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Design and optimization of piezoelectric energy harvesting systems for enhanced performance in wireless sensor networks

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Abstract

The appetite for seeking sustainable energy solutions has now reached a fever pitch and that is where the focus on new ways to tap into renewable energy sources has come to the forefront. Piezoelectric-based energy harvesting is a promising technology for providing electric power to Wireless Sensor Networks (WSNs) in order to extract relevant environmental information. The goal of this study is to maximize the both the mechanical and electomechanical design of such piezoelectric systems to improve their energy harvertsing1. With the help of MATLAB SIMULINK we do research for system response under different condition to understand electric to mechanical responses in an efficient way to arrest energy efficiency. These factors encompass mechanical stability, impedance matching, and efficient energy storage (as in rechargeable batteries). The results offer a general perspective for advancing piezoelectric energy harvesting technologies, and the proposed strategies serve as guidelines for future device design and optimization.

Keywords: Energy harvesting; Piezoelectric; Smart materials; Vibration; Wireless sensor networks (WSNs)

1. Introduction

Based on the recent technology growth the researchers are gaining interest in the area of energy harvesting from ambient vibration sources. It is with this use-case that this technique is particularly well-matches - power supply for low-powder little electronic devices and WSNs. This problem can be solve by using piezoelectric material i.e. converting the mechanical vibrations from environment to electrical energy by applying Piezoelectric materials which produces electric charge on applied physically squeezing [1,2]. A wide variety of efforts in this direction are motived form the demand in both autonomous and maintenance free systems, from healthcare devices to infrastructure monitoring [3,4]. The state of the art in each of these categories is reviewed in this paper, and advanced design strategies for improving energy harvesting performance are discussed.

2. Advances in Piezoelectric Materials and Fabrication

2.1. Recent Developments in Piezoelectric Materials

Piezoelectric materials have shown considerable advancements in their performance for energy harvesting applications. Lead zirconate titanate (PZT) is still well liked because has high piezoelectric coefficients and is stable as a standard material. Nevertheless, the security issues raised ecological concerns for which have given birth to lead-free substitutes such as barium titanate ($BaTiO3$) and potassium sodium niobate (KNN) that demonstrate similar characteristics without the hazardous nature [5,6]. The nanotechnology has now further extended the capability of

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piezoelectric film technology into piezoelectric nanofibers and thin films, which improved the efficiency and flexibility of the device[7,8]

2.2. Recent Developments in Piezoelectric Materials

Advances in fabrication techniques, including nano/microfabrication methods such as electrospinning and additive manufacturing, have enabled the production of nano-structured piezoelectric fibers and thin films. These improvements enhance the surface area and mechanical properties of piezoelectric devices, making them more effective for various applications [9,10]

3. Device Integration and Optimization

3.1. Device Integration

The energy harvesting system that integrates piezoelectric materials must optimize the mechanical design of transducers and the electrical circuits associated with them. The aim is to raise mechanical-to-electrical energy conversion efficiency. But you also have to ensure that your system is tough and reliable at whatever conditions it will work under.Moreover, various innovative configurations have been explored such as bimorph and unimorph structures.

In the area of energy conversion bimorph structures consist of two piezoelectric layers with a substrate sandwiched between them. The double layer produces increased energy harvest from mechanical vibrations while still being easy to implement. By contrast, unimorph structure consists simply of one piezoelectric layer attached to a substrate, direction which is also energy conversion properties [11,12].

Advanced power management circuits have been developed to further improve the energy extraction and storage efficiency. These are synchronised switch harvesting on inductors (SSHI) and other non-linear processing techniques. They help to cut losses of energy and improve overall energy harvesting system performance[13,14].

3.2. Piezoelectric Transducer Designs

In the universe of mechanical energy to electrical energy piezoelectric transducers play an important role. A piezoelectric cantilever beam - which is a design generally used, and consists of an active piezoelectric layer bonded onto a passive substrate beam. This design exploits the piezoelectric strain coefficient (d31) to achieve maximum energy conversion from mechanical vibration [15,16].

