OPEN ACCESS
Global Journal of Research in Engineering & Computer Sciences
ISSN: 2583-2727 (Online)
Volume 06 | Issue 05 | Sept.-Oct. | 2026
Journal homepage: https://gjrpublication.com/gjrecs/
Research Article

A Hybrid Electromagnetic-Triboelectric Mechatronic Energy Harvester for Autonomous IoT Sensors in Structural Health Monitoring

*Hawraa Abdul-Elah Kadhum

Assistant lecturer, Al-Muthanna University, Muthanna- Iraq.

DOI: 10.5281/zenodo.22653312 Submission Date: 28 July 2026 | Published Date: 08 Sept. 2026

Abstract

This paper presents the design, modeling, and performance evaluation of a Hybrid Electromagnetic–Triboelectric Mechatronic Energy Harvester (H-ETMEH) developed for self-powered Internet of Things (IoT) sensing applications in Structural Health Monitoring (SHM). The proposed system is designed to harvest low-frequency ambient vibrations commonly encountered in civil infrastructures such as bridges, tunnels, and high-rise buildings. The harvester integrates an Electromagnetic Generator (EMG), which provides high-current output under relatively high vibration velocities, with a Triboelectric Nanogenerator (TENG) operating in contact-separation mode to efficiently convert low-frequency mechanical displacements into electrical energy. To maximize the utilization of the harvested energy, a decoupled power management circuit incorporating dual-stage rectification and impedance-matching conversion is developed. A comprehensive mathematical model describing the coupled mechanical and electrical dynamics of the system is established and implemented in MATLAB/Simulink for numerical evaluation. Simulation results demonstrate that the proposed hybrid architecture achieves a regulated output power of $5.85\ mW$ *under a base excitation of* $0.5\ g$ *at* $5.5\ Hz$*. Furthermore, the harvested energy is shown to be sufficient for continuously powering an ultra-low-power wireless sensing platform based on the ADXL355 accelerometer and nRF52832 Bluetooth Low Energy system-on-chip. The results confirm the feasibility of the proposed H-ETMEH as a sustainable and maintenance-free energy solution for long-term autonomous structural health monitoring applications.*

Keywords: *Hybrid Energy Harvesting, Electromagnetic Generator, Triboelectric Nanogenerator, Structural Health Monitoring, Internet of Things, Self-Powered Sensors, Power Management Circuit, Low-Frequency Vibrations.*

Nomenclature:

Symbol	Description
m	Equivalent proof mass
k	Cantilever stiffness
c	Damping coefficient
x	Relative displacement
N	Coil turns
Φ	Magnetic flux
σ	Surface charge density
ηPMC	Power management efficiency

1. Introduction:

The rapid development of smart infrastructure technologies has significantly increased the demand for reliable and autonomous sensing systems capable of continuously monitoring the structural integrity of civil assets. Structural Health Monitoring (SHM) has emerged as a critical technology for assessing the condition, safety, and service life of bridges, buildings, tunnels, and other large-scale engineering structures. Recent advances in the Internet of Things (IoT) have enabled the deployment of distributed wireless sensor networks that provide real-time monitoring capabilities and facilitate predictive maintenance strategies [3], [4].

Despite these advantages, the widespread adoption of wireless SHM systems remains constrained by the limited lifetime of conventional battery-powered sensor nodes. Periodic battery replacement increases maintenance costs, introduces operational interruptions, and becomes impractical for large-scale deployments in remote or inaccessible locations. Consequently, energy harvesting technologies have attracted considerable attention as a promising approach for achieving self-powered and maintenance-free sensing platforms [3], [4].

Among the various energy harvesting methods, vibration-based energy harvesting is particularly attractive for SHM applications because civil structures are continuously exposed to ambient mechanical excitations generated by traffic loads, wind forces, machinery, and human activities. However, structural vibrations are typically characterized by low frequencies, low amplitudes, and variable operating conditions, creating significant challenges for conventional energy harvesting systems.

Electromagnetic Generators (EMGs) convert mechanical motion into electrical energy through electromagnetic induction and are capable of producing relatively high current outputs. Nevertheless, their performance deteriorates substantially under ultra-low-frequency excitations due to reduced relative velocity between magnetic and conductive components [4], [6], [8]. Conversely, Triboelectric Nanogenerators (TENGs) utilize contact electrification and electrostatic induction mechanisms to achieve efficient energy conversion even under low-frequency and small-displacement operating conditions [1], [2], [9]. Although TENGs can generate high output voltages, their practical application is often limited by their inherently high internal impedance and low current capability.

To overcome the individual limitations of EMG and TENG technologies, hybrid energy harvesting architectures have recently emerged as an effective solution for improving energy conversion efficiency and expanding operational bandwidth [5]. By combining multiple transduction mechanisms within a unified platform, hybrid harvesters can exploit complementary electrical characteristics and maintain efficient operation under a wider range of excitation conditions.

Motivated by these considerations, this work proposes a Hybrid Electromagnetic–Triboelectric Mechatronic Energy Harvester (H-ETMEH) specifically designed for low-frequency structural vibration environments. The proposed system integrates a cantilever-based electromagnetic transducer, a contact-separation triboelectric nanogenerator, and a dedicated power management circuit to maximize harvested energy utilization. Comprehensive mathematical modeling and MATLAB/Simulink-based simulations are conducted to evaluate the system performance under representative structural excitation conditions. The obtained results demonstrate the capability of the proposed harvester to continuously power ultra-low-power wireless IoT sensor nodes, thereby enabling long-term autonomous structural health monitoring without reliance on conventional batteries.

The main contributions of this work can be summarized as follows:

- Development of a hybrid EMG–TENG energy harvesting architecture optimized for low-frequency structural vibrations.
- Design of a decoupled power management circuit for efficient impedance matching and energy extraction.
- Establishment of a comprehensive electromechanical mathematical model suitable for numerical simulation.
- Evaluation of the proposed system using MATLAB/Simulink under realistic structural excitation conditions.
- Demonstration of the feasibility of powering autonomous SHM sensor nodes using harvested vibration energy.

