Electromagnetic Vibrational Energy Harvesting Principles

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As industries need more real-time monitoring and interconnected systems, the demand for wireless sensors expands. Vibrational energy harvesters are a potential solution for powering these sensors, as vibrations commonly exist where monitoring occurs. Developments in low-power circuitry have also led to the feasibility of these types of harvesters. Electromagnetic harvesters are a standout among various types of vibrational harvesters due to their ability to capture kinetic energy in a low-frequency range. This leads to these devices being more applicable in real-world applications where ambient vibrations are typical of having low frequencies.

electromagnetic vibration energy harvesters wireless sensor nodes (WSN) microelectromechanical systems (MEMS)

1. Introduction

In the last decade, extensive research has been carried out on the development of vibrational energy harvesters for Internet of things (IoT). This is due to advancements in ultra-low power (ULP) circuits, as well as the need for wireless sensing units [1]. Current wireless sensor nodes (WSN) typically use an electrochemical battery to power them. However, conventional batteries generally have a limited lifetime of up to 15 years when drawing currents in the μW range [2]. Some applications for these WSN lead to their battery replacement being either too difficult or too costly [3].

Renewable energy sources, such as UV radiation, thermal heat, and wind power, are well understood and applicable in outdoor environments. However, the majority of these are highly dependent on weather conditions and generate significantly less power when operated indoors [4][5]. This leads to vibrational energy harvesters being an advantageous power source alternative due to the large ambience of vibrations in the real world. Vibrational energy harvesters create energy by converting mechanical vibrations into electricity. These harvesters are typically grouped into piezoelectric, electrostatic, and electromagnetic categories according to their working principles. Each of these transducers has its own drawbacks and advantages.

Technologies for piezoelectric vibrational energy harvesting have recently received a lot of attention, and harvesters have been successfully used in a variety of sectors, including architecture, biomechanics, and human motion. Piezoelectric harvesters work off the piezoelectric effect, where a strain in a material leads to deformation of the structure, causing an imbalance in charge and thus producing a voltage [6]. Piezoelectric energy harvesters obtain the electric energy generated when these piezoelectric materials are vibrated [7]. They typically need to be operated at a high frequency (>1 kHz), which limits their kinetic energy harvesting capability, as ambient vibrations are usually on the scale of 1–100 Hz [8]. Piezoelectric harvesters have the advantages of self-powering, relatively high output voltage, compact size, and a high electromechanical coupling coefficient. However, they are subject to the adverse effect of piezoelectric materials producing varying outputs throughout their operational life [9] and can even totally fail due to brittle material fatigue [10]. Beeby et al. showed that while compressive strain piezoelectric materials can offer better material longevity, the nature of the required strain limits where and how they can be applied [11].

Electrostatic transducers work by a force, creating a change in capacitance, leading to voltage induction [12]. The electrostatic methodology comprises electret-type vibrational energy harvesting with MEMS, as well as triboelectric energy harvesting [13]. Electrostatic harvesters inherently require a high-voltage power supply or electret to build strong electric fields to push the electric current move, which makes the system complicated [14]. Additionally, considering that the changes in plate separation or area are typically in the mm range, they are less suitable for larger amplitude vibrations (as would be expected from human movement) without additional system complexity to gear the input environmental motion to a suitable scale [11].

Electromagnetic vibrational energy harvesters (EVEH), on the other hand, have a relatively simple construction and generate sound power at low frequencies, so they have received significant attention [1][15]. Electromagnetic harvesters use the principle of Faraday's law of induction in which a magnet passing through a coil induces a current [16]. Electromagnetic induction and inverse magnetostrictive effects are commonly adopted for electromagnetic energy conversions. In the inverse magnetostrictive method, the magnetization state of a magnetostrictive material is controlled by applying a bias magnetic field to the material using permanent magnets, followed by applying a strain to the material to generate a change in magnetic flux, which is converted into electric power using a coil [17][18].