Different shapes and sizes of cantilever beams, including unimorphs and bimorphs, have been widely analyzed for electromechanical behavior and power generation at resonance frequencies. By adding an inertial mass to the beam tip the resonance frequency of the system has been shown to decrease such that the responses of the device can achieve high-mechanical responses and power generation capabilities at low-amplitude excitations [17,18]. The use of innovative beam shapes such as triangular and trapezoidal profiles and new boundary conditions have additionally enhanced the performance of energy harvesting [19,20].

Figure 1: Piezoelectric Beam Harvester configurations Fig. Figure 1(a) illustrates a cantilever beam with an inertial mass that helps lower the resonance frequency and increase efficiency at lower frequencies. Fig. (c) (1) cantilever vibrational mechanism with a triangular cross-section for better strain distribution and energy harvesting efficiency. Fig. A further mechanical amplification of vibrations is introduced by the dynamic amplifier support in 1(c). Fig. Figure 1(d) shows an asymmetric tuned mass configuration based on the resonance characteristic of the beam. Fig. Figure 1(d) depicts multisectioned clamped clamped beam-loaded with multiple inertia masses for wideband frequency range of vibration energy harvesting.

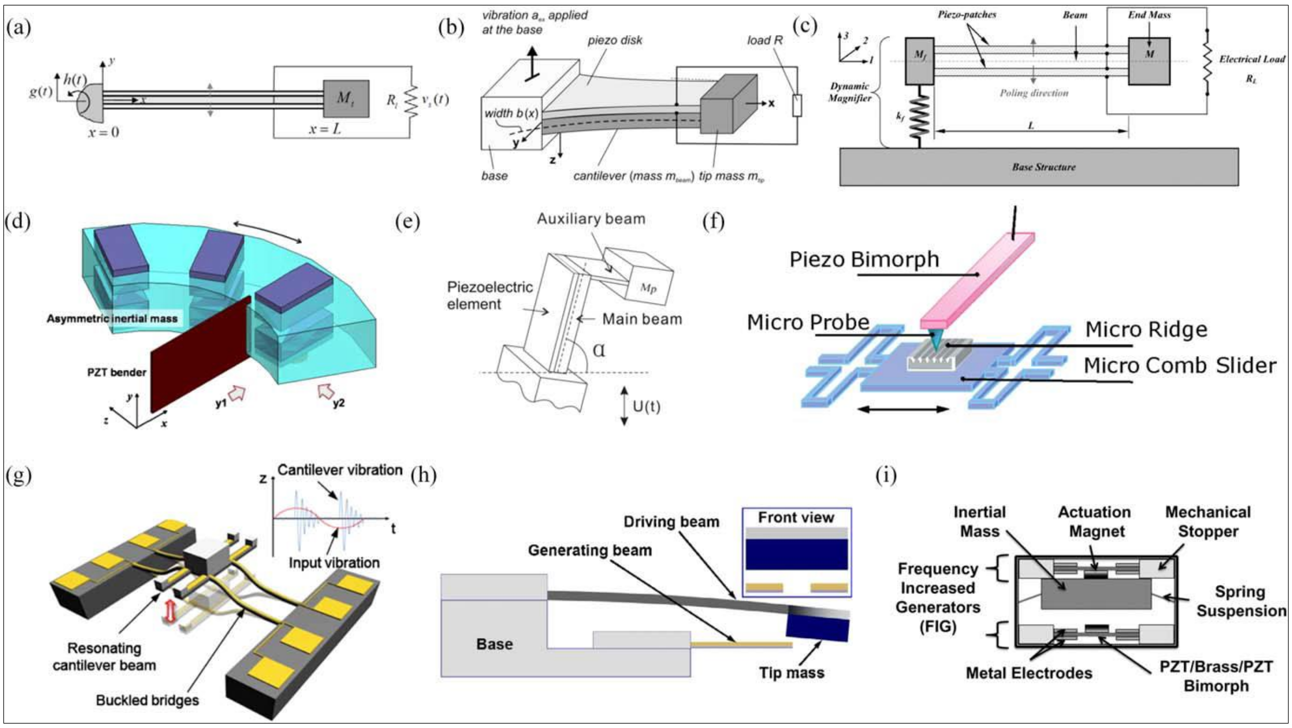

Figure 1 Various Piezoelectric Beam Harvesters

Several frequency up-conversion mechanisms have been developed to overcome the challenges of harvesting energy from low-frequency vibrations. This category consists of types like slider mechanisms, impact mechanisms, and snap-through mechanisms, for the transformation of slow, low-frequency motions to high-frequency vibrations, which means higher energy output [21, 22]. More advanced fabrication methods such as exploiting the attributes of superelastic shape memory alloys and compliant driving beams also were also examined to enhance the robustness and efficiency of piezoelectric transducers under different operational scenarios [23,24].

