the output voltage of a piezoelectric energy harvesting circuit, it does not enhance the output power. This means that the maximum power that can be harvested from the piezoelectric element is constrained by its size, sensitivity, and the ambient vibrations to which it is exposed.

Two Stage Piezoelectric Energy Harvesting Circuit

A two-stage piezoelectric energy harvesting circuit is a kind of energy harvesting circuit that consists of two stages for converting and storing energy. The circuit is developed to extract the maximum amount of power from piezoelectric elements by utilizing two stages of conversion: a rectifier and a DC-DC converter. In the first stage, the rectifier converts the AC voltage generated by the piezoelectric element into a DC voltage. The rectifier circuit typically consists of diodes that facilitate the flow of current in only one direction, and a capacitor that filters out the high-frequency noise and smooths the output voltage. In the second stage, the DC-DC converter boosts the voltage generated to a level that is able to use to power a load or charge a battery. Therefore, a DC-DC converter has the potential to be used after the rectifier to maximize the power delivered to the storage device. Guan and Liao [21]. designed an optimized two-stage energy harvester shown in Figure 5, where C_0 is a temporary storage capacitor.

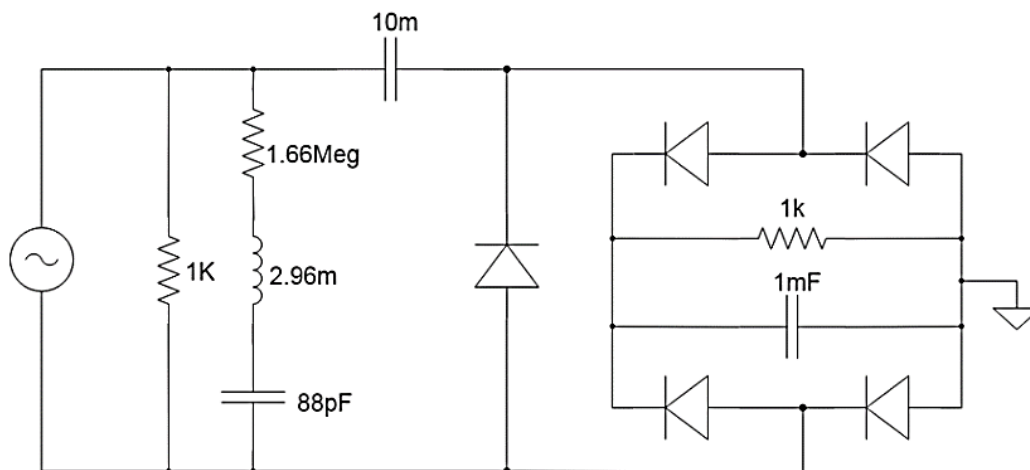


Figure 4. Voltage multiplier-based energy harvesting circuit.

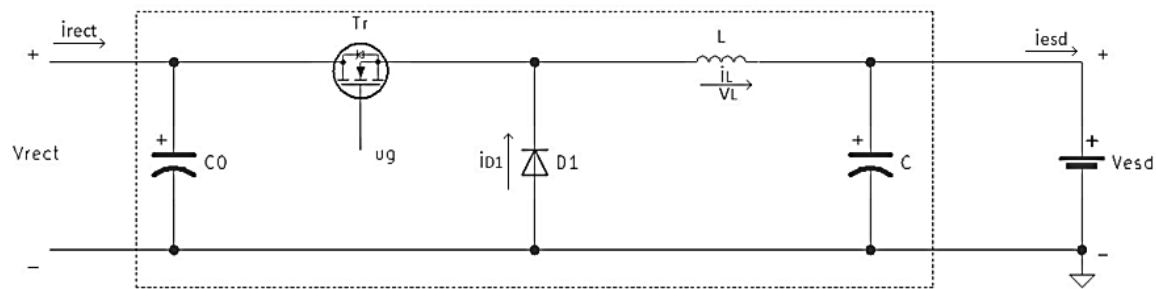


Figure 5. DC-DC converters in the two-stage energy harvesting scheme.