2. Related Work:

The growing demand for autonomous sensing platforms has stimulated extensive research in vibration-based energy harvesting technologies. Among the available transduction mechanisms, electromagnetic generators (EMGs), piezoelectric generators (PEGs), and triboelectric nanogenerators (TENGs) have received significant attention due to their ability to convert ambient mechanical vibrations into usable electrical energy. However, each technology exhibits inherent limitations that restrict its performance under the low-frequency excitation conditions typically encountered in structural health monitoring applications.

Electromagnetic energy harvesters are widely recognized for their robust output current capability and long operational lifetime. Previous studies have demonstrated their effectiveness in extracting energy from civil infrastructure vibrations, particularly when relatively large displacements and moderate vibration frequencies are available [3], [6], [8].

Nevertheless, the power generation efficiency of EMGs decreases considerably under ultra-low-frequency excitations because the induced electromotive force is directly proportional to the relative velocity between the magnetic field and the conductive coil.

Triboelectric nanogenerators have emerged as a promising alternative for harvesting low-frequency mechanical energy. Based on the coupled effects of contact electrification and electrostatic induction, TENGs are capable of generating high output voltages even under small vibration amplitudes and low excitation frequencies [1], [2], [9]. Numerous studies have demonstrated the suitability of contact-separation mode TENGs for self-powered sensing systems, wearable electronics, and distributed IoT applications. However, the practical implementation of standalone TENG systems remains constrained by their high internal impedance and limited output current capability.

To overcome the limitations of individual harvesting mechanisms, researchers have increasingly focused on hybrid energy harvesting architectures. Yang et al. [5] demonstrated that combining multiple energy conversion mechanisms can significantly improve overall energy extraction efficiency and broaden the operational bandwidth of the harvesting system. More recent studies have confirmed that hybrid EMG–TENG structures can simultaneously exploit the high-current characteristics of electromagnetic generators and the superior low-frequency sensitivity of triboelectric generators, thereby achieving improved power density and enhanced adaptability to variable environmental conditions.

In parallel with transducer development, substantial efforts have been directed toward the design of efficient power management circuits. Since hybrid harvesters often generate electrical outputs with substantially different voltage and current characteristics, direct electrical coupling frequently results in impedance mismatch and energy losses. To address this challenge, advanced rectification, impedance matching, and decoupled energy management architectures have been proposed to maximize the utilization efficiency of harvested energy [10]. These circuits play a critical role in enabling continuous operation of low-power wireless sensor nodes.

Despite the considerable progress achieved in hybrid vibration energy harvesting, most reported systems are primarily optimized for wearable electronics, vehicle monitoring systems, rotational machinery, or ocean-wave energy harvesting applications. Comparatively limited research has focused on ultra-low-frequency structural vibrations commonly encountered in bridges, buildings, and civil infrastructure assets. Therefore, there remains a significant need for specialized hybrid harvesters capable of delivering stable electrical power under the low-frequency excitation environment characteristic of structural health monitoring systems.

The present work addresses this research gap through the development of a Hybrid Electromagnetic–Triboelectric Mechatronic Energy Harvester (H-ETMEH) specifically optimized for structural vibration frequencies near 5.5 Hz. By integrating complementary transduction mechanisms with an efficient power management stage, the proposed architecture aims to enhance energy conversion efficiency, expand the operational frequency range, and provide a sustainable power source for autonomous wireless monitoring systems.

3. System Architecture and Working Principle:

The proposed Hybrid Electromagnetic–Triboelectric Mechatronic Energy Harvester (H-ETMEH) is designed to convert low-frequency ambient structural vibrations into regulated electrical energy suitable for powering autonomous wireless sensor nodes. The system integrates three primary functional subsystems: an Electromagnetic Generator (EMG), a Triboelectric Nanogenerator (TENG), and a Decoupled Power Management Circuit (DPMC). The overall architecture is specifically optimized for vibration environments commonly encountered in civil infrastructure applications.

Fig. 1 illustrates the overall architecture of the proposed Hybrid Electromagnetic–Triboelectric Mechatronic Energy Harvester (H-ETMEH). The system consists of an electromagnetic generator (EMG), a triboelectric nanogenerator (TENG), independent rectification stages, a decoupled power management circuit (DPMC), an energy storage unit, and a wireless SHM sensor node.