3.3. Frequency Up-Conversion Mechanisms

Fig.1(f) shows an example of such a slider mechanism that uses superelastic shape memory alloy ridges that transforms lower frequency vibrations to high frequency oscillations. Fig. Mechanical instabilities can alter the configurations of the hydrofoils to optimize energy conversion as shown in Figure 1(g) exhibiting such a snap-through mechanism using four buckled thin bridges. Fig. 3a1h shows a blow-impact based device with a pivoted-driven beam in intermittent contact with the piezoelectric beam to drive the PZ beam at its resonant frequency. Fig. Figure 1(i) shows an impact-driven piezoelectric energy harvester with spiral piezoelectric beams that aim at maximizing the harvested energy from the ambient low-frequency vibration of the base.

These features make the piezoelectric energy harvesting system not only farther, but also widely expand its application adaptable to various field of the design, application, and manufacturability. These developments are vital for the advancement of self-powered, fatigue-resilient device technologies, significant in a broad array of fields, including wireless sensor networks, healthcare monitors, and environmental sensing.

4. Methodology

Modeling and Simulation of Piezoelectric Energy Harvesting Systems using MATLAB SIMULINK State-space equations in Laplace transform domain were deduced to simulate different electrical circuit systems which simulate a power supply for the piezoelectric harvester with load fluctuation. This method provides the modeling of circuits with an efficient way as the differential equations are not to be solved. State-space equations were developed for all electrical circuit systems considered, and the matrix system (A, B, C) was derived. To this end, key parameters such as mechanical stability, impedance matching and energy storage efficiency were studied to achieve an optimum performance of the overall system [25,26].

$$F = L_1.\frac{\dot{I}_1}{dt} + R_1.I_1 + \frac{1}{c_1}\int I_1\,dt + V_1$$

$$F = L_1.\frac{\dot{I}_1}{dt} + R_1.I_1 + \frac{1}{c_1}\int I_1\,dt + \frac{1}{N}\int (I_2 + I_3)dt$$

$$I_2 = C_2.\frac{V_2}{dt}$$

$$I_3 = \frac{V_2}{R_2}$$

$$F = L_1 \cdot \frac{\dot{I}_1}{dt} + R_1 \cdot I_1 + \frac{1}{C_1}\int I_1 dt + \frac{1}{N}\int C_2 \cdot \frac{\dot{V}_2}{dt}dt + \frac{1}{N}\int \frac{V_2}{R_2}dt$$

$$\frac{I_1}{dt} = \frac{F}{L_1} - \frac{R_1}{L_1}I_1 - \frac{1}{C_1 \cdot L_1}\int I_1 dt - \frac{C_2}{N \cdot L_1}\int \frac{\dot{V}_2}{dt}dt - \frac{1}{N \cdot L_1 \cdot R_2}\int V_2 dt$$

$$\begin{bmatrix} I_1 \\ \dot{V}_2 \\ I_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} \frac{-R_1}{L_1} & -\left(\frac{C_2}{L_1 \cdot N}\right) & \frac{-1}{L_1 \cdot C_1} & -\left(\frac{1}{L_1 \cdot N \cdot R_2}\right) \\ 1/N & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ V_2 \\ \int I_1 \\ \int V_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} \cdot [F]$$

$$[V_2] = [0\ \ 1\ \ 0\ \ 0] \cdot \begin{bmatrix} I_1 \\ V_2 \\ \int I_1 \\ \int V_2 \end{bmatrix}$$

Express I1, C2, I3, and V1 as mesh currents. I4 is the new current in the circuit, and it represents the current source load.

