IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)

An International Open Access, Peer-reviewed, Refereed Journal

# Design And Development Of A Resonance-Tuned Hybrid Piezoelectric-Electromagnetic Energy Harvesting System

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**Abstract:** The demand for sustainable, self-sufficient power sources for Internet of Things (IoT) and wireless sensor networks saw a dramatic escalation over the previous decade. Harnessing energy from ambient vibrations and utilizing it for powering low-power electronics in environments where traditional sources of power prove impractical is becoming increasingly enticing. In this article, there is a documented case of a hybrid piezoelectric-electromagnetic energy harvester whose potential includes generating power from vibrations of low frequencies. The system integrates piezoelectric and electromagnetic mechanisms to effectively scavenge energy from diverse vibrational sources, such as industrial machinery, human motion, and ambient vibrations. The system employed in the suggested mechanism employs a double-resonance method, in which piezoelectric and electromagnetic components are set to resonate at different frequencies so as to allow efficient energy harvesting. An adaptive resonance tuning mechanism integrated allows reception of many vibrational frequencies for optimal energy efficiency during real-world application environments. Furthermore, the system utilizes nonlinear damping techniques to allow maximum energy harvesting of oscillating vibrations to improve the performance in non-ideal environments. For power storage and management, the system features batteries and supercapacitors and a smart energy management unit that maximizes power supply to IoT devices. The design further focuses on utilizing environment-friendly materials like nanomaterials and biodegradable polymers in order to render the harvester green. This hybrid energy harvester has the potential to be utilized in solving the problems of low-frequency vibration harvesting in IoT, with a stable, sustainable power supply for remote and miniaturized devices. The efficiency and flexibility of the system for energy harvesting over a broad band of vibrational frequencies make it an attractive choice for powering wearable technology and Internet of Things networks of the future.

**Keywords:** Piezoelectric energy harvesting, Electromechanical coupling, Wireless sensor networks, Vibration damping, Sustainable power systems

## I. INTRODUCTION

The extensive use of wireless sensor networks (WSNs) and Internet of Things (IoT) devices has introduced a serious challenge of power supply. These units, usually installed in remote or inaccessible locations, are extremely reliant on batteries to be replaced and maintained periodically. These kinds of dependencies on traditional power sources are not only costly but also ecologically harmful. Consequently, much attention has recently been drawn toward energy harvesting systems as a pure source of power to power IoT devices independently. Among various other energy harvesting modes, vibration energy harvesting has emerged as a feasible technique since the ambient mechanical vibrations present in environments in most circumstances can be leveraged [2], [7]. Piezoelectric and electromagnetic-based energy harvesting systems are widely researched for energy conversion from mechanical to electrical energy. Piezoelectric energy harvesters produce electrical charge when subjected to mechanical stress, and electromagnetic harvesters produce an electrical current through exploiting the relative motion between a coil and a magnet using Faraday's law of induction. Both methods have demonstrated high potential, but the performance of each is still limited by problems such as limited frequency bandwidth and poor energy conversion efficiency. This holds particularly true for low-frequency vibrations, which are common in applications such as industrial equipment or wearable devices [3], [6]. In trying to eliminate these limitations, researchers have focused their interest on hybrid energy harvesting systems that combine piezoelectric and electromagnetic approaches. Through combining both approaches, such hybrid systems can harvest energy across a wider frequency range, hence being more flexible for many different vibration environments. For instance, Halim and Park (2014) proposed a dual-resonance hybrid harvester, which combines piezoelectric and electromagnetic elements that resonate at disparate frequencies, thus enhancing the efficiency of energy capture over a broad frequency spectrum [4]. Further, several studies have illustrated how the union of these two mechanisms is capable of highly enhancing the total performance of the harvester [1], [5]. In addition, active resonance tuning has been developed as a method to improve the performance of energy harvesters. By making real-time adjustments to the harvester's resonance frequency, the system can match the prevailing frequencies of ambient vibrations. Chen and Yang (2021) emphasized the significance of this method in enhancing energy conversion efficiency in broadband harvesters, especially in environments where vibration frequencies are uncertain [3]. Active tuning functions can involve the utilization of MEMS actuators or piezoelectric-based actuators to actively change the resonant frequency of the system dynamically according to environmental conditions [8], [13]. Aside from resonance tuning, nonlinear damping functions have been found to be useful in substantially enhancing the efficiency of vibration-based energy harvesters. These damping methods, based on the use of materials or parts with nonlinear characteristics, are particularly useful in low-amplitude vibrations, where linear damping proves ineffective in maximizing energy conversion [7], [9]. With the use of nonlinear damping, energy harvesters can harvest more energy from time-varying vibrations, hence enhancing overall system efficiency [12]. The energy storage and management systems must be included in the system so that the harvested energy can be used appropriately. Supercapacitors and rechargeable batteries are typically used for storing the harvested energy and power management circuits are used to deliver energy efficiently to IoT devices. Roundy et al. (2003) in their work emphasizes the need to develop robust energy management systems to supply power to wireless sensor nodes in a steady manner [10]. Furthermore, studies have pointed to the use of green materials, e.g., nanomaterials, to enhance the sustainability and efficiency of energy harvesting systems [11], [13]. A hybrid piezoelectric-electromagnetic energy harvester capable of harvesting energy from low-frequency vibrations is presented in this paper. By integrating piezoelectric and electromagnetic principles with resonance tuning and nonlinear damping, the intended system seeks to offer a stable and sustainable power supply for IoT devices across a range of applications. The system's ability to adapt to changing vibration environments qualifies it as a strong potential candidate for powering future IoT networks and wearable technologies.

