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Vibration Energy Harvesting From Low-Frequency Machinery

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Abstract

Low-frequency vibration generated by rotating, reciprocating, pumping, and intermittently loaded machinery represents a locally available energy source that can potentially support autonomous condition-monitoring sensors, low-power wireless nodes, and embedded diagnostic electronics. Conventional resonant vibration energy harvesters can convert mechanical oscillation into electricity efficiently when their natural frequency closely matches a dominant excitation frequency, but machinery vibration frequently changes with rotational speed, loading, wear, start-stop operation, and operating state. This frequency variability creates a fundamental design challenge, particularly at low excitation frequencies where achieving resonance may require relatively low structural stiffness, increased proof mass, or larger displacement.

This study develops a simulation-based framework for comparing energy-harvesting strategies for machinery vibration without presenting hypothetical electrical outputs as experimental measurements. Five configurations are evaluated: a conventional linear piezoelectric harvester, a low-frequency electromagnetic harvester, a multi-resonant piezoelectric system, a nonlinear bistable piezoelectric system, and a nonlinear hybrid piezoelectric-electromagnetic harvester. A Low-Frequency Machinery Energy Harvesting Index is constructed from low-frequency coupling, bandwidth robustness, conversion potential, integration practicality, and operational durability. Simulated index values range from 63.6 for the conventional linear piezoelectric configuration to 84.7 for the nonlinear hybrid architecture. A complementary frequency-response simulation across 6–30 Hz shows that the linear piezoelectric system achieves the highest narrowband peak around its tuned resonance but declines rapidly during frequency mismatch, whereas electromagnetic and nonlinear hybrid systems retain stronger normalized performance across a wider excitation band.

The study demonstrates that harvested-energy performance should be evaluated against the actual machinery vibration spectrum, displacement constraints, electrical load, rectification losses, and sensor duty cycle rather than peak laboratory voltage alone. The proposed framework supports selective use of linear resonance where machinery speed is stable, electromagnetic conversion where low-frequency displacement is available, and nonlinear or hybrid systems where frequency variation makes broadband response more valuable than a single maximum-power operating point.

Keywords: vibration energy harvesting, low-frequency machinery, piezoelectric harvesting, electromagnetic harvesting, nonlinear energy harvester, wireless sensor nodes, machinery monitoring, broadband harvesting

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1. Introduction

Industrial, agricultural, and small mechanical systems continuously dissipate part of their supplied energy through vibration. Motors, pumps, compressors, gearboxes, fans, rotating shafts, reciprocating engines, machine tools, and other mechanical assemblies generate oscillatory motion through mass imbalance, rotating forces, gear meshing, fluid excitation, impacts, structural resonance, and cyclic loading. Most of this vibrational energy is too dispersed to be recovered economically as a significant contribution to the primary machine power demand. At the scale of low-power electronics, however, even relatively modest locally harvested energy can be valuable. Early energy-scavenging research demonstrated that low-level vibration could provide a credible power source for appropriately designed wireless sensor nodes, particularly where electronic duty cycles are low and battery replacement is inconvenient.

Vibration energy harvesters generally contain an inertial or deformable mechanical element that responds to base motion and a transduction mechanism that converts mechanical response into electrical energy. Piezoelectric materials generate electric charge when mechanically strained, electromagnetic harvesters generate voltage through relative motion between a magnetic field and electrical conductor, electrostatic systems use changing capacitance, and hybrid architectures combine two or more conversion mechanisms. Beeby, Tudor, and White established these transduction routes as major foundations of vibration-based microsystem energy harvesting, while later reviews have demonstrated substantial development of piezoelectric, electromagnetic, and hybrid devices for powering low-energy sensing systems.

Low-frequency machinery creates a specific difficulty because conventional inertial harvesters are often resonant devices. For a simplified mass-spring system, the undamped natural frequency is

$$f_n=\frac{1}{2\pi}\sqrt{\frac{k}{m}}$$

where (k) is effective stiffness and (m) is proof mass. Lowering (f_n) therefore requires lower stiffness, greater mass, or a combination of both. In a physically compact harvester, each option introduces a trade-off. Very compliant structures may experience excessive travel or fatigue, whereas large proof masses increase device dimensions and attachment loads. Research focused specifically on low-frequency excitation has therefore found electromagnetic and magnetoelectric conversion particularly attractive where appreciable relative motion is available.