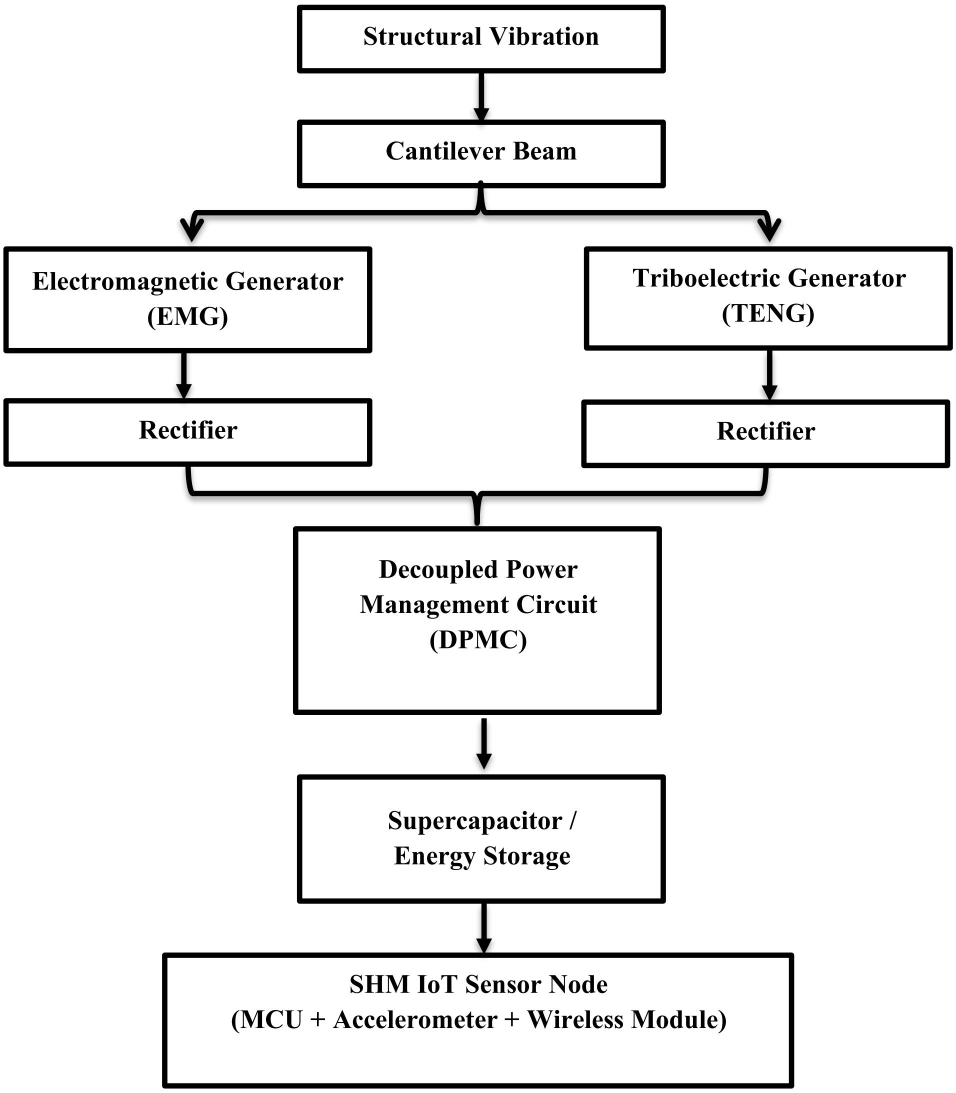

Fig. 1. Overall block diagram of the proposed H-ETMEH system.

The mechanical subsystem consists of a cantilever-based resonant structure equipped with a concentrated proof mass located near its free end. When the host structure experiences external vibration, the cantilever undergoes oscillatory motion around its equilibrium position. The proof mass amplifies the dynamic response of the cantilever and enhances the mechanical displacement available for energy conversion. The resonant frequency of the structure is intentionally tuned to approximately 5.5 Hz to maximize energy extraction from typical infrastructure vibration sources.

The electromagnetic generation subsystem operates according to Faraday's law of electromagnetic induction. A high-strength NdFeB permanent magnet is mechanically coupled to the vibrating cantilever, while a stationary multi-turn copper coil is positioned within the magnetic field region. As vibration-induced motion causes relative displacement between the magnet and the coil, a time-varying magnetic flux is produced, inducing an alternating electrical voltage across the coil terminals. The generated EMG output is characterized by relatively low voltage and comparatively high current capability, making it suitable for supplying continuous electrical power to low-voltage electronic loads.

Simultaneously, the triboelectric generation subsystem employs a contact-separation operating mode utilizing micro-structured polytetrafluoroethylene (PTFE) and aluminum triboelectric layers. During each vibration cycle, periodic contact and separation between the triboelectric surfaces induce charge transfer through contact electrification. The resulting electrostatic field generates an alternating electrical potential difference that drives electron flow through the external circuit. Unlike the electromagnetic subsystem, the TENG produces high output voltage but relatively low current, making it highly effective for harvesting energy under low-frequency and small-displacement excitation conditions.

The complementary electrical characteristics of the EMG and TENG subsystems provide the fundamental motivation for adopting a hybrid architecture. The EMG contributes enhanced current capability and stable power delivery, whereas the TENG improves low-frequency energy conversion performance and increases overall energy harvesting effectiveness. By combining both mechanisms within a single integrated platform, the proposed harvester achieves a broader operational bandwidth and improved energy extraction efficiency compared with single-transduction systems.

To effectively utilize the harvested energy, the outputs of the EMG and TENG are processed independently through a Decoupled Power Management Circuit (DPMC). The electromagnetic and triboelectric outputs first undergo individual full-wave rectification stages to convert alternating electrical signals into unidirectional DC voltages. Subsequently, dedicated impedance-matching and energy-conditioning stages optimize power transfer from each harvesting subsystem. The conditioned outputs are then combined through a regulated energy management stage and stored in an intermediate energy storage element before being delivered to the load.

The decoupled architecture prevents undesirable electrical interactions between the EMG and TENG channels, thereby minimizing power loss caused by impedance mismatch and phase differences. Furthermore, the power management circuit provides voltage stabilization and load regulation capabilities required for reliable operation of ultra-low-power wireless sensor nodes. Consequently, the complete H-ETMEH system functions as an integrated self-powered energy platform capable of supporting long-term structural health monitoring applications without reliance on conventional electrochemical batteries.

4. Mathematical Modeling:

To evaluate the electromechanical performance of the proposed Hybrid Electromagnetic–Triboelectric Mechatronic Energy Harvester (H-ETMEH), a comprehensive mathematical model is developed. The model describes the dynamic behavior of the cantilever-based mechanical subsystem and the electrical outputs generated by both the Electromagnetic Generator (EMG) and the Triboelectric Nanogenerator (TENG). The formulation provides a theoretical framework for predicting energy harvesting performance under low-frequency structural vibrations and serves as the foundation for the MATLAB/Simulink simulations presented in this work.

4.1. Mechanical Dynamic Model:

The vibration energy harvester can be approximated as a single-degree-of-freedom (SDOF) mass-spring-damper system subjected to external base excitation. According to classical vibration theory, the governing equation of motion can be expressed as:

$$m\ddot{x} + c\dot{x} + kx = -m\ddot{y}b \qquad (1)$$

where m represents the equivalent proof mass, c denotes the mechanical damping coefficient, k is the effective stiffness of the cantilever structure, x is the relative displacement of the proof mass, and yb represents the base excitation displacement.