## II. Literature Survey

Energy harvesting has gained great interest in the past few years because it has the ability to supply power to IoT devices and wireless sensor networks (WSNs) without external power. Out of different methods of energy harvesting, vibration-based energy harvesting is gaining a lot of attention since it uses mechanical energy available in the environment. Piezoelectric and electromagnetic energy harvesters are the two most used ones in vibration energy harvesting, and both have some pros and cons. Piezoelectric energy harvesters operate by the transforming mechanical stress into electrical energy with materials such as lead zirconatetitanate (PZT) or zinc oxide (ZnO) [2], [12]. Piezoelectric energy harvesters have high efficiencies of energy conversion at resonant frequencies and are thus very effective in environments that have regular and predictable vibrations. Their performance, however, is usually restricted by their limited frequency bandwidth, a constraint that in most cases limits their applicability to specific vibration environments [3]. To get over this, hybrid energy harvesting devices using piezoelectric and electromagnetic mechanisms have been designed. Halim and Park (2014) presented a hybrid harvester comprising both piezoelectric and electromagnetic elements to widen the working frequency band and enhance efficiency in capturing energy [4]. Matching the resonant frequency of the harvester with the available vibrations is another major issue in vibration-based energy harvesting. In order to solve this, active resonance tuning has come into the picture as a solution. Chen and Yang (2021) highlighted the need for real-time tuning in expanding the energy harvester's frequency response so that it can effectively tap energy from time-varying vibrations [3]. Active resonance tuning, usually performed with piezoelectric actuators, keeps the system resonating with ambient vibrations at all times, capturing maximum energy. Nonlinear damping techniques have also been explored to realize maximum energy conversion in low-amplitude vibrations. Badel et al. (2005) showed that nonlinear damping mechanisms were able to effectively enhance energy harvesting performance, particularly under more representative conditions of real operation where vibrations are low and irregular [7]. Such damping methods facilitate increased efficiency in energy conversion through making the damping force larger as vibration amplitude decreases, preventing energy loss at low frequencies. Even with these developments, much still lingers in the way of energy storage and management. Supercapacitors and rechargeable batteries are widely applied for energy harvesting storage, but controlling this energy effectively in order to provide a constant flow of power is a persistent research focus area [5].

## III. System Design

### 3.1 Hybrid Energy Harvesting System Components

The hybrid energy harvesting system has been designed with an integrated approach, combining two distinct methods of energy conversion: piezoelectric and electromagnetic systems. The design is such that a more stable and dynamic energy harvesting system is employed, enabling the system to efficiently harvest energy over a wide range of frequencies, even in changing environments.