One disadvantage of a two-stage piezoelectric energy harvesting circuit is that it requires more components and is more complex than a single-stage circuit. This can lead to increased costs and reduced reliability, as there are more potential points of failure. Additionally, the multiple stages may introduce additional noise and losses, reducing the overall performance of the system. Finally, the two-stage circuit may not be suitable for all applications, as the voltage and current requirements may vary depending on the specific load and harvesting conditions. Another failure of this circuit is that it requires external source to start the clock pulse, but in case of remote areas where we want completely extraction of piezoelectric energy without using any external sources, so this is not suitable for that conditions.

Synchronized Switch Harvesting on Inductor (SSHI)

The energy harvesting system which exhibits weak coupling, the captured energy can be enhanced through the implementation of a nonlinear method known as synchronized switch harvesting on inductor (SSHI) [22]. In this approach a resonance circuit is formed by the internal capacitor of the piezoelectric transducer and an external inductor. The external inductor rapidly alters the capacitor voltage, neutralizing the impact of the capacitive term. Consequently, the energy previously used to charge the internal capacitor for diode bridge conduction, that energy might have been wasted is now effectively captured.

In the traditional AC-DC energy harvesting circuit, negative power is generated due to a phase mismatch between the output current and the generated voltage. This discrepancy implies that some of the harvested energy might revert to the mechanical component, resulting in a loss of harvested power [23]. The SSHI circuit (depicted in Figure 6 and Figure 7) addresses this issue by introducing a switch path, comprising the switch S1 and the inductor L1. This modification allows the circuit to capture the capacitor charge instead of it being dissipated as waste. There are two SSHI circuits name as series SSHI circuit (Figure 6) and parallel SSHI circuit (Figure 7). Both circuits can increase the output voltage [24]. The difference between the parallel SSHI and series SSHI circuit is the connection of switch path whether it is connected in parallel or in series with the rectifier.

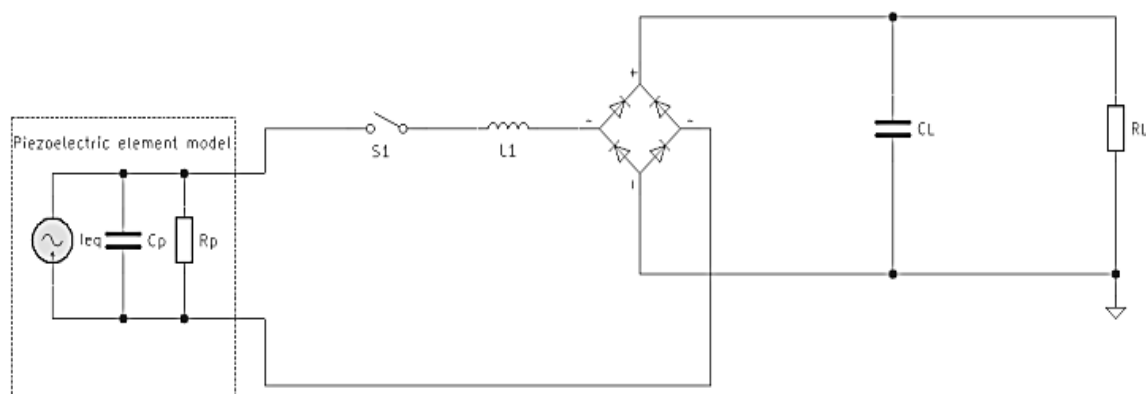


Figure 6. Series-synchronized switch harvesting on inductor (SSHI) energy harvesting circuit.

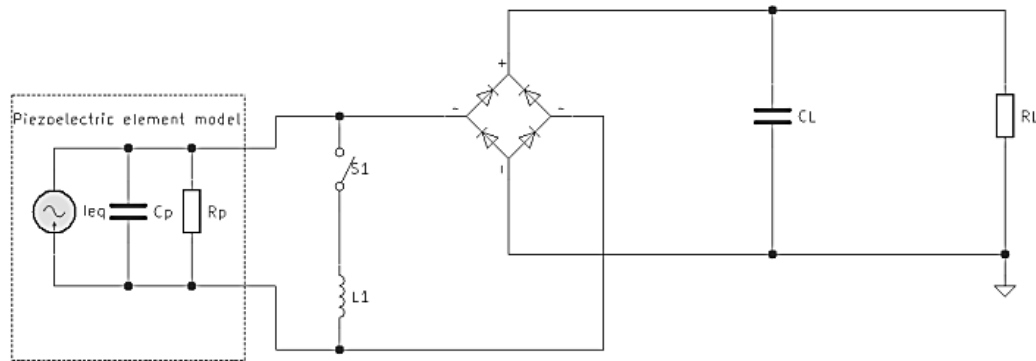


Figure 7. Parallel-synchronized switch harvesting on inductor (SSHI) energy harvesting circuit.