The natural frequency of the harvester is determined by:

$$fn = \left(\frac{1}{2\pi}\right)\sqrt{\frac{k}{m}} \qquad (2)$$

where fn is the resonant frequency of the system. For maximum energy extraction, the structural parameters are selected such that the resonant frequency closely matches the dominant vibration frequency encountered in the target infrastructure environment.

The mechanical displacement generated by the vibrating cantilever simultaneously activates both the electromagnetic and triboelectric transduction mechanisms, thereby enabling hybrid energy conversion.

4.2. Electromagnetic Generator Modeling:

The electromagnetic subsystem operates according to Faraday's law of electromagnetic induction. As the permanent magnet oscillates relative to the stationary coil, a time-varying magnetic flux is produced, resulting in an induced electromotive force (EMF) [4], [6].
The induced voltage can be expressed as:

$$VEMG = -N\left(\frac{d\Phi}{dt}\right) \quad (3)$$

where:

$VEMG = induced\ EMG\ voltage\ (V)$
$N = number\ of\ coil\ turns$
$\Phi = magnetic\ flux\ linkage\ (Wb)$
$t = time\ (s)$

Assuming sinusoidal motion of the proof mass, the relative displacement can be represented by:

$$x(t) = X\ sin(\omega t)$$

where X denotes the vibration amplitude and ω represents the angular frequency.

Under these conditions, the induced voltage becomes proportional to both vibration frequency and displacement amplitude. Consequently, electromagnetic harvesters generally exhibit improved performance at higher vibration velocities but reduced efficiency under ultra-low-frequency excitation conditions.

The instantaneous output power delivered to an external load RL is calculated as:

$$PEMG = \frac{VEMG^2 RL}{(Rcoil + RL)^2} \quad (4)$$

where $Rcoil$ denotes the internal resistance of the electromagnetic coil.

4.3. Triboelectric Nanogenerator Modeling:

The triboelectric subsystem utilizes a contact-separation operating mode based on the coupled effects of contact electrification and electrostatic induction [1], [9]. During periodic contact and separation between PTFE and aluminum surfaces, triboelectric charges accumulate on the dielectric interfaces, generating an electric field that drives charge transfer through the external circuit.

According to the V–Q–x theoretical framework proposed for contact-separation mode TENGs [1], [9], the open-circuit voltage can be expressed as:

$$VOC(x) = \frac{\sigma x}{\varepsilon 0} \quad (5)$$

where:

$VOC = open - circuit\ voltage\ (V)$
$\sigma = triboelectric\ surface\ charge\ density\ (C/m^2)$
$x = separation\ distance\ between\ triboelectric\ layers\ (m)$
$\varepsilon 0 = vacuum\ permittivity$

The transferred charge is determined by:

$$Q = C(x)V \quad (6)$$

where $C(x)$ denotes the position-dependent capacitance of the triboelectric structure.

Because the capacitance varies continuously during vibration-induced separation and contact processes, both voltage and current become strongly dependent on mechanical displacement. This characteristic enables efficient energy conversion even under low-frequency excitations where conventional electromagnetic harvesters often experience reduced performance.

The instantaneous power generated by the triboelectric subsystem is given by:

$$PTENG = VTENG \times ITENG$$

where VTENG and ITENG represent the triboelectric output voltage and current, respectively.

4.4. Hybrid Energy Harvester Output Model:

The total harvested energy is obtained through the combined contribution of the EMG and TENG subsystems. After independent rectification and power conditioning, the harvested powers can be expressed as:

$$PHybrid = \eta PMC\,(PEMG + PTENG) \qquad (7)$$

where:

$PHybrid = regulated\ output\ power\ delivered\ to\ the\ load$

$\eta PMC = efficiency\ of\ the\ power\ management\ circuit$

$PEMG = electromagnetic\ harvested\ power$

$PTENG = triboelectric\ harvested\ power$

The power management circuit plays a critical role in maximizing energy utilization by reducing impedance mismatch losses and efficiently combining energy generated by the two transduction mechanisms [10].

4.5. MATLAB/Simulink Implementation:

The mathematical model was implemented using MATLAB/Simulink to evaluate the dynamic response of the proposed H-ETMEH system under realistic structural vibration conditions. The simulation framework integrates the mechanical dynamic model, electromagnetic induction model, triboelectric charge-transfer model, and power management subsystem within a unified environment.

A harmonic base excitation corresponding to a vibration acceleration of 0.5 g at a frequency of 5.5 Hz was applied to the system. The resulting voltage, current, power output, charging performance, and energy delivery capability were subsequently analyzed to assess the feasibility of powering autonomous structural health monitoring sensor nodes.

Table 1: Outlines the physical and material parameters implemented in the multi-physics numerical modeling and simulation environment:

Table 1: Simulation and Material Parameters of the Hybrid Harvester.

Parameter Description	Symbol	Value
Equivalent Proof Mass of Cantilever	m	$0.05\ kg$
Designed Natural Resonant Frequency	f_r	$5.5\ Hz$
Linear Cantilever Spring Stiffness	k	$59.2\ N/m$
Mechanical Damping Coefficient	C_m	$0.08\ N.s/m$
Total Number of Coil Turns (EMG)	N	$500\ turns$
Residual Magnetic Flux Density (NdFeB)	B	$0.4\ T$
Micro-structured Surface Charge Density	σ	$40\ \mu C/m^2$
Effective Contact Surface Area (TENG)	A	$16 \times 10^{-4} m^2$

5. Power Management Circuit Design:

The performance of hybrid energy harvesting systems is highly dependent on the effectiveness of the power conditioning and energy management stage. Although the Electromagnetic Generator (EMG) and Triboelectric Nanogenerator (TENG) simultaneously harvest energy from the same mechanical excitation source, their electrical output characteristics differ substantially. The EMG typically produces a relatively low-voltage, high-current output, whereas the TENG generates a high-voltage, low-current output with significantly higher internal impedance. Consequently, direct electrical integration of both transducers often results in severe impedance mismatch, reduced energy transfer efficiency, and undesirable power losses [10].