Frequency stability presents a second challenge. A harvester tuned precisely to a machine operating at one rotational speed can produce strong output around resonance, but its performance may fall rapidly when speed changes. Zhu, Tudor, and Beeby identify resonance mismatch as a fundamental limitation of conventional vibration microgenerators and review approaches including mechanical or electrical tuning, generator arrays, nonlinear springs, mechanical stoppers, and bistable structures for widening the operating range. Nonlinear vibration harvesting research has subsequently examined Duffing behavior, bistability, multistability, parametric excitation, frequency conversion, and other mechanisms designed to trade narrowband peak performance for greater responsiveness across variable or broadband vibration.

The present study investigates vibration energy harvesting from low-frequency machinery through a simulation-based comparative framework. The simulated frequency interval of 6–30 Hz is used as an illustrative machinery-operating band rather than as a universal definition of low-frequency vibration. No shaker-table measurements, rotating-machine experiments, harvested-voltage recordings, or measured power densities are presented as original evidence. Instead, the paper compares major transduction and bandwidth-management strategies through consistent engineering criteria. Particular attention is given to the distinction between peak resonant output and usable energy accumulated across realistic operating variability. The study proposes that machinery harvesters should be designed around the spectral and operational characteristics of the host machine rather than selected primarily according to the highest electrical output reported under one controlled excitation.

2. Objectives of the Study

2.1 To Compare Low-Frequency Energy-Harvesting Mechanisms

The first objective is to compare piezoelectric, electromagnetic, multi-resonant, nonlinear, and hybrid energy-harvesting architectures under low-frequency machinery excitation. The analysis considers how each mechanism converts mechanical vibration and whether its physical architecture remains practical as resonance is shifted toward lower frequencies.

Piezoelectric harvesting is evaluated for its high electromechanical coupling and structural simplicity, while electromagnetic conversion is considered in relation to the relatively large displacement available at lower frequencies. Hybrid systems are assessed for their ability to extract energy through more than one transduction mechanism without assuming that additional conversion stages automatically increase net useful power.

2.2 To Evaluate Resonance Mismatch and Bandwidth Robustness

The second objective is to examine the effect of changing machinery frequency on harvested-energy performance. A machine operating at nominally constant speed may still experience frequency drift caused by load variation, controller action, belt slip, process changes, component wear, or switching among operating states.

The study therefore distinguishes peak power from band-integrated harvesting capability. A narrowband system can be preferable when excitation is stable and predictable, whereas broader response can become more valuable when the machine spends substantial operating time away from one resonance frequency.

2.3 To Develop a Machinery-Oriented Harvester Selection Framework

The third objective is to create a selection framework that incorporates mechanical response, electrical conversion, installation constraints, and long-term service requirements. Harvester suitability is evaluated according to the machinery vibration spectrum, expected acceleration, available displacement, attachment location, environmental conditions, required sensor power, and electrical interface.

The resulting framework is intended primarily for autonomous sensing and condition-monitoring applications. It does not assume that low-frequency vibration harvesting will recover a meaningful fraction of the machine's main operating energy. Its role is instead to convert otherwise dissipated local vibration into enough electrical energy to reduce battery dependence for appropriately designed low-power electronics.

3. Review of Literature

3.1 Resonant Piezoelectric and Electromagnetic Energy Harvesting

Early vibration-energy-harvesting research established the basic importance of matching an inertial generator to the characteristics of the ambient vibration source. Roundy, Wright, and Rabaey examined low-level vibration as a power source for wireless sensor nodes and demonstrated that practical energy-harvesting potential depends jointly on the vibration environment and the power requirements of the electronics. Beeby, Tudor, and White subsequently reviewed inertial vibration-powered generators and formalized piezoelectric, electromagnetic, and electrostatic conversion as the three principal microsystem transduction mechanisms.