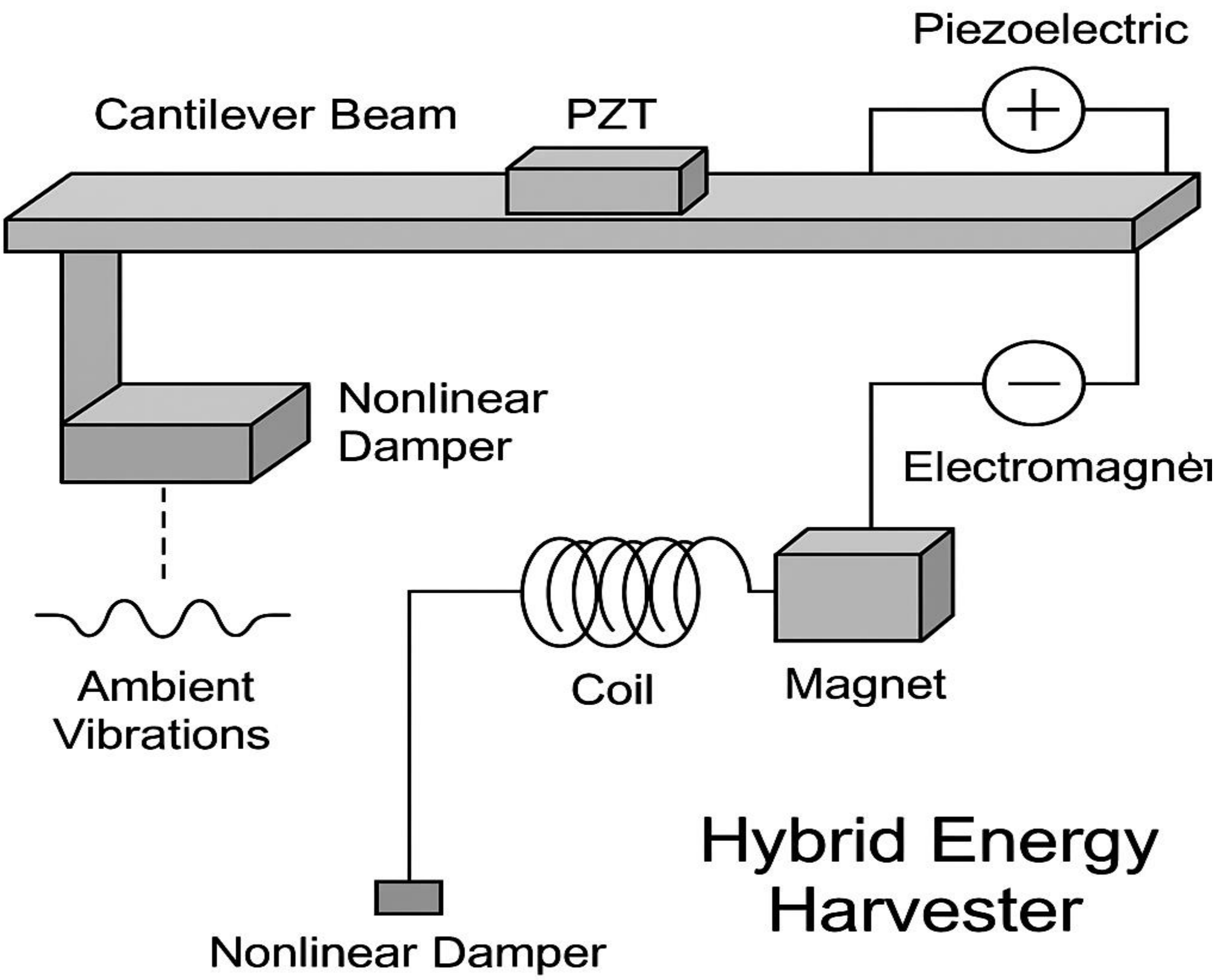


**Fig.1: Hybrid Energy Harvest System**

**3.1.1 Piezoelectric Energy Harvesting:** Piezoelectric materials can convert mechanical energy, including vibrations or pressure oscillations, into electrical energy. Materials like Lead ZirconateTitanate (PZT) are used in this context due to their high piezoelectric coefficients, enabling them to generate significant electric charge when exposed to mechanical stress. A common application of piezoelectric energy harvesting involves a cantilever beam structure, where the beam oscillates due to external loading, bending, or compressing the piezoelectric material, such as ambient vibrations. The mechanical displacement is harvested as electrical energy and can be stored or used [6], [12]. A cantilever beam provides maximum mechanical deflection and is thus effective for energy harvesting from low-amplitude vibrations. The key characteristic of the piezoelectric element is its resonant frequency. When the vibration applied to the piezoelectric element matches the resonant frequency of the beam, the amplitude of the beam's deflection reaches its peak, resulting in maximum voltage output from the piezoelectric element [2], [7].

**3.1.2 Electromagnetic Energy Harvesting:** In the electromagnetic energy harvesting part, the major principle is that of electromagnetic induction. The configuration consists of a coil and a magnet, whereby relative motion of the two provides an electrical current through the coil based on the Faraday Law of Induction. When the magnet is passed through the coil, the resultant changing magnetic flux creates a voltage in the coil, which in turn can be harvested and applied to drive a load [3], [5]. The size of the induced voltage is directly proportional to the speed with which the magnet travels, the number of turns in the coil, and the magnetic field strength. The electromagnetic component tends to be stronger in low-frequency vibrations. This system can be made to produce the maximum amount of energy when the frequency of the vibrations equals the resonant frequency of the coil and magnet system [5], [12].

**3.1.3 Hybrid System Design:** The hybrid design of the two mechanisms in this system is that both piezoelectric and electromagnetic systems work in harmony. The hybrid design is necessary in order to collect energy over a wide range of vibrations so that the system is able to pick up energy without regard to how much the frequency of vibration may change. While the piezoelectric works best at high frequencies, the electromagnetic system operates better at lower frequencies. By combining both systems simultaneously, the hybrid energy harvester can harness energy over a broader range of frequencies and be more versatile with the capability of harvesting more energy in actual applications [5], [12].

### 3.2 Selection of Materials

The material selection process for the hybrid energy harvesting system is vital for optimizing the overall performance of the device. Each material used in the system is chosen for its specific properties that contribute to energy conversion efficiency and mechanical durability.