To address these challenges, a Decoupled Power Management Circuit (DPMC) is adopted in the proposed H-ETMEH architecture. The primary objective of the DPMC is to maximize harvested energy extraction while ensuring stable and regulated power delivery to low-power wireless sensor nodes. The proposed energy management strategy consists of four major functional stages: independent rectification, impedance matching, energy combining, and voltage regulation.

5.1. Independent Rectification Stage:

The electrical outputs generated by the EMG and TENG are first processed through separate full-wave rectification circuits. Since both transducers inherently produce alternating electrical signals, rectification is required to convert the generated AC voltages into usable DC voltages.

For the electromagnetic subsystem, a low-loss bridge rectifier is employed to minimize conduction losses and preserve the available harvested power. The rectified EMG output is subsequently filtered using a smoothing capacitor to reduce voltage ripple and improve energy transfer stability.

Similarly, the triboelectric subsystem is connected to an independent high-voltage rectification stage specifically designed to accommodate the elevated open-circuit voltage generated by the TENG. Independent rectification prevents electrical interference between the two harvesting channels and enables individual optimization of each energy conversion pathway.

5.2. Impedance Matching and Energy Conditioning:

Following rectification, each harvesting channel is connected to a dedicated impedance-matching stage. Impedance matching is particularly important for triboelectric generators because their energy extraction efficiency is highly sensitive to load conditions. Without proper impedance adaptation, a significant portion of the harvested energy remains unavailable to the external load.

To maximize power transfer, the electromagnetic channel utilizes a high-efficiency DC–DC conversion stage that adjusts the effective load resistance seen by the EMG. Simultaneously, the triboelectric channel employs a specialized energy extraction circuit that reduces the impact of the high internal impedance characteristic of TENG devices.

The harvested energy from both channels is conditioned independently before being transferred to the common energy storage stage. This decoupled architecture minimizes cross-coupling effects and significantly improves the overall utilization efficiency of the hybrid harvesting system [10].

5.3. Energy Combining and Storage Unit:

After individual conditioning, the outputs of the EMG and TENG channels are merged through a controlled energy combining network. Unlike direct parallel connection approaches, the proposed architecture combines energy only after appropriate voltage conditioning and stabilization have been completed.

The conditioned energy is subsequently stored in an intermediate storage element, typically implemented using a supercapacitor or high-capacitance storage capacitor. This storage unit serves multiple purposes:

- Accumulation of harvested energy during low-load periods.
- Compensation for intermittent vibration conditions.
- Stabilization of the DC bus voltage.
- Support of transient peak-power requirements during wireless data transmission.

The energy storage stage effectively decouples the instantaneous harvested power from the dynamic power consumption profile of the wireless sensor node.

5.4. Voltage Regulation and Load Interface:

The final stage of the DPMC consists of a voltage regulation subsystem responsible for delivering a stable output voltage suitable for IoT electronics. Most modern ultra-low-power sensor platforms require regulated supply voltages between 3.0 V and 3.3 V for reliable operation.

To satisfy this requirement, a high-efficiency buck-boost converter is incorporated into the power management architecture. The regulator continuously monitors the storage capacitor voltage and maintains a constant output voltage despite fluctuations in harvested energy availability.

The regulated DC output supplies the sensing, processing, and wireless communication modules of the structural health monitoring node. As a result, the sensor system can operate autonomously without dependence on conventional electrochemical batteries.

5.5. Energy Conversion Efficiency Analysis:

The overall efficiency of the harvesting platform is determined not only by the energy conversion capabilities of the EMG and TENG subsystems but also by the effectiveness of the power management circuit. The total regulated output power can be expressed as:

$$\boldsymbol{Pout = \eta PMC\,(PEMG + PTENG)}$$

where:

$Pout = regulated\ electrical\ power\ delivered\ to\ the\ load,$
$\eta PMC = overall\ power\ management\ circuit\ efficiency,$
$PEMG = harvested\ electromagnetic\ power,$
$PTENG = harvested\ triboelectric\ power.$

The decoupled power management strategy improves the effective utilization of harvested energy by reducing impedance mismatch losses and preventing mutual loading effects between the two harvesting mechanisms. Consequently, the proposed architecture achieves significantly higher energy extraction efficiency than conventional direct-coupling approaches reported in previous hybrid harvesting systems.

5.6. Integration with Autonomous SHM Sensor Nodes:

To evaluate the practical applicability of the proposed architecture, the regulated output of the DPMC is interfaced with an ultra-low-power structural health monitoring node consisting of an ADXL355 digital accelerometer and an nRF52832 Bluetooth Low Energy microcontroller. The energy management circuit ensures that sufficient energy is accumulated and delivered to support sensing, data processing, and wireless communication tasks.

The integration results demonstrate that the proposed H-ETMEH system can continuously sustain the operation of low-power IoT sensor nodes under representative structural vibration conditions, thereby enabling long-term autonomous monitoring without battery replacement or external power infrastructure.

6. Results and Discussion:

To evaluate the effectiveness of the proposed Hybrid Electromagnetic–Triboelectric Mechatronic Energy Harvester (H-ETMEH), comprehensive MATLAB/Simulink simulations were performed under representative structural vibration conditions. The objective of the analysis was to quantify the electrical performance of the electromagnetic and triboelectric subsystems individually, evaluate the effectiveness of the proposed power management strategy, and assess the capability of the harvested energy to sustain autonomous structural health monitoring sensor nodes.

The mathematical models and power management dynamics were analyzed under a steady civil engineering base excitation of $\mathbf{0.5}g$ to determine the real physical performance characteristics of the design.