Piezoelectric harvesters commonly use a cantilever beam carrying a piezoceramic layer and tip mass. Base excitation bends the beam, produces strain in the piezoelectric layer, and generates an alternating electrical potential. Priya's review of low-profile piezoelectric transducers describes piezoelectric harvesting as a major approach for converting local mechanical vibration into electrical energy and emphasizes the importance of material selection, resonant operation, structural geometry, and electromechanical modeling. Anton and Sodano similarly show that piezoelectric energy harvesting is attractive for self-powered sensors because the transducer can be structurally simple and requires no moving magnetic assembly.

The main difficulty is that a conventional piezoelectric resonator can have a relatively narrow useful frequency band. When the excitation moves away from resonance, strain amplitude and harvested power can fall sharply. Zhu, Tudor, and Beeby demonstrate that this is a general limitation of resonant generators rather than an exclusively piezoelectric problem. Erturk and Inman's electromechanical modeling framework further establishes that mechanical dynamics and the electrical load interact, meaning that optimum harvested power cannot be determined from mechanical resonance alone.

where (e) is induced voltage, (N) is the effective number of coil turns, and (\Phi) is magnetic flux. Relative motion between a magnet and coil changes the linked magnetic flux and produces electrical output. Naifar and colleagues' survey of harvesters for low-frequency excitation concludes that electromagnetic and magnetoelectric principles are particularly promising within low-frequency applications because they can exploit comparatively large mechanical displacement. The trade-off is that coils, magnets, air gaps, electrical resistance, and moving assemblies can increase device size or manufacturing complexity compared with a simple bonded piezoelectric element.

3.2 Frequency Tuning, Broadband Response, and Nonlinear Dynamics

A resonant harvester is most effective when the mechanical excitation remains close to its tuned natural frequency. Machinery vibration rarely behaves as one perfectly stationary sinusoid. Even when one rotational order dominates, sidebands, harmonics, gear-mesh components, load-dependent resonances, and transient behavior can contribute additional spectral content. The challenge is therefore to obtain useful response without making the harvester unnecessarily complex.

Frequency tuning represents one approach. Zhu, Tudor, and Beeby classify tuning strategies into mechanisms that alter the resonant characteristics of the harvester and mechanisms that broaden its effective response. Tuning can be mechanical or electrical, passive or actively controlled, but active tuning has an important limitation: the energy required to identify and maintain the correct tuning condition must not consume the additional energy obtained from the process. Multi-resonant structures offer another strategy by incorporating several natural frequencies within the required operating band.

Nonlinear vibration harvesters seek to exploit behavior unavailable in linear oscillators. Bistable systems contain two stable equilibrium positions separated by an energy barrier. Under suitable excitation, the oscillator can undergo snap-through motion between the wells, creating large-amplitude displacement across a broader frequency interval. Pellegrini and colleagues identify bistability as a potential solution to the difficulty of harvesting low-frequency broadband vibration using narrowband linear systems. Harne and Wang similarly review bistable systems and show that interwell motion can enhance broadband energy-harvesting capability under appropriate excitation.

The nonlinear advantage is conditional rather than universal. Jia's comprehensive nonlinear vibration-harvesting review emphasizes that Duffing stiffness, bistability, parametric mechanisms, frequency conversion, and stochastic effects can broaden frequency response or improve peak output, but the benefits depend strongly on excitation amplitude and dynamic state.

3.3 Hybrid Harvesting and Power-Management Requirements

Hybrid harvesters combine conversion mechanisms with the aim of capturing energy that would otherwise remain underutilized by one transducer. Piezoelectric-electromagnetic hybrids are particularly common because bending strain can activate the piezoelectric element while proof-mass or magnet motion simultaneously drives electromagnetic induction. Comparative reviews show that hybrid systems can produce strong power density and can be configured as resonant, multi-mode, nonlinear, frequency-tuned, or frequency-up-conversion devices.

Combining transducers does not eliminate fundamental energy constraints. Both conversion mechanisms draw energy from the same mechanical source, and each adds electromechanical damping. Increasing electrical extraction can therefore modify vibration amplitude itself. A valid comparison must be based on net useful electrical energy after rectification, impedance matching, power conditioning, storage losses, and converter standby demand rather than summing open-circuit voltages.

