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ABSTRACT

With the increasing demand for power supply in power Internet-of-Things (IoT) sensor nodes, providing stable, self-powered operation near power-frequency transformers remains a critical challenge. This paper presents the design of an energy harvester based on FeCoV–PZT laminated magnetoelectric composites for efficiently harvesting 50 Hz stray magnetic field energy around power transformers. This study leverages the Ericsson cycle theory as a guiding principle for the critical selection of the magnetostrictive phase, ultimately identifying FeCoV for its optimal energy conversion potential. By employing a cantilever structure integrated with an NdFeB permanent magnet at the free end, the resonant frequency of the device is significantly reduced and matched to the power frequency, thereby enhancing the magnetoelectric conversion efficiency without requiring a bias magnetic field. Experimental results demonstrate that, through structural optimization, the resonant frequency can be reduced to ≈50 Hz, substantially improving conversion efficiency; a peak magnetoelectric coefficient of 3.8 V/(cm Oe) and a maximum output volume power density of 7.6 μW/cm^3 were achieved, showing its potential for practical applications.

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I. INTRODUCTION

With the rapid development of the Internet of Things and smart grid technologies, a large number of sensor nodes have been deployed for condition monitoring of electrical equipment. Relying on batteries with limited lifespans to power sensors not only leads to costly and difficult maintenance, especially in inaccessible locations, but also creates environmental problems from battery disposal.[1] Providing a continuous, stable, and maintenance-free energy supply for these distributed sensor devices remains a key obstacle to their large-scale application.[2]

Environmental energy harvesting technology, which aims to convert widely available environmental energy (such as mechanical vibration, magnetic fields, and thermal energy) into electrical energy, offers a promising alternative to batteries for powering sensors.[3] In power systems, operational transformers are surrounded by untapped stray magnetic energy. Efficiently harvesting this energy to power nearby monitoring sensors holds significant application value and research importance. Magnetoelectric (ME) composites are comprised of a magnetostrictive phase and a piezoelectric phase.[4] The coupling between the magnetostrictive effect and the piezoelectric effect gives rise to the magnetoelectric effect. Energy harvesters based on such ME composites are capable of converting stray magnetic fields around operational transformers into electrical energy.[5]

The Ericsson cycle is a thermodynamic cycle that, through innovative extension, can be applied to describe the magneto-mechanical energy conversion process in magnetostrictive materials under alternating constant stress and constant magnetic field.[6] The area enclosed by the cycle on the B–H curve represents the maximum magneto-mechanical energy the material can convert under ideal conditions. In this study, following a theoretical comparison of different magnetostrictive materials based on the Ericsson cycle, FeCoV was selected as the magnetostrictive phase after a comprehensive evaluation of properties including mechanical strength, toughness, and high-temperature resistance.[7] With optimized

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structural design and performance tuning, we fabricated a laminated magnetoelectric composite using FeCoV soft magnetic material and PZT ($Pb[Zr_xTi_{1-x}]O_3$) piezoelectric ceramic for harvesting stray magnetic energy near power transformers.

II. MATERIAL SELECTION AND STRUCTURAL DESIGN

A. Selection of magnetostrictive materials based on the Ericsson cycle

In thermodynamics, the Ericsson cycle is an ideal heat engine cycle consisting of two isothermal processes and two isobaric processes. In the thermodynamic cycle, work is done by altering the state of the gaseous working fluid through changes in pressure and temperature. In magnetostrictive materials, the magnetic state is altered by applying mechanical stress σ and a magnetic field H, enabling energy conversion during this process. The four-stage Ericsson cycle proceeds as follows: first, stress is varied from σ_1 to σ_2 at $H = 0$; second, H is raised to H_{max} at constant σ_2; third, stress is returned to σ_1 at constant $H = H_{max}$; and finally, H is reduced back to 0 at constant σ_1 to complete the cycle.

In this study, a cantilever beam structure is employed. When the beam vibrates, the magnetostrictive layer is primarily subjected to bending stress along its length. This corresponds to an Ericsson cycle where one curve is the stress-free magnetization curve ($\sigma = 0$), and the second is obtained under uniaxial stress applied parallel to the external magnetic field. For this specific case, Laurent Daniel proposed a simplified formula for calculating the area of the Ericsson cycle:[8]

$$A_v(H_m, \sigma, 0) = \frac{\mu_0 M_s}{\kappa} \ln\left(\frac{\exp(\alpha\ \sigma)\cos(\kappa\ H_b) + 2}{\exp(\alpha\ \sigma)\cos(\kappa\ H_m) + 2} \times \frac{\cosh(\kappa\ H_m) + 2}{\cosh(\kappa\ H_b) + 2}\right) \quad (1)$$

where

$$\kappa = \frac{3\chi^0}{M_s} \quad \text{and} \quad \alpha = \frac{9\lambda_s\chi^0}{2\mu_0 M_s}. \quad (2)$$