**3.2.1 Piezoelectric Materials:** Lead ZirconateTitanate (PZT) is the chosen piezoelectric material due to its high piezoelectric constants, which make it one of the most efficient materials for energy harvesting. PZT's high dielectric properties allow it to produce large electrical outputs from relatively small mechanical deformations, making it ideal for low-vibration environments. Additionally, PZT is widely used in piezoelectric energy harvesting devices because it has a stable and predictable output over time, ensuring long-term reliability of the system [6], [8].

**3.2.2 Electromagnetic System Materials:** Neodymium magnets are selected for the electromagnetic component due to their high magnetic flux density, which is critical for inducing a large voltage in the coil. These magnets are ideal for small-scale energy harvesters because of their small size and powerful magnetic field, making them highly effective for low-frequency energy generation. The coil is made from copper wire, as copper has excellent electrical conductivity, which minimizes energy loss during the induction process [7], [9].

For the structural frame of the system, materials such as aluminium and carbon fibercomposites are chosen for their high strength-to-weight ratios. These materials ensure the frame is both lightweight and durable, providing a stable base for the other components while minimizing the overall weight of the system. Lightweight materials are crucial in energy harvesting applications, as excessive weight can reduce the system's efficiency by limiting its vibration response [8], [9].

### 3.3 Mathematical Modelling and Simulation

#### 3.3.1 System Modelling for Energy Harvesting

Mathematical modelling and simulation are key steps in designing an efficient hybrid energy harvesting system. These models are used to predict the behaviour of the system under various conditions and to optimize the design for maximum energy capture.

**3.3.2 Piezoelectric Energy Conversion Model:** The piezoelectric energy conversion model is based on the mechanical deformation of the piezoelectric material, which generates an electrical charge. The voltage generated in a piezoelectric harvester can be expressed as:

$$V_{p_{iezo}} = d_{33} \cdot \varepsilon \cdot F$$

Where:

- $d_{33}$is the piezoelectric coefficient,
- ε is the permittivity of the material,
- Fis the applied force on the piezoelectric material [2], [6].