The electrical interface becomes especially important at low harvested power. Piezoelectric devices can generate comparatively high alternating voltage at relatively low current, whereas electromagnetic devices may generate lower voltage with higher current depending on the coil and motion. Rectifiers, synchronous switching circuits, DC-DC converters, storage capacitors, rechargeable microbatteries, and sensor duty cycling must therefore be matched to the transducer. Mitcheson and colleagues emphasize that energy-harvesting design for wireless electronic devices requires joint consideration of the mechanical source, generator limits, and electronic power requirements rather than evaluating transduction independently.

4. Research Methodology

4.1 Simulation Design and Machinery Vibration Envelope

The study uses a comparative simulation representing a machine whose dominant vibration frequency changes between 6 and 30 Hz. The excitation is assumed to originate from rotating or reciprocating operation and to possess sufficient mechanical vibration for local energy harvesting. The frequency range is illustrative and is not intended as a universal machinery specification.

Five harvester architectures are examined: a linear piezoelectric resonator, a low-frequency electromagnetic generator, a multi-resonant piezoelectric harvester, a nonlinear bistable piezoelectric harvester, and a nonlinear piezoelectric-electromagnetic hybrid. All systems are treated as conceptual devices of comparable application scale. Numerical results represent normalized simulation outputs rather than measured power.The formulation demonstrates why increased electrical extraction affects the mechanical response rather than acting independently of it.

4.2 Low-Frequency Machinery Energy Harvesting Index

A Low-Frequency Machinery Energy Harvesting Index (LFMEHI) is introduced to compare design suitability. The index deliberately includes bandwidth, integration, and durability instead of ranking architectures using peak electrical output alone.

Table 1: Criteria Used in the Low-Frequency Machinery Energy Harvesting Index

Criterion	Engineering interpretation	Weight
Low-frequency mechanical coupling	Ability to develop useful relative motion or strain under low-frequency machine excitation	0.25
Bandwidth robustness	Ability to retain useful harvesting performance under frequency variation	0.25
Electrical conversion potential	Capacity to convert available mechanical motion into usable electrical power	0.20
Machinery integration practicality	Compactness, attachment practicality, displacement requirement, and installation complexity	0.15
Operational durability	Ability to withstand repeated vibration, environmental exposure, and prolonged cycling	0.15

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The weighting places equal emphasis on low-frequency coupling and bandwidth because both are central to machinery applications. High conversion efficiency at one frequency provides limited practical advantage if normal machine operation repeatedly moves outside that frequency.

4.3 Frequency-Response and Usable-Power Assessment

A normalized harvested-power response is simulated at excitation frequencies of 6, 8, 10, 12, 15, 18, 22, 26, and 30 Hz. Three representative architectures are highlighted graphically: the conventional linear piezoelectric resonator, a low-frequency electromagnetic device, and the nonlinear hybrid architecture.

The linear piezoelectric response is deliberately narrow and reaches its maximum normalized value around 15 Hz. The electromagnetic response is modeled with a lower peak but broader usable range, reflecting displacement-oriented low-frequency conversion. The nonlinear hybrid is assigned the broadest high-performance region because nonlinear dynamics and dual transduction are assumed to distribute useful response across several machinery conditions.

5. Analysis

5.1 Comparative Performance of Harvester Architectures

The simulated results reveal a clear distinction between resonance-dominated peak performance and broad low-frequency robustness. The conventional linear piezoelectric architecture produces an LFMEHI of 63.6. Its strengths include structural integration, durability, and potentially high electrical conversion near resonance. Its principal weakness is bandwidth sensitivity.

The low-frequency electromagnetic architecture achieves 76.6. It scores strongly for low-frequency coupling because the concept can exploit larger relative displacement, and its simulated response is less sharply concentrated around one frequency. Its integration score remains below that of the simple piezoelectric device because magnets, coils, clearance requirements, and moving elements can increase package complexity.