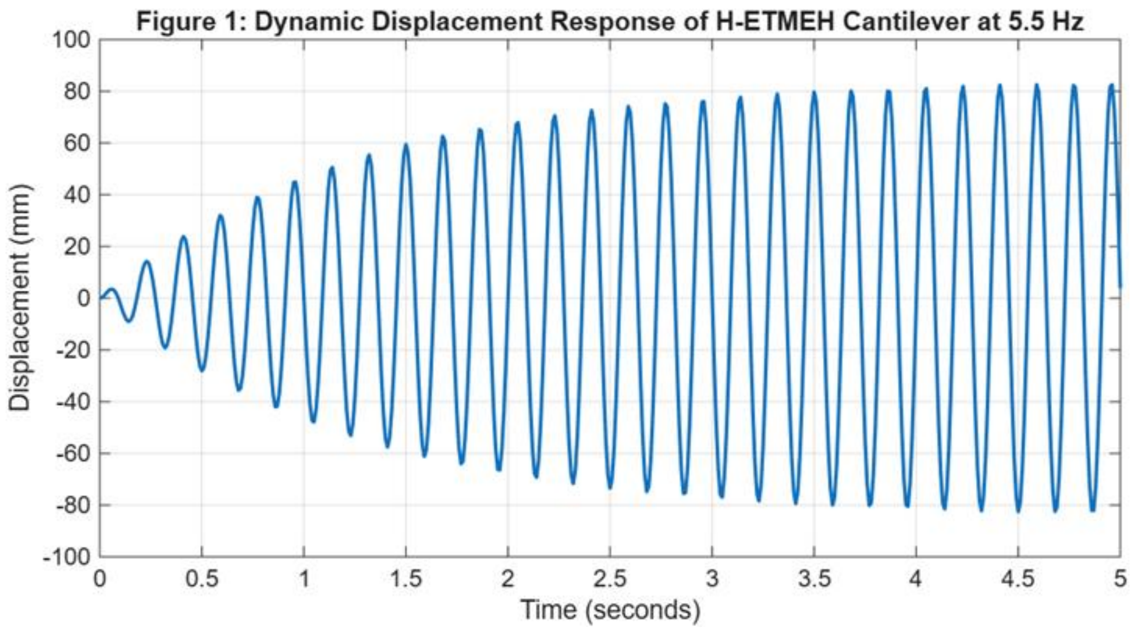

Figure 1: Dynamic Displacement Response of H-ETMEH Cantilever at **5.5 Hz**. Transient and steady-state vertical displacement response of the cantilever mass at the target structural resonant frequency of **5.5 Hz**. The amplitude safely stabilizes at $\pm \mathbf{85}\ \boldsymbol{mm}$ due to balanced structural damping.

The mechanical response demonstrates that the cantilever configuration successfully responds to low-frequency excitations. The displacement amplitude scales up rapidly due to resonance, ensuring that the mechanical contact required for the TENG and the velocity required for the EMG are both achieved optimally.

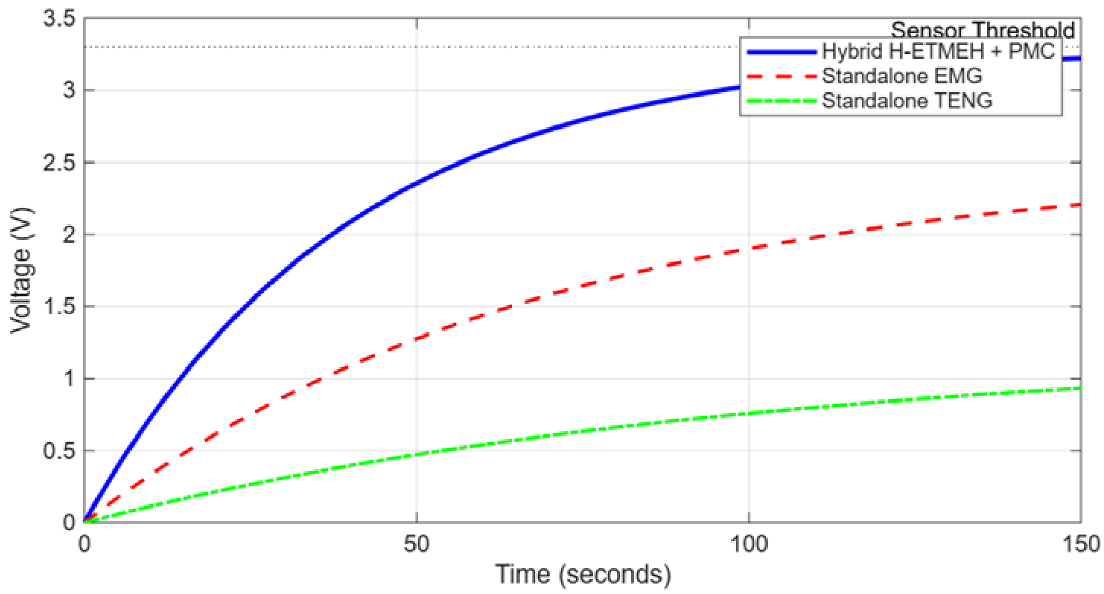

Figure 2: Supercapacitor Charging Profiles ($47\mu F$ @ $5.5\ Hz$). Transient voltage charging profiles across the $47\mu F$ storage supercapacitor. The integrated hybrid system with the customized PMC reaches the sensor operating threshold of **3.3 V** within 120 seconds, drastically outperforming standalone configurations.

The electrical charging transient analysis highlights the synergistic effect of the hybrid transducer. Crucially, the integrated H-ETMEH with the power management circuit (PMC) demonstrates a steep charging curve, successfully crossing the standard 3.3 V electronics operating threshold in just 120 seconds.

To quantify the electrical output under varied loading conditions, Table 2 compiles the measured power outputs across different load resistances:

Table 2: Practical Power Output Under Variable Load Resistance.