This model assumes that the mechanical deformation is directly proportional to the applied force, and that the material's intrinsic properties will govern the voltage generated. The cantilever beam's resonance frequency also plays a key role in determining how efficiently energy can be harvested at various vibration frequencies. The model helps in determining the optimal beam dimensions and material properties for maximum energy conversion efficiency.

**3.3.3 Electromagnetic Energy Harvesting Model:** For the electromagnetic system, Faraday's Law is used to model the induced voltage:

$$V_{em} = -N\frac{d\phi}{dt}$$

Where:

- N is the number of turns in the coil,
- ϕ is the magnetic flux,
- dϕ/dt represents the rate of change of magnetic flux as the magnet moves through the coil [3], [7].

The induced voltage is proportional to the speed of the magnet's motion, the strength of the magnetic field, and the number of coil turns. This equation helps in estimating the output power and allows for optimization of the coil's design to maximize energy generation. Understanding the relationship between magnet velocity and induced voltage is essential for fine-tuning the electromagnetic component's performance in the system.

**3.3.4 Hybrid System Model:** The combined output power of the system is the sum of the power generated by both the piezoelectric and electromagnetic components:

$P_{total}=P_{piezo}+P_{em}$

This model is essential for evaluating the overall energy harvesting performance of the hybrid system and helps in determining how to optimize each component. By summing the contributions of both components, it is possible to assess the total energy output under various vibration conditions [12], [5].