The multi-resonant piezoelectric architecture achieves 73.8. Multiple resonant modes improve bandwidth compared with a single linear resonator, although each mode still has a finite operating region. The design can therefore be attractive where a machine repeatedly operates at several known discrete speeds.

Table 2: Simulated Comparative Performance of Low-Frequency Machinery Energy Harvesters

Harvester configuration	Low-frequency coupling	Bandwidth robustness	Conversion potential	Integration practicality	Durability	LFMEHI
Linear piezoelectric resonator	55	35	78	88	82	63.6
Low-frequency electromagnetic	86	68	74	75	80	76.6
Multi-resonant piezoelectric	70	72	76	76	78	73.8
Nonlinear bistable piezoelectric	80	88	79	70	74	79.4
Nonlinear piezoelectric-electromagnetic hybrid	90	92	88	68	76	84.7

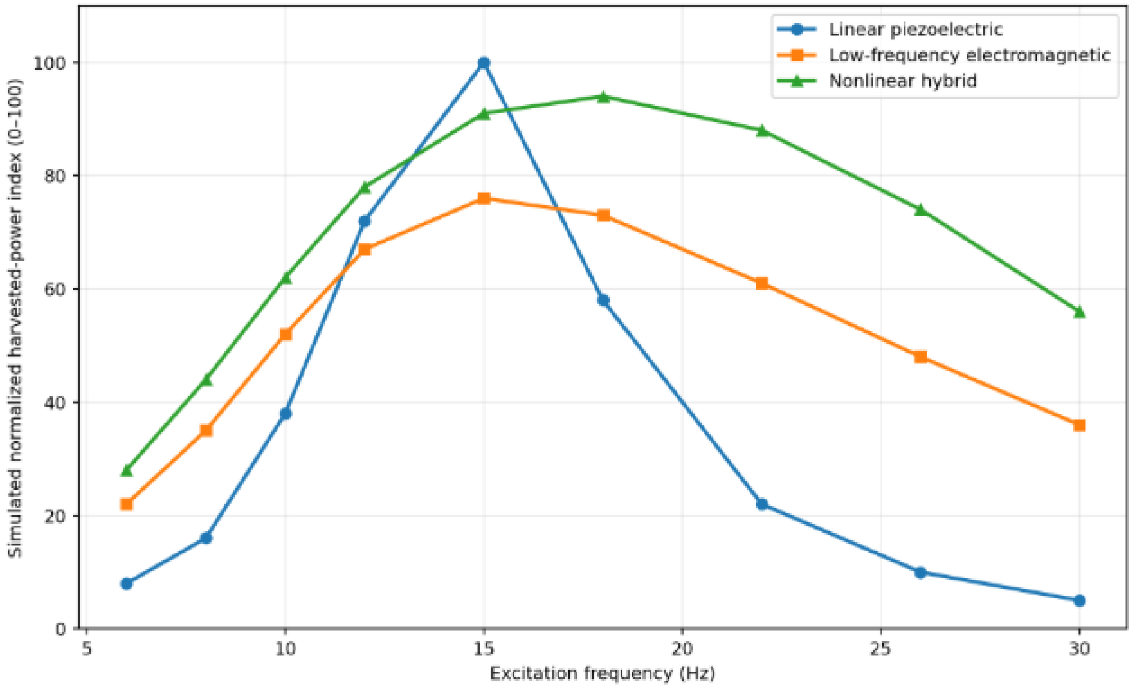
The nonlinear bistable piezoelectric architecture reaches 79.4, mainly because of its simulated bandwidth performance. This benefit assumes excitation of sufficient amplitude to generate the desired nonlinear dynamic state. The hybrid architecture obtains the highest overall index, 84.7, because it combines broad mechanical response with two electrical conversion routes. Its integration score is intentionally lower because additional components, wiring, magnetic elements, and power-conditioning requirements increase physical and control complexity.

5.2 Frequency Dependence of Harvested-Energy Performance

The simulated linear piezoelectric harvester provides the most concentrated frequency response. Its normalized harvested-power index rises from 8 at 6 Hz to 100 at 15 Hz before declining to 58 at 18 Hz and 5 at 30 Hz. The result illustrates the principal advantage and disadvantage of classical resonance: excellent output near the design point but strong sensitivity to detuning.