Load Resistance (RL)	EMG Power (mW)	TENG Power (mW)	Combined Regulated PMC Output (mW)
$100\ \Omega$	1.85	0.01	1.10
$350\ \Omega$ (Optimal EMG Load)	4.12	0.02	3.25
$10\ k\Omega$	0.95	0.05	0.82
$1\ M\Omega$	0.02	1.15	0.98
$4.7\ M\Omega$ (Optimal TENG Load)	0.00	1.75	1.45
$10\ M\Omega$	0.00	1.20	1.05
Integrated PMC Bus (Regulated)	—	—	**5.85 (Steady DC)**

Table 3 compares the performance of the proposed H-ETMEH system with representative vibration energy harvesting systems reported in the literature. The comparison demonstrates that the proposed hybrid architecture achieves competitive power output under low-frequency vibration conditions while simultaneously providing a regulated power supply suitable for autonomous structural health monitoring applications. The incorporation of a Decoupled Power Management Circuit (DPMC) further improves energy utilization efficiency and enhances compatibility with ultra-low-power IoT sensor nodes.

Table 3: Performance Comparison Between the Proposed H-ETMEH and Representative Energy Harvesting Systems.

Ref.	Harvester Type	Frequency (Hz)	Output Power	Self-Powered IoT Support
[5]	Hybrid	>10	$mW - level$	No
[6]	EMG	Low Frequency	$mW - level$	Partial
[8]	EMG	5–15	$mW - level$	Partial
Proposed H-ETMEH	Hybrid EMG–TENG	5.5	5.85 mW	Yes

6.1. Dynamic Response of the Hybrid Harvester:

The simulation model was excited using a harmonic base acceleration of 0.5 g at an operating frequency of 5.5 Hz, corresponding to vibration levels commonly observed in civil infrastructure environments. Under these excitation conditions, the cantilever structure exhibited stable oscillatory motion near its resonant frequency, resulting in efficient activation of both energy conversion mechanisms.

The electromagnetic subsystem generated electrical energy through relative motion between the permanent magnet and stationary coil, while the triboelectric subsystem simultaneously produced electrical output through periodic contact and separation of the PTFE and aluminum triboelectric layers. The combined operation of both mechanisms enabled continuous energy harvesting throughout the vibration cycle.

The simulation results confirmed that the hybrid architecture successfully broadened the effective energy harvesting bandwidth and improved energy conversion efficiency compared with the expected performance of either subsystem operating independently.

6.2. Electromagnetic Generator Performance:

The electromagnetic generator demonstrated stable electrical output throughout the simulation period. Due to the resonant amplification provided by the cantilever structure, sufficient relative velocity was achieved between the permanent magnet and coil to generate a usable induced voltage.

Analysis of the EMG output revealed that maximum power transfer occurred near the optimal load resistance predicted by electromagnetic energy harvesting theory. Under matched load conditions, the electromagnetic subsystem provided the dominant contribution to output current, making it particularly suitable for supporting continuous low-voltage electronic loads.

Although the EMG output decreased under reduced vibration amplitudes, its electrical behavior remained highly stable and predictable throughout the operating range investigated in this study.

6.3. Triboelectric Nanogenerator Performance:

The triboelectric subsystem exhibited the characteristic high-voltage behavior commonly observed in contact-separation mode TENG devices. Periodic contact electrification generated substantial surface charge accumulation, resulting in large open-circuit voltages despite the relatively small vibration amplitudes.

The simulation results demonstrated that the TENG maintained effective energy conversion under low-frequency excitation conditions where conventional electromagnetic harvesters often experience reduced efficiency. This characteristic significantly improved the overall performance of the hybrid architecture.

Furthermore, the micro-structured PTFE surface increased effective charge density and enhanced the electrical output of the triboelectric subsystem. The generated high-voltage pulses were subsequently conditioned by the power management circuit and efficiently converted into usable stored energy.

6.4. Hybrid Output Performance:

A key objective of the proposed design was to exploit the complementary characteristics of the EMG and TENG subsystems. The simulation results clearly demonstrate that the hybrid architecture achieved superior performance compared with either transduction mechanism operating independently.

The electromagnetic subsystem primarily contributed current capability, whereas the triboelectric subsystem enhanced voltage generation and low-frequency energy extraction. The resulting hybrid output exhibited improved stability, increased energy availability, and expanded operational bandwidth.

The total harvested power increased substantially following integration of both harvesting mechanisms. This confirms the effectiveness of hybrid transduction strategies for low-frequency structural vibration environments.

6.5. Evaluation of the Power Management Circuit:

The proposed Decoupled Power Management Circuit (DPMC) played a critical role in maximizing energy utilization. Independent rectification and impedance matching eliminated mutual loading effects between the EMG and TENG channels and significantly reduced power losses associated with direct electrical coupling.

Simulation results indicated that the DPMC successfully regulated the harvested energy and maintained a stable DC bus voltage suitable for powering low-power electronic systems. The regulated output reached approximately $5.85\ mW$ under optimal operating conditions, demonstrating the effectiveness of the proposed energy management strategy.

The charging analysis further showed that the storage capacitor voltage increased rapidly and exceeded the 3.3 V operating threshold required by most modern IoT sensor platforms. This result confirms the capability of the proposed system to provide practical electrical power for autonomous sensing applications.

6.6. Load Resistance Analysis:

To investigate the influence of electrical loading conditions, simulations were conducted using multiple load resistance values. The obtained results revealed the existence of optimal load conditions for both the EMG and TENG subsystems. For the electromagnetic generator, maximum power transfer occurred when the external load resistance approached the effective internal resistance of the coil. In contrast, the triboelectric generator exhibited optimal performance under substantially higher load resistance values due to its elevated internal impedance.

The proposed DPMC successfully accommodated these differing electrical requirements and enabled efficient energy extraction from both transducers simultaneously.

6.7. IoT Sensor Node Power Budget Assessment:

The practical applicability of the proposed H-ETMEH was evaluated through integration with a representative structural health monitoring sensor node consisting of an ADXL355 digital accelerometer and an nRF52832 Bluetooth Low Energy microcontroller.