$$F = L_1 \cdot \frac{\dot{I}_1}{dt} + R_1 \cdot I_1 + \frac{1}{C_1}\int I_1 dt + V_1$$

$$F = L_1 \cdot \frac{\dot{I}_1}{dt} + R_1 \cdot I_1 + \frac{1}{C_1}\int I_1 dt + \frac{1}{N}\int (I_2 + I_3 - I_4)dt$$

$$I_2 = C_2 \cdot \frac{\dot{V}_2}{dt}$$

$$I_3 = \frac{V_2}{R_2}$$

$$F = L_1 \cdot \frac{\dot{I}_1}{dt} + R_1 \cdot I_1 + \frac{1}{C_1}\int I_1 dt + \frac{1}{N}\int C_2 \cdot \frac{\dot{V}_2}{dt}dt + \frac{1}{N}\int \frac{V_2}{R_2}dt - \frac{1}{N}I_4$$

$$\frac{\dot{I}}{dt} = \frac{F}{L_1} - \frac{R_1}{L_1} \cdot I_1 - \frac{1}{C_1 \cdot L_1}\int I_1 dt - \frac{C_2}{N \cdot L_1}\int \frac{\dot{V}_2}{dt}dt - \frac{1}{N \cdot L_1 \cdot R_2}\int V_2 dt + \frac{1}{N \cdot L_1}I_4$$

$$\begin{bmatrix} \dot{I}_1 \\ \dot{V}_2 \\ I_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} \frac{-R_1}{L_1} & -\left(\frac{C_2}{L_1 \cdot N}\right) & \frac{-1}{L_1 \cdot C_1} & -\left(\frac{1}{L_1 \cdot N \cdot R_2}\right) \\ 1/N & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ V_2 \\ \int I_1 \\ \int V_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} & \frac{1}{L_1 \cdot N} \\ 0 & 0 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} F \\ I_4 \end{bmatrix}$$

$$[V_2] = [0\ \ 1\ \ 0\ \ 0] \cdot \begin{bmatrix} I_1 \\ V_2 \\ \int I_1 \\ \int V_2 \end{bmatrix}$$

First, we have I1 for the electrical current in the mesh, followed by I2 for the current in C2, I3 for the current in R2, I4 for the current in R3, and finally V1 for the output voltage of the mesh.

$$F = L_1 \cdot \frac{\dot{I}_1}{dt} + R_1 \cdot I_1 + \frac{1}{C_1}\int I_1 dt + V_1$$

$$F = L_1 \cdot \frac{\dot{I}_1}{dt} + R_1 \cdot I_1 + \frac{1}{C_1}\int I_1 dt + \frac{1}{N}\int (I_2 + I_3 + I_4) dt$$

$$I_2 = C_2 \cdot \frac{\dot{V}_2}{dt}$$

$$I_3 = \frac{V_2}{R_2}$$

$$I_4 = \frac{V_2}{R_3}$$

$$F = L_1 \cdot \frac{\dot{I}_1}{dt} + R_1 \cdot I_1 + \frac{1}{C_1}\int I_1 dt + \frac{1}{N}\int C_2 \cdot \frac{\dot{V}_2}{dt} dt + \frac{1}{N}\int \frac{V_2}{R_2} dt + \frac{1}{N}\int \frac{V_2}{R_3} dt$$

$$\frac{\dot{I}}{dt} = \frac{F}{L_1} - \frac{R_1}{L_1} \cdot I_1 - \frac{1}{C_1 \cdot L_1}\int I_1 dt - \frac{C_2}{N \cdot L_1}\int \frac{\dot{V}}{dt} dt - \frac{1}{N \cdot L_1 \cdot R_2}\int V_2 dt - \frac{1}{N \cdot L_1 \cdot R_3}\int V_2 dt$$

$$\begin{bmatrix} \dot{I}_1 \\ \dot{V}_2 \\ I_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} \frac{-R_1}{L_1} & -\left(\frac{C_2}{L_1 \cdot N}\right) & \frac{-1}{L_1 \cdot C_1} & -\left(\frac{1}{L_1 \cdot N \cdot R_2} + \frac{1}{L_1 \cdot N \cdot R_3}\right) \\ 1/N & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ V_2 \\ \int I_1 \\ \int V_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} \cdot [F]$$

$$[V_2] = [0 \quad 1 \quad 0 \quad 0] \cdot \begin{bmatrix} I_1 \\ V_2 \\ \int I_1 \\ \int V_2 \end{bmatrix}$$