The electromagnetic configuration develops a lower maximum normalized value of 76 but retains substantially stronger response outside the piezoelectric resonance. Between approximately 10 and 26 Hz, its simulated normalized index remains between 48 and 76. This broader behavior is consistent with literature identifying electromagnetic conversion as particularly promising for low-frequency excitation.

Graph 1: Simulated Low-Frequency Response of Alternative Vibration Energy Harvesters



The nonlinear hybrid architecture retains the strongest simulated performance over the complete operating band. Its normalized response rises from 28 at 6 Hz to 94 at 18 Hz and remains 74 at 26 Hz. The graph should not be interpreted as proof that a nonlinear hybrid will always outperform a well-tuned linear device. Around the linear resonance, the simple piezoelectric design still produces the highest simulated peak. The advantage of the nonlinear hybrid lies in the wider high-output operating region rather than one isolated maximum.

5.3 Machinery Operating State and Net Usable Energy

Peak output can be misleading when machinery changes state. Consider a machine that spends only a small proportion of operating time near 15 Hz and most of its time between 10 and 25 Hz. A harvester optimized solely for the 15 Hz peak could report impressive laboratory power while accumulating less energy over a full operating cycle than a lower-peak broadband device.

This quantity inherently incorporates frequency, acceleration, downtime, startup, and electrical conversion efficiency when those variables are measured experimentally.

Sensor demand should be evaluated on the same basis. A vibration-monitoring node may not require continuous transmission. It can accumulate energy in a capacitor, perform periodic acceleration or temperature measurements, process the data locally, and transmit only when sufficient energy is available. Energy harvesting can consequently remain useful even when instantaneous electrical power is below the transmitter's peak requirement.

6. Discussion

6.1 Resonance Matching Versus Broadband Harvesting

The central engineering decision is whether the host machine provides sufficiently stable vibration for narrowband resonance to remain advantageous. When rotational speed is tightly controlled and one structural mode dominates continuously, a tuned linear piezoelectric harvester can be attractive because it is mechanically simple and can produce strong strain amplification at resonance. Piezoelectric harvesting theory and established low-profile transducer research provide a mature basis for such designs.

The situation changes when frequency varies significantly. Zhu, Tudor, and Beeby demonstrate that mismatch between ambient vibration and harvester resonance can reduce generated power substantially. Under these conditions, multi-resonant, tunable, nonlinear, or hybrid architectures become more defensible, but they should be selected according to the actual distribution of operating frequency rather than simply described as “broadband.”

Bandwidth must also be defined carefully. A nonlinear device can show a large theoretical response interval during one frequency-sweep direction while exhibiting different behavior during the reverse sweep or under random excitation. Bistable systems may require a minimum excitation level before high-energy interwell oscillation becomes established. Harne and Wang and Pellegrini and colleagues both show that nonlinear broadband behavior is accompanied by dynamic complexity that must be evaluated experimentally.

6.2 Low-Frequency Mechanics, Displacement Constraints, and Transducer Choice

Low-frequency energy harvesting creates a mechanical scaling challenge. To obtain low resonant frequencies in a compact inertial structure, the designer generally requires low stiffness or high proof mass. Both can increase relative displacement, and available displacement is often constrained by enclosure size, fatigue limits, surrounding machine components, and acceptable reaction forces.

This issue favors electromagnetic conversion in some applications because relative magnet-coil travel can be exploited directly. Naifar and colleagues identify electromagnetic and magnetoelectric methods as particularly promising for low-frequency vibration sources. Electromagnetic architectures can nevertheless become inefficient when physical scale becomes extremely small because coil resistance and magnetic-circuit limitations become comparatively important.

Piezoelectric devices offer a different advantage. They can convert structural strain without requiring sliding electrical contacts or coil windings. A compliant cantilever with a tip mass can be tuned to relatively low frequencies, but excessive beam travel may become a fatigue or packaging problem. Compliant-mechanism research on piezoelectric harvesting consequently focuses on structural amplification, multimode designs, and frequency-management mechanisms rather than relying only on increasingly long flexible cantilevers.