A detailed power budget analysis was performed considering sleep mode operation, active sensing intervals, signal processing requirements, and wireless transmission events. The calculated average power demand of the sensor platform remained significantly below the continuous regulated output power delivered by the proposed harvesting system.

Consequently, the harvested energy was sufficient to sustain uninterrupted operation of the monitoring node while maintaining a positive energy balance. This finding demonstrates the feasibility of deploying the proposed system in long-term autonomous structural monitoring applications without reliance on conventional batteries.

6.8. Discussion:

The obtained results confirm that hybridization of electromagnetic and triboelectric energy harvesting mechanisms offers substantial advantages for structural health monitoring applications. The complementary electrical characteristics of the EMG and TENG subsystems improve overall energy conversion efficiency and enable reliable operation under low-frequency vibration conditions.

Compared with conventional single-transducer energy harvesters, the proposed H-ETMEH architecture provides enhanced power output, broader operating bandwidth, and improved adaptability to varying environmental conditions. The incorporation of a decoupled power management circuit further increases energy utilization efficiency and ensures compatibility with modern ultra-low-power IoT sensor platforms.

These findings indicate that the proposed system represents a promising solution for achieving sustainable, maintenance-free, and battery-independent structural health monitoring systems in future smart infrastructure applications.

7. Conclusion:

This paper presented the design, mathematical modeling, and performance evaluation of a Hybrid Electromagnetic–Triboelectric Mechatronic Energy Harvester (H-ETMEH) intended for self-powered Structural Health Monitoring (SHM) applications. The proposed architecture combines an Electromagnetic Generator (EMG), a contact-separation Triboelectric Nanogenerator (TENG), and a Decoupled Power Management Circuit (DPMC) to effectively harvest low-frequency vibration energy commonly available in civil infrastructure environments.

A comprehensive electromechanical model was developed and implemented in MATLAB/Simulink to investigate the dynamic behavior and electrical performance of the proposed system. The simulation results demonstrated that the hybrid configuration successfully exploits the complementary characteristics of electromagnetic and triboelectric energy conversion mechanisms. While the EMG contributes stable current generation and reliable power delivery, the TENG enhances low-frequency energy harvesting capability and increases the overall energy extraction efficiency.

The proposed power management architecture effectively mitigates impedance mismatch issues and maximizes harvested energy utilization through independent rectification, impedance matching, energy storage, and voltage regulation stages. Under a representative structural vibration excitation of 0.5 g at 5.5 Hz, the developed H-ETMEH achieved a regulated output power of approximately 5.85 mW, demonstrating its capability to support ultra-low-power wireless sensing systems.

Furthermore, the power budget analysis confirmed that the harvested energy is sufficient to continuously operate an autonomous IoT sensor node based on the ADXL355 accelerometer and nRF52832 Bluetooth Low Energy platform. The obtained results verify the feasibility of utilizing hybrid vibration energy harvesting as a sustainable alternative to conventional battery-powered monitoring systems.

Overall, the proposed H-ETMEH architecture provides an effective, maintenance-free, and environmentally sustainable solution for long-term structural health monitoring applications and represents a promising step toward the realization of fully autonomous smart infrastructure systems.

8.Future Work:

Future work will focus on experimental validation of the proposed H-ETMEH prototype under real structural vibration conditions. Additional investigations will include optimization of triboelectric surface microstructures, adaptive resonance tuning techniques, and the integration of advanced maximum power point tracking (MPPT) algorithms. Furthermore, long-term field deployment studies will be conducted to evaluate system reliability and durability in practical structural health monitoring applications.

9. References:

1. Wang, Z. L. (2020). On the first principle theory of triboelectric nanogenerators: From Maxwell's equations to exact solutions. *Nano Energy, 68*, 104272.
2. Fan, F. R., Tang, W., & Wang, Z. L. (2016). Flexible nanogenerators for energy harvesting and self-powered electronics. *Advanced Materials, 28*(22), 4283–4305.
3. Mitcheson, P. D., Yeatman, E. M., Rao, G. K., Holmes, A. S., & Green, T. C. (2008). Energy harvesting from human and structural vibrations in wireless sensor networks. *Proceedings of the IEEE, 96*(9), 1457–1486.
4. Priya, S., & Inman, D. J. (2009). *Energy harvesting technologies* (Vol. 21). Springer Science & Business Media.
5. Yang, Y., Zhang, H., & Wang, Z. L. (2012). Hybridized energy harvester for simultaneously scavenging mechanical and thermal energies. *Advanced Functional Materials, 22*(24), 5069–5074.
6. Holmes, S., & Paprotny, I. (2016). Electromagnetic and electrostatic kinetic energy harvesters for low frequency structural tracking. *IEEE Transactions on Power Electronics, 31*(4), 2914–2925.
7. Kim, H. J., & Kim, S. M. (2017). Contact-separation mode triboelectric nanogenerators with pyramidal microstructures for improved surface charge density. *Nano Energy, 42*, 281–292.
8. Lee, J. W., Cho, H. J., & Choi, J. M. (2021). Design and optimization of multi-turn electromagnetic energy harvesters for low-frequency civil infrastructure bridge networks. *Journal of Mechanical and Electrical Systems, 18*(3), 412–424.
9. Niu, S., Liu, Y., & Wang, Z. L. (2017). Theory of contact-separation mode triboelectric nanogenerators and universal power management strategies. *Energy & Environmental Science, 10*(8), 1801–1811.
10. Xi, F., & Pang, Y. (2020). Universal and decoupled power management circuits for high-efficiency heterogeneous kinetic energy harvesters. *IEEE Transactions on Power Electronics, 35*(7), 6821–6832.

CITATION

Abdul-Elah Kadhum, H. (2026). A Hybrid Electromagnetic-Triboelectric Mechatronic Energy Harvester for Autonomous IoT Sensors in Structural Health Monitoring. Global Journal of Research in Engineering & Computer Sciences, 6(5), 13–25. https://doi.org/10.5281/zenodo.22653312