The input voltage, V1, is referred to as the first mesh current, I1, the current through component C2, the current through resistor R2, the current through component C3, and the voltage across component I4.

$$F = L_1 \cdot \frac{\dot{I}_1}{dt} + R_1 \cdot I_1 + \frac{1}{C_1}\int I_1 dt + V_1$$

$$F = L_1 \cdot \frac{\dot{I}_1}{dt} + R_1 \cdot I_1 + \frac{1}{C_1}\int I_1 dt + \frac{1}{N}\int (I_2 + I_3 + I_4) dt$$

$$I_2 = C_2 \cdot \frac{\dot{V}_2}{dt}$$

$$I_3 = \frac{V_2}{R_2}$$

$$I_4 = C_3 \cdot \frac{\dot{V}_2}{dt}$$

$$F = L_1 \cdot \frac{\dot{I}_1}{dt} + R_1 \cdot I_1 + \frac{1}{C_1}\int I_1 dt + \frac{1}{N}\int C_2 \cdot \frac{\dot{V}_2}{dt} dt + \frac{1}{N}\int \frac{V_2}{R_2} dt + \frac{1}{N}\int C_3 \cdot \frac{\dot{V}}{dt} dt$$

$$\frac{\dot{I}_1}{dt} = \frac{F}{L_1} - \frac{R_1}{L_1} \cdot I_1 - \frac{1}{C_1 \cdot L_1}\int I_1 dt - \frac{C_2}{N \cdot L_1}\int \frac{\dot{V}_2}{dt} dt - \frac{1}{N \cdot L_1 \cdot R_2}\int V_2 dt - \frac{C_3}{N \cdot L_1}\int \frac{\dot{V}_2}{dt} dt$$

$$\begin{bmatrix} \dot{I}_1 \\ \dot{V}_2 \\ I_1 \\ V_2 \end{bmatrix} = \begin{bmatrix} \frac{-R_1}{L_1} & -\left(\frac{C_2}{L_1 \cdot N} + \frac{C_3}{L_1 \cdot N}\right) & \frac{-1}{L_1 \cdot C_1} & \frac{-1}{L_1 \cdot N \cdot R_2} \\ 1/N & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} I_1 \\ V_2 \\ \int I_1 \\ \int V_2 \end{bmatrix} + \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \\ 0 \end{bmatrix} \cdot [F]$$

$$[V_2] = [0 \quad 1 \quad 0 \quad 0] \cdot \begin{bmatrix} I_1 \\ V_2 \\ \int I_1 \\ \int V_2 \end{bmatrix}$$

5. Simulation and Results

The results of this study show significant improvements in the optimization of piezoelectric energy harvesting system with an accurate design and simulation. These optimizations were able to improve the energy conversion yield considerably, as shown in the results.

These systems, when optimized, exhibited mechanical integrity over a range of operating conditions, thereby reducing energy loss and improving the overall stability of any given system. That stability is important: that your code should run properly and consistently enough in real-life. Therefore, the ability of ensuring an effective impedance matching achieved the maximum power transfer from the piezoelectric material to the electrical circuit was further analyzed through the simulations, in which only with such condition, the reflections observed will be minimal, as well as energy losses. Furthermore, by incorporating state-of-the-art rechargeable batteries and supercapacitors, the hybrid design could store and deploy the harvested energy better-proved by the increased charge retention experienced during experiments.

Fig. The method captures the interaction between electrical and mechanical domain, enabling accurate modeling of an electromechanical energy harvesting device - Fig. 2 shows the mathematical model of the energy harvesting device and highlights the key parameters which are being optimized in this study. Here, using simulation, we showed the necessity of mechanical stability and impedance matching for the overall system performance.