Lallart and Guyomar [24]. developed a self-powered SSHI interface which is able to perform switching actions automatically once the output voltage attained that maximum level. These circuit are categorized into two i.e., (a) self -power parallel SSHI circuit and (b) self-power series SSHI circuit.

Self -Power Parallel SSHI Circuit

The self-powered parallel-SSHI energy harvesting circuit is a kind of energy harvesting circuit that combines the benefits of parallel connection and synchronous switch harvesting on inductor (SSHI) to enhance the overall system performance.

The self-powered parallel-SSHI energy harvesting circuit is a modified version of the SSHI circuit as illustrate in Fig. 8. In this circuit, two SSHI circuits are connected in parallel with opposite polarities to eliminate the need for a rectifier circuit. This configuration enables the circuit to harvest energy in both directions of vibration and can increase the overall power yield by the system. A significant advantage of the self-powered parallel-SSHI circuit is that it allows for a higher output power compared to the conventional SSHI circuit, also increases the output voltage. Additionally, the parallel combination of the piezoelectric transducers reduces the impedance mismatch and increases the power transfer efficiency. However, the self-powered parallel-SSHI circuit also has some disadvantages. One disadvantage is that it requires two piezoelectric elements, which can increase the dimension and mass of the system. Another disadvantage indicates the circuit may have a lower efficiency compared to other circuits, depending on the specific application and vibration conditions.

Self-Power Series SSHI Circuit

The Self-Powered Series-SSHI energy harvesting circuit is a modified form of the SSHI circuit designed to enable self-sustaining operation without relying on an external power supply. This modified circuit employs a series arrangement of piezoelectric components to generate an increased output voltage. Subsequently, this voltage is rectified and stabilized via a buck-boost converter, ensuring a consistent output voltage as illustrate in Figure 9. The operation of the SSHI circuit occurs in two distinct phases. In the initial phase, the mechanical vibrations charge the piezoelectric elements and the generated charge is stored in a capacitor. This charging procedure is managed by a switch that turns on and off regularly to uphold a consistent voltage across the piezoelectric elements. Subsequently, in the following phase, the stored charge within the capacitor is released through a sequence of diodes and the buck-boost converter to generate a steady direct current (DC) output voltage.

Compared to the traditional SSHI circuit, the self-power SSHI circuit offers several advantages. First, the self-power SSHI circuit doesn't require any external power source, which makes it ideal for low-power applications. Second, it provides a higher output voltage because of the series connection of piezoelectric elements, which is capable of being used in certain applications. Finally, the buck-boost converter improves the overall performance of the energy harvesting process by allowing for maximum power extraction from that element. However, the SSHI circuit also has some limitations. The charging and discharging process of the capacitor can lead to energy losses and reduced efficiency, especially if the capacitor has a low capacity.