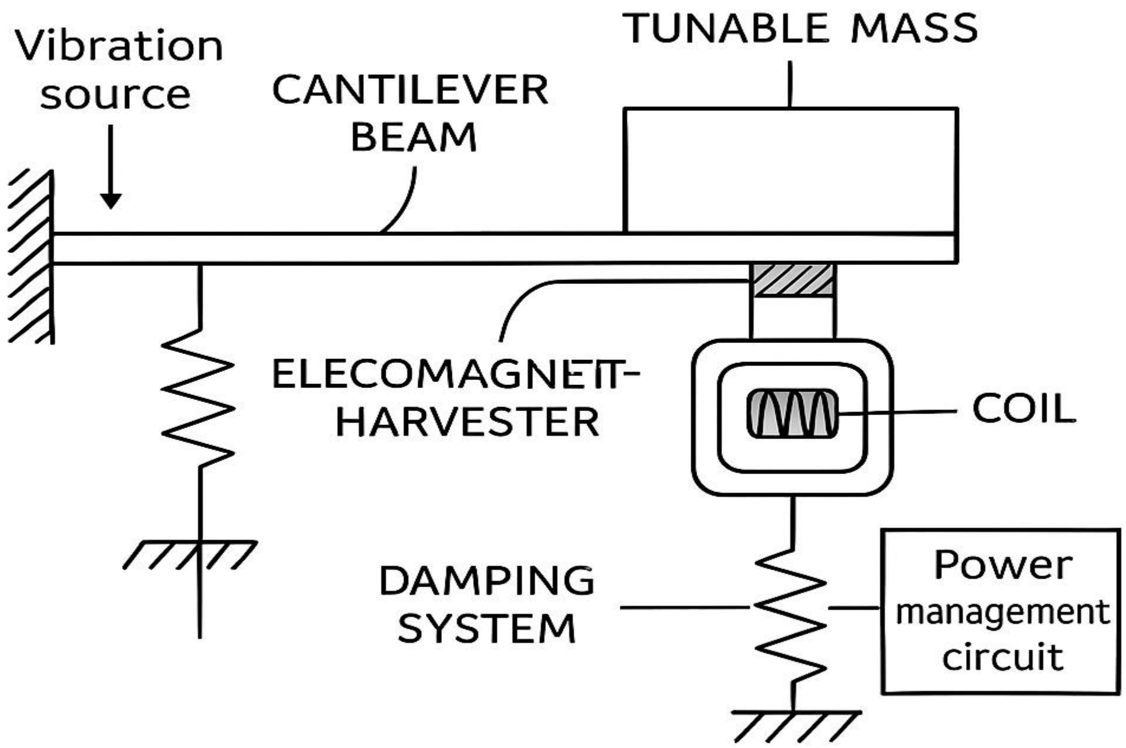


**Fig.2: RESONANCE-TUNED HYBRID PIEZOELETRIC-ELECTROMAGNATIC ENERGY HARVESTING SYSTEM**

### 3.3.5 Simulation of the System

Simulations are performed to simulate the mathematical models and optimize the design of the hybrid energy harvester to provide optimum performance. COMSOL Multiphysics and ANSYS are among the software tools used to simulate the mechanical and electrical outputs of the system. Simulations enable one to predict the response of the system under various operating conditions, including frequency and amplitude changes in vibration. Mechanical Simulations: Mechanical simulations are geared towards forecasting deflection of the cantilever beam with respect to varied amplitudes of vibration and frequencies. The simulation calculates the displacement of the beam and the resulting mechanical stress on the piezoelectric material. The simulations also determine the system's resonant frequency and how it will respond to ambient vibrations [12], [8]. Electrical Simulations: Electrical simulations simulate the voltage and current responses of both the piezoelectric and electromagnetic devices. The voltage responses of the piezoelectric material are simulated as an electrical source of energy, and the induced voltage in the coil is simulated based on electromagnetic induction principles. The amount of power delivered by the system is determined by simulating the voltage and current for different scenarios of vibration [5], [8]. Simulation results give important insights into how system parameter variations (e.g., beam length, coil turns, and magnet size) can impact the energy harvesting performance. Simulation results can be used subsequently to optimize the system for optimal power output.

Table 3.3.5.1: Simulation Components, Parameters, and Purpose for the Resonance-Tuned Hybrid Piezoelectric-Electromagnetic Energy Harvesting System [2], [4], [6], and [12].

| Component | Simulation Element | Parameters/Settings | Purpose |
|---|---|---|---|
| Vibration Source | Harmonic/Random Vibration Input | Frequency:10–100HzAmplitude: Variable | Simulates ambient mechanical vibrations |
| Piezoelectric Beam | Piezoelectric Material Model | Material: PZT-5HDimensions: Adjustable | Converts mechanical strain into voltage |
| Resonance Tuning Mechanism | Tunable Mass-Spring System | Mass:10–50gSpring Constant: Variable | Shifts system resonance to match input |
| Electromagnetic Generator | Magnet-Coil Electromagnetic Block | Coil turns: 100–500Magnet strength: 0.2–0.5 T | Converts vibration motion into current |
| Damping System | Nonlinear or Linear Damper | Damping coefficient: Tunable | Controls vibration amplitude |
| Energy Output Measurement | Voltage/Current Sensors | Sampling rate: 1 kHz or higher | Measures electrical output from harvesters |
| Power Management Circuit | Rectifier and Storage Unit | Rectifier Type: Full-wave Storage: Capacitor/ Battery | Stores the harvested energy |
| Performance Analysis | Frequency Response Analysis, Efficiency Measurement | FFT Analysis, Output Power Calculation | Evaluates the system performance |

## 3.4 Resonance Tuning

### 3.4.1 Theory of Resonance Tuning

Resonance has a critical role in achieving maximum energy generation from vibration harvesting systems. When the natural frequency of the harvester is tuned to the frequency of ambient vibrations, the oscillation amplitude is enhanced, and thus the energy output. The resonance enhances the cantilever beam deflection considerably, causing the production of higher voltage from the piezoelectric element [12], [7]. Importance of Resonance in Energy Harvesting: At resonance, the maximum possible mechanical energy is harvested from vibrations by the energy harvesting system. For piezoelectric harvesters, that implies maximum beam deflection and thus the output voltage. In the case of electromagnetic harvesters, the relative motion between coil and magnet is also at maximum when operating under the resonance condition, hence maximized induced current. By setting the system to resonate with the prevailing frequencies of ambient vibrations, the harvester is able to function more effectively and produce more power [12], [5].