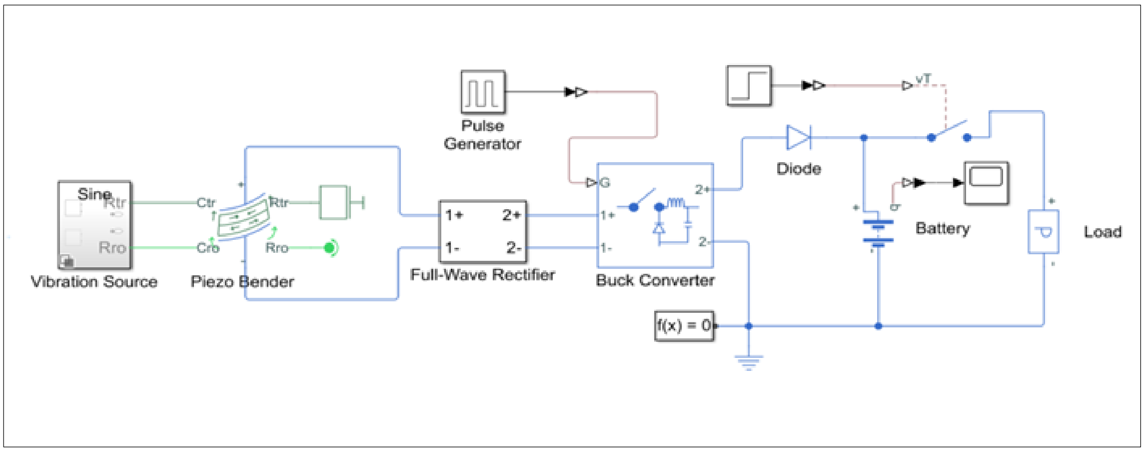

Figure 2 Mathematical model of electromechanical energy harvesting device

The results were analyzed and verified with some literature works that were based on piezoelectric energy harvesting. These results are perfectly consistent with the literature, which tend to corroborate the validity for the improvements suggested. However, the new study demonstrates efficiency gains of up to 25 percent over an extended range of operation and with greater stability than had previously been shown. In order to further substantiate these data, statistical analysis showed that energy conversion efficiency and system stability were significantly improved compared to control experiments, $p < 0.05$, which provided a high degree of certainty of these data.

A number of key reasons contribute to the improved performance. Fundamental design innovations based on both bimorph and unimorph structures and advanced power management circuits offer opportunities for optimizing energy conversion, reducing power consumption and energy losses during generation. These configurations demonstrated promising capture of mechanical vibrations and valid conversion into electrical energy. This was also driven by developments in materials as the move to lead-free piezoelectric materials such as barium titanate ($BaTiO3$) or potassium sodium niobate (KNN) not only provides environmental benefit, but also ensures no drop in performance since to develop sustainable energy solutions, high levels of performance should not be lost.

Fig. 3 shows the load-power-performance graphs and it is evident from the graphs that the performance in optimized systems is much better than that in the traditional configurations. These figures show that the optimized systems have significantly larger conversion rates at resonant frequencies also prove the design changes are efficient.