M_s is the saturation magnetisation of the material. χ^0 is the initial anhysteretic susceptibility of the material under stress-free conditions. λ_s is the saturation magnetostriction of the material. In the case no bias-field is applied, the value of H_b is taken as the coercive field H_c, and μ_0 is the vacuum permeability. Therefore, the area of the Ericsson cycle can be estimated using only the four material parameters mentioned above. To select a suitable magnetostrictive material for the energy harvester design, this study compares three representative options: Terfenol-D (TbDyFe), known for its extremely high magnetostrictive coefficient; FeCoV alloy, which offers high saturation magnetization and a moderate magnetostrictive coefficient; and Permalloy characterized by high initial permeability and a low magnetostrictive coefficient.[9] The stray magnetic field around power transformers typically ranges from tens to hundreds of A/m. Therefore, the Ericsson cycle area per unit volume for the three materials was calculated under a magnetic field range of H_m = 50–1000 A/m and a stress of 10–50 MPa. The results are presented in Table I.

Based on the computational results, it can be observed that within the weak magnetic field range (H_m = 50–200 A/m), Fe50–Ni50 (Permalloy-like) exhibits the best performance. This is attributed to its exceptionally high initial magnetic susceptibility. In weak magnetic fields, a high susceptibility means the material is easily magnetized, leading to a significant change in magnetic induction. At higher magnetic field strengths (H_m > 600 A/m), FeCoV demonstrates the superior performance. This advantage stems from its combination of a high saturation magnetization and a relatively high magnetostriction coefficient (λ_s = 60 ppm). Throughout the entire computational range, the performance of Terfenol-D was negligibly low. This clearly indicates that for energy harvesting from low-frequency, low-intensity stray magnetic fields around power transformers, traditional "giant magnetostrictive materials" are not an effective choice, as they require a strong bias magnetic field to operate effectively. Furthermore, compared to Fe50–Ni50, FeCoV offers advantages such as high mechanical strength, good toughness, low cost, and a high Curie temperature. ME composites based on FeCoV can thus withstand high-temperature operating conditions near transformers and demonstrate greater stability in vibrating environments.

B. Structural design of ME composites

The resonant frequency of the harvester was specifically designed to be 50 Hz. This design choice is based on the fact that the stray magnetic field around power transformers originates from the AC current in the windings, which operates at the standard power frequency of 50 Hz. Therefore, to maximize energy conversion efficiency, the harvester's resonant frequency must match the frequency of the available energy source, as operating at resonance significantly amplifies the vibration amplitude and output power. Most currently studied layered ME composites have relatively high resonant frequencies, resulting in poor low-frequency response, which hinders efficient harvesting of stray magnetic energy around transformers.

TABLE I. Comparison based on volume efficiency: area A_v (H_m, σ, 0) of the Ericsson cycle (in $\mu J/cm^3$) for different materials.

H_m (A/m)	50			200			600			1000		
$\lvert\sigma\rvert$ (MPa)	10	30	50	10	30	50	10	30	50	10	30	50
Terfenol-D	0.005	0.0013	0.0025	0.0081	0.0218	0.0433	0.73	1.57	2.78	8.1	17.4	30.8
FeCoV	0.12	0.31	0.61	7.86	21.1	**41.9**	**196**	**406**	**647**	**490**	**702**	**970**
Fe50–Ni50	**0.31**	**0.52**	**0.69**	**18.44**	**30.74**	40.97	147.1	245.6	327.5	220.5	367.5	490

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To reduce the resonant frequency and enhance the low-frequency performance, we optimized the material design in two aspects. Firstly, a cantilever beam structure was adopted to effectively lower its natural resonant frequency.[10] The first-order resonant frequency of the ME composite can be approximated as follows:

$$f = \frac{1}{2\pi}\sqrt{\frac{k_{eq}}{m_{eq}}} = \frac{1}{2\pi}\sqrt{\frac{3EI}{l^3 m_{eq}}} \tag{3}$$

where k_{eq} is the equivalent stiffness of the material, m_{eq} is the equivalent mass, E is the elastic modulus of the material, I is the moment of inertia of the beam cross-section, and l represents the length of the beam. The equivalent stiffness of the ME composite is inversely proportional to the cube of the length of the cantilever. Therefore, increasing the length of the beam can significantly reduce the resonant frequency of the structure. Secondly, an NdFeB permanent magnet is attached to the free end of the cantilever. Attaching an NdFeB magnet to the free end introduces two key effects: it increases m_{eq} to further lower the frequency, and its magnetization, misaligned with the external AC magnetic field, generates a driving torque that excites vibration and induces electrical charge in the piezoelectric layer. By varying the mass and position of the NdFeB magnet, precise adjustment of the resonant frequency of the ME composite can be achieved. A schematic diagram of the ME composite structure and a photo of the PZT/FeCoV cantilever is shown in Fig. 1.