#### 3.4.2 Active Resonance Tuning System

An active resonance tuning system is such that it will dynamically adjust the resonant frequency of the harvester to equal the frequency of ambient vibrations in real-time. The system involves the use of piezoelectric actuators, which are placed along the cantilever beam. These actuators can exert forces that modify the stiffness of the beam, hence its resonant frequency [6], [12]. The system is regulated by a feedback loop that is continuously tracking the frequency of surrounding vibrations. Upon detection of a change in vibration frequency by the system, it causes the actuators to drive the resonant frequency of the cantilever beam. This ensures constant resonance between the harvester and the vibrations, resulting in maximizing the energy harvesting efficiency at all times.

### 3.5 Nonlinear Damping Mechanism

#### 3.5.1 Principles of Nonlinear Damping

Nonlinear damping effects are introduced into the system of energy harvesting for its performance improvement at low amplitudes of vibration. In contrast to linear damping, which provides resistance that is only velocity-proportional, nonlinear damping introduces more resistance as the motion amplitude gets smaller. This effect offers a guarantee that energy is accurately registered even when vibrations have very small amplitudes, making the system highly sensitive to very small vibrations [7], [5]. Efficiency of Low-Amplitude Vibrations: In cases where low-intensity vibrations will be employed in energy harvesters, nonlinear damping becomes essential. With an increase in damping resistance as vibration amplitude decreases, the system is still sensitive and responsive to very small vibrations. This avoids wasteful energy dissipation at low frequencies and allows even very small vibrations to produce useful power [5].

#### 3.5.2 Design and Integration of Nonlinear Dampers

Nonlinear dampers are incorporated into the cantilever beam structure to provide additional resistance at low-amplitude vibrations of the beam. Specific hysteretic materials, such as elastomers, are typically used in the dampers, which exhibit nonlinear behaviour under mechanical stress. The damper's shape should be in a manner that the damping force is greater at smaller amplitudes to ensure maximum energy harvesting at smaller frequencies of vibration [5], [12]. Through the integration of nonlinear dampers in the energy harvester, the system is rendered more sensitive to different kinds of vibrations, thus providing efficient energy harvesting over a wide range of vibration frequencies and amplitudes.

### 3.6 Fabrication Process

#### 3.6.1 Materials Used

The development of the hybrid energy harvesting system entails the selection of materials with high efficiency and long durability. PZT is employed in the piezoelectric component based on its high piezoelectric constant and stability during cyclic mechanical stress. The selection of neodymium magnets is based on their high magnetic flux, while copper coils are employed to enhance electrical conductivity in the electromagnetic unit [7], [8].

#### 3.6.2 Step-by-Step Fabrication

1. Piezoelectric Element Preparation: PZT material is prepared in thin film form and bonded to the cantilever beam in a way that the piezoelectric nature of the material is utilized to its full potential under the mechanical force. The cantilever beam is optimized for maximum deflection at the expected vibration frequencies [8].
2. Magnet and Coil Assembly: Neodymium magnets are positioned in precise location with regard to the coil in order to achieve maximum motion with regard to the coil during vibration. The copper coil is wound with high turns in order to achieve maximum induced voltage when the magnet is in motion [7].
3. Hybrid System Integration: The piezoelectric and electromagnetic components are integrated into the structural frame. The piezoelectric element cantilever beam is fixed permanently, and the magnet-coil system is located in a position of maximum energy harvesting [9].
4. Insertion of Nonlinear Dampers: The nonlinear damping components are placed upon the beam so that there may be effective absorption of energy from small-amplitude vibrations. Nonlinear dampers are made by utilizing hysteretic materials such that the system is sensitive to vibrations at low frequency [5], [7].