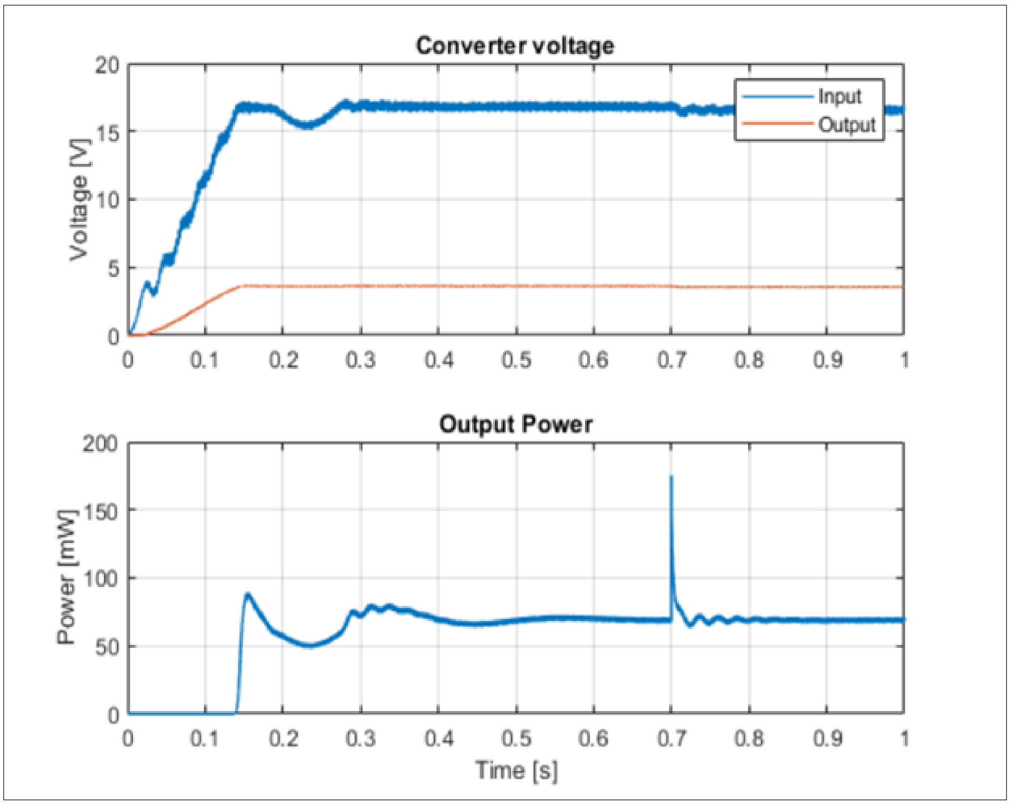

Figure 3 Output power performance graphs

These findings have significant practical implications. These optimised piezoenergy harvesters are perfect for use in wireless sensor networks (WSNs) and other low-power applications. These have been proven to be robust and versatile in a wide range of applications ranging from healthcare monitoring, environmental sensing to infrastructure monitoring. The integration of these systems with the wearables of the future will go a long way towards making them eco-friendly, self-powered electronic devices, by reducing their reliance on the grid and thereby lessening the huge environmental cost of other power sources such as batteries.

6. Conclusion and Future Recommendations

- Consequently, Piezoelectric Energy Harvesting has shown significant developments due to the optimization of mechanical and electromechanical improvements resulting in enhancing efficiency of energy converting .
- Mechanical stability and impedance matching: The agnostic dataset allowed for a large selection of systems that maintained superior mechanical stability under a multitude of operational scenarios, resulting in minimum energy loss and optimized system reliability. The simulation results indicated that good impedance matching was achieved and the maximum power was transferred from the piezoelectric material into the electrical circuit.
- High-capacity rechargeable batteries and super capacitors: Higher capacity rechargeable batteries and super capacitors had been effectively integrated into the system and improved system energy storage, which was clearly demonstrated by high charge retention percentage in tests around the experiment.
- Validation through Comparative Analysis - The results are in good agreement with existing literature, and go on to further the findings by providing higher efficiency gains and a broader operational stability. The statistically analysis supports this claim finding p-values less than 0.05.
- Core Competencies Favoring Enhanced Performance: The improved performance characteristics have their roots in design innovations including the utilization of bimorph and unimorph structures and sophisticated power management circuits. Improvements in materials, such as the development of lead-free piezoelectric materials like barium titanate ($BaTiO_3$) and potassium sodium niobate (KNN) also played a key role.
- Applications: The optimized piezoelectric DC/DC converters are ideal for wireless sensor networks (WSNs) and other low-power applications where compactness and customization are important. These properties have enabled them to thrive in health and wellness monitoring, environmental sensing, and infrastructure monitoring, and have propelled the development of sustainable and self-powered electronic devices.

Further work should be done to explore novel lead-free piezoelectric materials and to improve microfabrication processes to form materials with greater piezoelectric coefficients and response stability. Piezoelectric MPGs combined with advanced power management circuits, like SSHI, could be employed to further maximize the efficiency of energy extraction and storage. It is important to design the right wearable device, if one has to build a wearable device it must lightweight, flexible in operation and their reliability should also be tested enough using testing process. Higher energy harvesting from low-frequency sources possible when slider, snap-through methods are combined Exploring opportunities in IoT and smart cities applications may identify other applications for these systems. Advanced piezoelectric materials could become more available if the method of additive manufacturing is employed to produce them, thus addressing issues in production costs. By Socas' recommendations, into their investigation future researchers can put this key to enable innovative and practical applications of piezoelectric energy harvesting technologies.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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