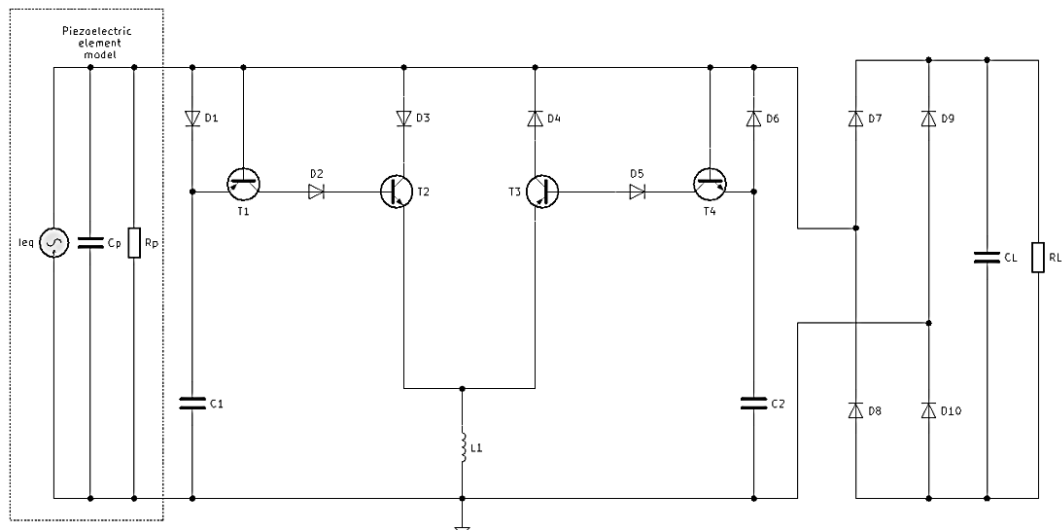


Figure 8. Self-powered parallel-SSHI energy harvesting circuit.

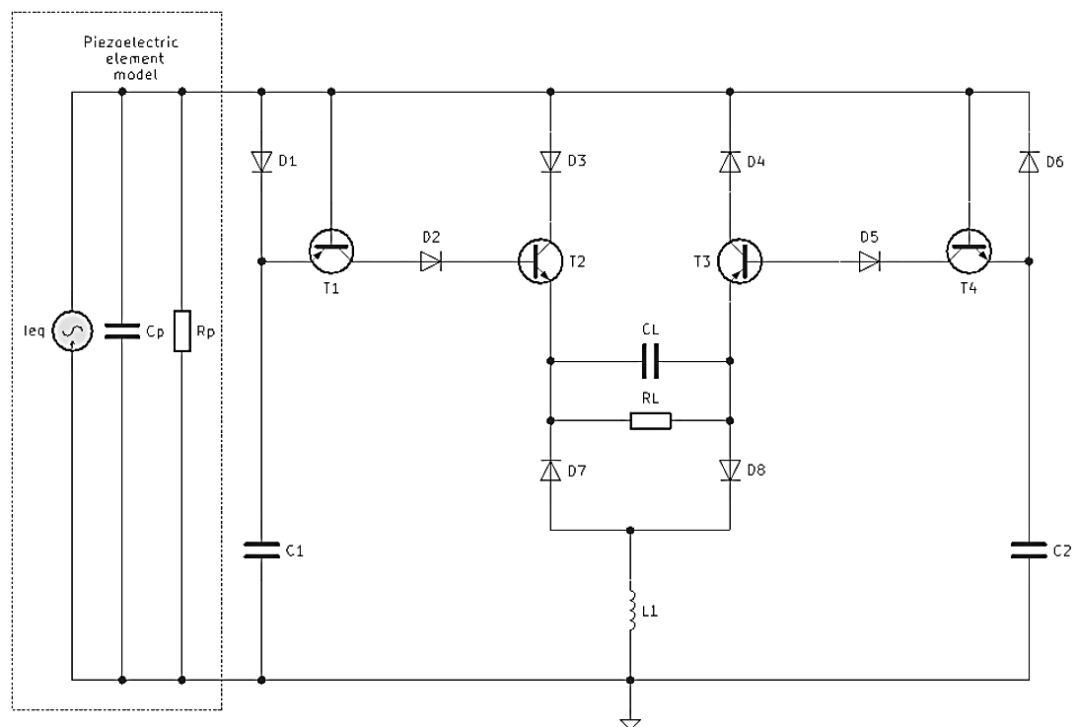


Figure 9. Self-powered series-SSHI energy harvesting circuit.

These circuits have the ability to store harvested energy in a storage element like a super capacitor or battery. Both circuits can be used in a diverse field of applications where it is essential for energy harvesting from vibration sources.

Synchronous Electrical Charge Extraction Circuit (SECE)

Synchronous Electrical Charge Extraction (SECE) is an additional method employed in piezoelectric energy harvesting circuits to capture the electrical charges produced by the piezoelectric material. The working principle of a Synchronous Electrical Charge Extraction (SECE) circuit involves the synchronization of the switching of a power switch and the polarity of the piezoelectric transducer. The SECE circuit uses an inductor to store and transfer the energy produced by the piezoelectric transducer to the output.