In this design, the dimensions of the PZT piezoelectric layer were fixed. Parameter optimization simulations were conducted using the finite element analysis software to systematically investigate the effects of two parameters—the length of the cantilever beam and the mass of the end mass block—on the first-order resonant frequency of ME composites. In the simulation model, FeCoV layer with different lengths and NdFeB permanent magnet with different masses were configured, and modal analysis was performed to calculate the resonant frequencies. The simulation results are presented in Fig. 2. Simulation results show that the first-order resonant frequency of ME composites can be successfully adjusted to 50 Hz by varying the length of the cantilever beam and the mass of the NdFeB permanent magnet.

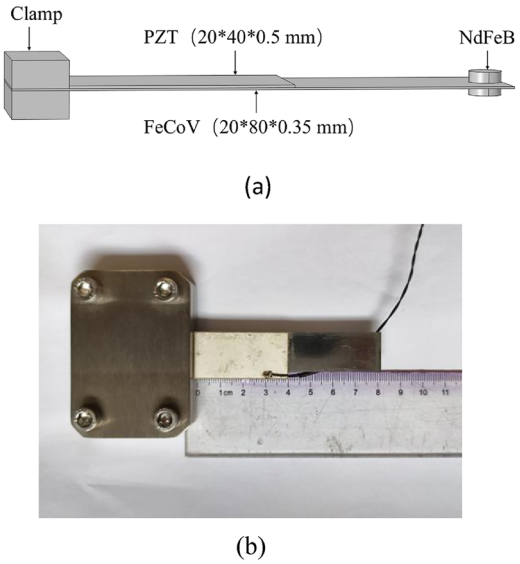


FIG. 1. (a) Schematic view picture of the PZT/FeCoV cantilever. (b) Photo of the PZT/FeCoV cantilever.

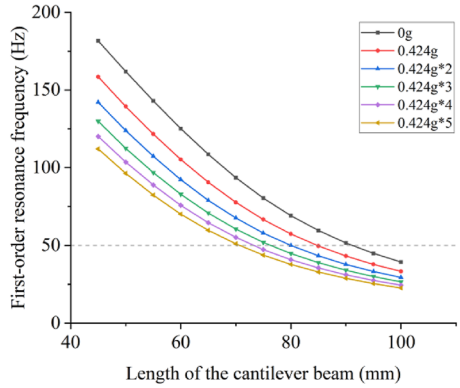


FIG. 2. The first-order resonant frequency of ME composites under different cantilever beam lengths and NdFeB permanent magnet masses.

III. EXPERIMENTS AND RESULTS

A test system was established to apply an alternating magnetic field with a fixed amplitude and variable frequency to the material. A sinusoidal signal was generated by a signal generator (Tektronix AFG 2021-SC), amplified by a power amplifier (Europower Ep4000), and then used to drive a long straight solenoid. This setup produced an alternating magnetic field with uniform amplitude and adjustable frequency inside the solenoid. The fabricated ME composite cantilever beam was fixed in the uniform magnetic field region at the center of the solenoid, with its free end suspended freely. The open-circuit voltage generated by the PZT layer was directly collected by a high-impedance digital oscilloscope (DSO-X 3034A). To protect the power amplifier, a high-power protective resistor was connected in series at its output terminal.

The magnetoelectric coefficient α is the core parameter for evaluating the performance of ME composites, and its calculation formula is as follows:

$$\alpha_{ME} = \frac{V_{out}}{t \cdot H_{ac}} \tag{4}$$

where V_{out} is the measured open-circuit voltage, t is the thickness of the sample, and H_{ac} is the amplitude of the alternating magnetic field. Figure 3 shows the curves of the magnetoelectric coefficient varying with frequency under different magnet masses. Experimental results show that increasing the tip magnet's mass reduces the resonant frequency, aligning with simulations, and significantly enhances the magnetoelectric coefficient. This performance improvement stems from two synergistic mechanisms. First, the mass increase primarily serves to down-shift the resonant frequency to 50 Hz, which is a prerequisite for exciting resonance. Second, a larger magnet mass provides a greater magnetic moment. This enhanced magnetic moment, whose magnetization is oriented