Hybrid systems combine these characteristics but should not be selected automatically. The extra electromagnetic subsystem adds mass and electromagnetic damping to the mechanical oscillator; the piezoelectric element adds stiffness and electromechanical coupling. These interactions can be beneficial when co-designed, but simply attaching two separate generators to one oscillator does not guarantee greater net energy.

6.3 From Laboratory Output to Self-Powered Machinery Monitoring

The most compelling use of low-frequency machinery energy harvesting is the support of sensing and communication systems located directly on or near the vibrating component. Remote bearing housings, pumps, gearboxes, motors, agricultural machinery, or distributed processing equipment can be difficult to wire or require repeated battery maintenance. Energy harvesting can reduce this maintenance burden where local vibration remains available during the periods when sensing is most important.

A useful prototype should therefore be tested as part of an end-to-end energy system. Mechanical vibration enters the harvester; the transducer generates AC electrical output; conditioning electronics rectify and regulate it; energy is stored; and the sensor consumes the stored energy according to its measurement and communication schedule. A high open-circuit voltage is not sufficient evidence of useful harvesting because an unloaded transducer can generate voltage while delivering little power.

Evaluation should report at least excitation frequency, acceleration amplitude, displacement constraints, harvester dimensions, proof mass, electrical load, rectifier configuration, storage element, delivered DC power, startup behavior, and usable operating bandwidth. Reviews comparing piezoelectric, electromagnetic, and hybrid harvesters show that published devices vary considerably in geometry, resonance frequency, and output, making standardized reporting essential for meaningful comparison.

Long-term reliability should receive equal attention. A machinery-mounted harvester may experience millions of vibration cycles, temperature change, oil mist, dust, electromagnetic interference, mounting looseness, and accidental shock. Piezoelectric ceramics can crack under excessive strain, bonded layers can delaminate, electromagnetic clearances can change, magnets can detach, and nonlinear structures can experience repeated impact or snap-through stresses. A system intended to eliminate battery maintenance should not introduce a maintenance-intensive mechanical energy harvester.

7. Conclusion

Low-frequency machinery vibration offers a realistic local energy source for autonomous condition-monitoring systems, but successful harvesting requires a close match between the mechanical source, transducer, electrical interface, and sensor demand. The main opportunity is not recovery of a substantial proportion of primary machine energy; rather, it is conversion of otherwise dissipated vibration into sufficient electrical energy to support low-power sensing, local processing, and intermittent wireless communication.

The simulation developed in this study shows why peak resonant output should not be used as the only performance criterion. The conventional linear piezoelectric configuration achieves strong simulated output at its tuned resonance but receives an LFMEHI of 63.6 because of frequency sensitivity. The low-frequency electromagnetic system reaches 76.6, the multi-resonant piezoelectric system 73.8, the nonlinear bistable system 79.4, and the nonlinear hybrid configuration 84.7. These scores are methodological illustrations rather than experimentally measured efficiencies.

The frequency-response analysis further demonstrates that different architectures serve different machinery environments. A linear piezoelectric harvester remains attractive for stable narrowband excitation. Electromagnetic conversion becomes advantageous when low-frequency relative displacement is available. Multi-resonant devices are useful for machinery operating repeatedly at several discrete speeds, while nonlinear or hybrid architectures become more attractive when frequency variation is sufficiently large to justify the additional mechanical and electrical complexity. No architecture is universally optimal.

Future empirical research should begin with long-duration vibration measurements on the intended host machine rather than with harvester fabrication. Representative spectra should be obtained under startup, steady operation, part load, full load, shutdown, and relevant fault conditions. Candidate harvesters should then be tested using these measured excitation histories, with delivered DC energy evaluated after rectification and storage. Reliability tests should include frequency drift, temperature, repeated cycling, shock, and mounting variation. This source-first methodology would allow vibration energy harvesting to progress from resonant laboratory demonstrations toward reliable self-powered sensing systems designed around the real operating behavior of low-frequency machinery.

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