During the positive phase of the input voltage received from the piezoelectric transducer, the power switch is activated, causing the inductor current to rise steadily. In this phase the inductor current flow through the diode and charge the output capacitor. When the input voltage reaches to zero, the power switch is deactivated. During the negative phase of the input voltage, the power switch is once again activated, but owing to the reversed polarity of the piezoelectric transducer, the inductor current flows in the opposite direction. Upon reaching zero voltage, the power switch is deactivated again, enabling the inductor current to pass through the diode and charge the output capacitor with a negative voltage. This cycle leads to the accumulation of both positive and negative charges on the output capacitor, leading to the generation of an alternating current (AC) voltage. The AC voltage is subsequently converted to direct current (DC) voltage through a full-bridge rectifier. Finally, the output of full bridge rectifier is connected to a voltage regulator, which keeps the output voltage constant across the load.

The Synchronous Electrical Charge Extraction Circuit is represented by Figure 10. In this circuit a MOSFET transistor is used and the gate voltage (u_g) is determined by a control circuit that measures the rectified voltage V_{rect} as well as the performance of the power converter system. When the rectified voltage reaches its maximum value, a voltage is imposed to the transistor gate (T). This initiates conduction and allow the transfer of electric charge from the piezoelectric transducers to the coupled inductor. Once the electrical charge from the piezoelectric transducer is completely extracted, the control circuit detects the absence of the rectified voltage, and blocked the transistor (T). Afterward, as the transistor is blocked, the piezoelectric transducer returns to an open circuit state, and the energy stored in the inductor is delivered to the storage capacitor. As the rectified (DC) voltage attained its maximum value again, in sync with mechanical displacement, the subsequent electric charge extraction process occurs [25].

SECE circuit has the advantage of being able to harvest energy from low-frequency and high-amplitude vibrations, making it suitable for a broad range of applications. It also has boasts high energy conversion efficiency and can operate with a low input voltage, making it well-suited for low-power applications.

OPTIMIZATION

The voltage output of a piezoelectric energy harvesting system influenced by the type of piezoelectric materials employed. Table 1 presents various piezoelectric materials with different dimensions and their corresponding output power generated under varying forces, pressure and acceleration [26]. Table 1 indicates that piezoelectric ceramics deliver a higher power output compared to other materials but are less capable of withstanding large strains. On the other hand, piezoelectric polymers offer the smallest power output but possess the greatest flexibility and the smallest coupling coefficients. Piezoelectric single crystals boast superior power density relative to other piezoelectric materials, though they are very expensive [27]. For applications of energy harvesting PZT ceramics are used at low frequencies, as well as high frequencies as PZT ceramic can take any shape depending upon the type of transducer and has high piezoelectric coefficient (d_{33}). So here we have used the PZT-5 rectangular ceramic.

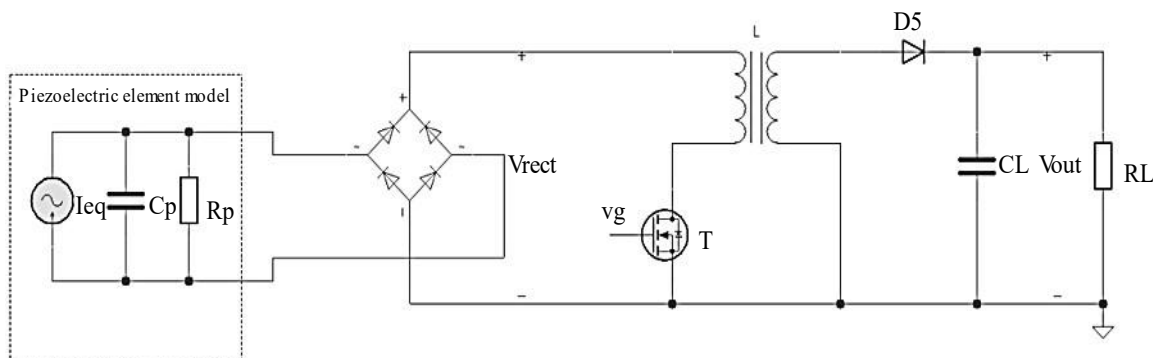


Figure 10. Synchronous electrical charge extraction (SECE) energy harvesting circuit.

As the generated voltage and power depends upon the configuration of transducer. Among the various types of transducer, stack transducer show effective output voltage and has capacity to tolerate high stress. The stacks are formed by taking 10 rectangular ceramic of PZT-5 having dimensions $1\text{cm} \times 1\text{cm} \times 1\text{mm}$ each.