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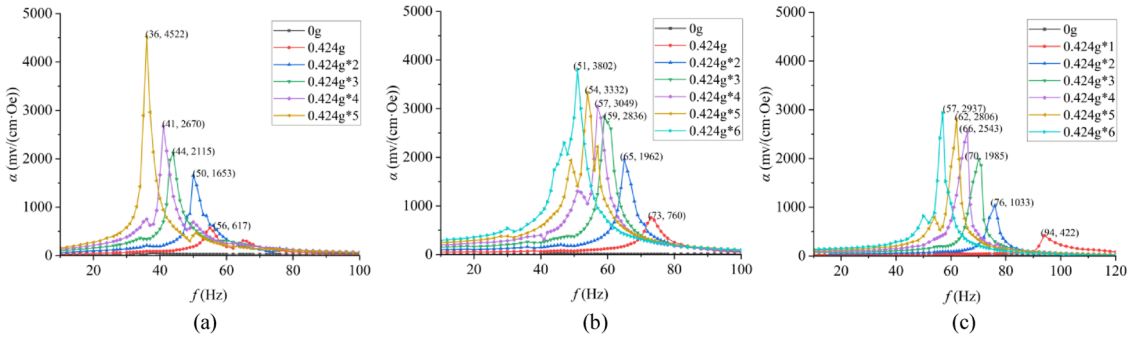


FIG. 3. Variation of ME Coupling Coefficient with Frequency under Different NdFeB Masses: (a) FeCoV layer length = 80 mm, (b) FeCoV layer length = 70 mm, (c) FeCoV layer length = 60 mm.

perpendicular to the external AC magnetic field, results in a stronger driving torque. This torque effectively drives the cantilever's vibration, leading to a higher output voltage from the piezoelectric layer. Thus, while frequency tuning is the essential prerequisite for high performance, the enhanced magnetic torque is the key mechanism for further boosting the output once resonance is achieved. According to the experimental results, it can be observed that as the length of the FeCoV layer decreases, the magnetoelectric coefficient of the ME composite also decreases. This reduction is attributed to the diminished strain generation, which leads to a smaller output voltage from the piezoelectric layer. When the FeCoV layer length is 70 mm, the ME composite achieves a magnetoelectric coefficient of 3.8 V/(cm Oe) at 51 Hz. To further evaluate its application potential, the output power was quantified under a 10 Oe magnetic field, yielding a maximum volume power density of 7.6 μW/cm^3. When integrated with a high-efficiency energy management circuit and a storage capacitor, the device is capable of supplying the required energy for intermittently operating ultra-low-power sensor nodes (such as the TI TMP117, which has a typical quiescent current of 3.5 μA, an operating voltage of 3.3 V, and a 1 Hz conversion cycle). This result demonstrates that the magnetoelectric energy harvester designed in this work possesses practical application potential for replacing batteries in the condition monitoring of power equipment.

IV. CONCLUSION

In this paper, an energy harvester based on FeCoV-PZT laminated magnetoelectric composites was designed and fabricated, designed to harvest the 50 Hz stray magnetic-field energy around power transformers. The selection of the FeCoV alloy as the magnetostrictive layer was guided by a theoretical assessment based on the Ericsson cycle. Through the design of a cantilever beam structure combined with NdFeB permanent magnets, precise adjustment of the resonant frequency of the material is achieved, making it match the frequency of the power frequency magnetic field.

Simulation and experimental results show that the resonant frequency of the structure can be effectively reduced to 50 Hz by adjusting the length of the magnetostrictive layer and the mass of the end magnets. Experimental results indicate that the energy harvester demonstrates excellent frequency response and output performance under low-frequency magnetic fields. The magnetoelectric coefficient can reach 3.8 V/(cm Oe) at 51 Hz and achieve a maximum output power of 7.6 μW/cm^3, showing application potential in replacing batteries for condition monitoring of power equipment.

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AUTHOR DECLARATIONS

Conflict of Interest

The authors have no conflicts to disclose.

Author Contributions

Changgeng Zhang: Funding acquisition (equal); Writing – review & editing (equal). **Ziyang Wang**: Data curation (equal); Writing – original draft (equal). **Haiming Jiao**: Investigation (equal); Validation (equal). **Mingming Li**: Conceptualization (equal); Formal analysis (equal). **Yongjian Li**: Funding acquisition (equal); Writing – review & editing (equal). **Zhiwei Lin**: Writing – review & editing (equal).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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