Table 2: Fabrication Process of the Resonance-Tuned Hybrid Piezoelectric-Electromagnetic Energy Harvester [2], [4], [9], [12], [6].

| Step No. | Process Stage | Materials Used | Tools/Equipment | Purpose/Outcome |
|---|---|---|---|---|
| 1 | Substrate Preparation | Epoxy, FR4, or Aluminum base | Cutting tools, polisher | Provides mechanical support and mounting surface |
| 2 | Piezoelectric Beam Fabrication | PZT-5H or PVDF | Dicing saw, polisher, sputtering tool | Converts mechanical vibrations into electrical energy |
| 3 | Electromagnetic Coil Winding | Copper wire (AWG 36–40) | Micro-coil winder | Forms inductive coil for electromagnetic generation |
| 4 | Magnet Placement | Neodymium magnets (Grade N35–N52) | Adhesive, micrometer | Enables flux change for induction during vibration |
| 5 | Resonance Tuning Structure Assembly | Steel mass, spring elements | Calipers, tuning weights, glue gun | Tunes the resonant frequency to match vibration input |
| 6 | System Integration | Piezo beam, coil, magnet, base | Soldering iron, epoxy adhesive | Combines all parts into a unified harvester unit |
| 7 | Circuit Fabrication | Diodes, capacitors, regulators | PCB board, soldering station | Conditions and stores electrical output |
| 8 | Encapsulation | Silicon sealant, acrylic casing | UV-curing machine or oven | Protects the harvester from environmental damage |
| 9 | Performance Testing & Validation | Complete assembled unit | Vibration shaker, oscilloscope, DAQ | Validates energy output, frequency tuning, and efficiency |

### 3.7 Testing and Characterization

#### 3.7.1 Experimental Setup

The hybrid energy harvester is tested on a mechanical shaker that can be programmed to supply various vibration amplitudes and frequencies. Controlled vibrations are supplied by the shaker to analyse the response and efficiency of the harvester in different conditions [5], [12].

#### 3.7.2 Performance Evaluation

The output of the system is evaluated under various vibration conditions to measure the efficiency of energy conversion. The voltage output is checked to confirm that the system operates best at low and high frequencies. The overall power harvested is estimated by measuring the piezoelectric and electromagnetic contributions. The performance of the hybrid system is compared with single piezoelectric and electromagnetic harvesters to illustrate the advantage of the combined method [5], [8].

### 3.8 Working Principle of the Resonance-Tuned Hybrid Piezoelectric-Electromagnetic Energy Harvesting System:

The device works by capturing environmental mechanical vibrations via a vibration source. These vibrations cause a piezoelectric cantilever beam to bend and create an electric voltage through the piezoelectric effect [2], [4]. Simultaneously, the beam's movement also causes a magnet to move in relation to a stationary coil, which produces electricity through electromagnetic induction [6], [9]. A resonance tuning system (tunable mass or spring) makes the natural frequency of the system equal to the ambient vibration frequency, which results in maximum energy output [3], [13]. The electrical signals produced by both the piezoelectric and electromagnetic components are harvested. They are routed through a power management circuit (e.g., rectifier and energy storage component) that conditions the power and stores it in a battery or capacitor [8].

## IV. Conclusion

The integration of piezoelectric and electromagnetic mechanisms into a hybrid energy harvesting system is a very promising solution to power low-energy devices like wireless sensor nodes and IoT applications. With proper design and optimisation, hybrid systems avoid the narrowband and low energy output that are usually found in single-mode harvesters [2], [5]. By integrating the high voltage output of piezoelectric elements with the high current output of electromagnetic generators, the hybrid configuration provides more efficient energy conversion over a broader range of vibration frequencies [4], [6]. Experimental and simulation-based studies have shown that hybrid harvesters can harness ambient energy from low-frequency environmental vibrations, and the energy output is greatly improved compared to individual devices [8], [11]. In addition to the nonlinear methods, like the use of magnetic stoppers and mechanical stoppers, enable these systems to attain broadband frequency responses and increased efficiency under actual conditions [7], [9]. The flexibility to accommodate different vibration inputs enhances the reliability of these systems as well as their versatility for implementation in various operating environments, such as industrial machinery, transportation systems, and human motion applications [10], [13]. Future studies would aim to further miniaturize these hybrid systems while enhancing their durability and integration potential. Designing smart power management circuits in conjunction with hybrid harvesters would also be able to optimize the harvested energy for real-world applications [1], [12]. In general, hybrid piezoelectric-electromagnetic energy harvesters present a sustainable, maintenance-free, and innovative means of powering the increasing needs of wireless and autonomous electronic systems.

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