Another factor on which the output voltage and power of piezoelectric harvester depend is its electrical module which consists of electrical circuits. As discussed above different electrical circuits were design and optimized by using Multisim software. It was observed that the piezoelectric harvester with switch only rectifier possess good output. So this circuit was physically designed by taking 1N4007 diode, $50\mu\text{F}$ capacitor, 1K resister and got the results as shown in the Figure 11 (a). The Figure 11 (b) shows the circuit of a switch only rectifier circuit based piezoelectric energy harvester, in which we have attached a piezoelectric element and after applying strain on it by human finger we get the output voltage of 1.2V on average and we have also recorded the highest voltage of 1.9V. This energy harvester is useful in a way where we can use it to glow LED bulb with low threshold current and it will be helpful for remote areas where there is no electricity available.

Table 1. Various piezoelectric energy harvesters and their performances.

Material	Volume	Frequency (Hz)	Peak power (μW)	Excitation (acceleration, force or pressure)
PVDF	$30 \times 12 \times 0.005 \text{ mm}^3$	2	0.0005	3-point bending at 3 N
PVDF	$10.94 \times 22 \times 0.354 \text{ mm}^3$	104	2.75	1G
PVDF	$20 \times 16.1 \times 0.2 \text{ mm}^3$	146	2	9 Pa
PVDF	$72 \times 16 \times 0.41 \text{ mm}^3$	3	610	Wind speed of 4 m/s
PZT ceramic	$1 \times 1 \times 2 \text{ cm}^3$	1	265	900N
PZT ceramic	$25 \times 10 \times 0.8 \text{ mm}^3$ bimorph	1	47	Shook by hand
PZT ceramic	$45 \times 20 \times 0.3 \text{ mm}^3$	20	2000	1N
PZT ceramic	$31.8 \times 6.4 \times 0.3 \text{ mm}^3$	36	40	0.2G
PZT ceramic	1 cm^3	100	60	0.23G
PZT ceramic	1 cm^3	100	39000	7.8N
PZT ceramic	1.5 cm^3	100	52000	70N
PZT ceramic		2580	1800	2G
PZT fiber		180	750	
PZT fiber	2.2 cm^3		120000	0.033N
PMN-PZT single crystal	$20 \times 5 \times 0.5 \text{ mm}^3$	1744	14.7	
PMN-PT single crystal	$1.7 \times 1.7 \times 0.00084 \text{ cm}^3$	0.3	6.7	Bending motion at a strain of 0.36 %
PMN-PT single crystal	$25 \times 5 \times 1 \text{ mm}^3$	102	3700	3.2 G

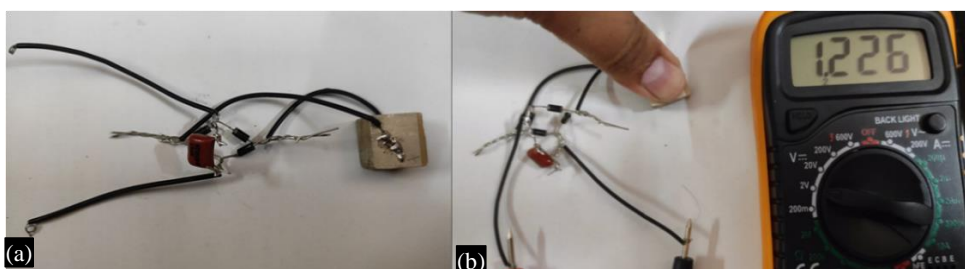


Figure 11. (a) Switch only rectifier circuit and (b) output voltage of switch only rectifier circuit.

CONCLUSION

In the modern era, the necessity for developing energy harvesting systems is evident. Specifically, piezoelectric energy harvesting is crucial because it can be utilized in areas where battery replacement or maintenance is challenging. The output voltage generated in the electrical circuits as optimized, giving force on piezoelement stack by human fingers is nearly 2 volts. However, on a larger scale, this technology can power low-energy devices if installed in high-traffic areas or in floor tiles of railway stations. This article explores various electronic circuit configurations and optimization methods, demonstrating that piezoelectric devices have a broad range of applications.

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