2. Electromagnetic Vibrational Energy Harvesting Principles

2.1. Electromagnetic Theory

In 1831, Michael Faraday discovered that when a wire and magnet move relative to one another, the cutting of the magnetic flux results in a current being induced to the wire, in turn producing a voltage. The amount of voltage that can be produced depends on the number of loops in the coil and the rate of change in the magnetic flux [1][19]. This principle is summarized by Faraday's law:

$$\varepsilon = -N\frac{\Delta\phi}{\Delta t} \tag{1}$$

where, ε is the voltage produced in terms of EMF, N is the number of loops of the coil, and φ is the magnetic flux. A negative sign arises due to Lenz's law.

The above formula can be broken down further by investigating the rate of change in magnetic flux. This leads the equation to become:

$$\varepsilon = \beta l v \tag{2}$$

where, β is the strength of the magnetic field, l is the length of the wire, and v is the relative velocity between the magnet and the wire [20]. Implicated in Equation (2), to increase the generated voltage, magnetic field, wire length, and relative velocity are the key factors that must be increased.

In a mass-spring-damper-based electromagnetic generator (either a moving magnet or moving coil configuration), the maximum harvested power is [21]:

$$P_{max} = \frac{mY_0^2\omega^3}{4\zeta} \tag{3}$$

where m is the movable structure's mass in the harvester. ζ is the transducer damping factor (depending on the transducer impedance). Y_0 and ω are the vibration amplitudes and frequencies from the environment, respectively. To maximize harvested power, the damping factor should be low, and the natural frequency of the seismic suspension of the micro generator should be equal to the vibration frequency of the source.

When an electromagnetic energy generator delivers energy to an electrical load, the maximum electrical power is extracted when the electrical damping is equal to the parasitic mechanical damping [22]. In the case where parasitic damping is much greater than electromagnetic damping, the optimum load resistance becomes coil resistance.

2.2. Vibration Frequency Considerations

Another factor that dictates an electromagnetic harvester's potential usage is its resonance frequency. As most harvesters rely on suspension systems, whether a coil or magnet supported by a spring or magnetic levitation, they act as a spring-mass-damper system [23]. This leads to harvesters being considered as a 2nd order system in which they have a resonance frequency [24][25]. A harvester will have spikes in voltage when excited by an input with the same frequency as the resonance [26]. The resonance frequency can be altered by adjusting the dampening of the system, the weight of the proof mass, or the spring constant [27]. Ibrahim et al. [28] described a vibration-based electromagnetic energy harvester whose resonance frequency can be tuned to match the excitation frequency. The frequency was adjusted by controlling a rotatable arm with tuning masses at the tip of a cantilever-type energy harvester, thereby changing the system's effective mass moment of inertia. The rotatable arm was mounted on a servomotor that was autonomously controlled by a microcontroller and a photosensor to maintain resonance for maximum power generation. To predict the system response for different design parameters and estimate the generated power, a mathematical model was developed. A distributed parameter model was used to examine the system's natural frequency variation and dynamic response. The analytical model was then validated experimentally by tuning the frequency from 8 Hz to 10.25 Hz.

To maximize the harvested energy, vibrations at different frequencies need to be included in the harvesting system. Some designs have tried to increase the bandwidth of energy harvesting by placing an array of harvesters with different resonance frequencies. However, these are bulky and have a low power density. Liu et al. [29] was able to develop an MEMS harvester that had at least 9 resonance frequencies over a frequency range of 100 Hz to 800 Hz. The harvester was only able to produce voltages ranging from 0.01 mV to 0.13 mV. However, it was the first MEMS device capable of achieving nine resonant peaks for its size. The use of multiple cells was investigated by Liu et al. [30]. The MEMS device was able to harvest vibrations from 3-dimensional excitation. The device utilized 3 coils mounted to a circular structure with the capability to flex in any direction. Due to this, the harvester had 3 resonance frequencies of 1285, 1470, and 1550 Hz. Marin et al. [31] constructed a traditional mechanically fabricated harvester in which it had 2 cells for power harvesting. The design used wound coils attached to cantilevers with magnets arranged around the coils. The prototype was compared to a single-cell harvester of a similar design. The double cell saw an increase in power density of 66%.

To power wireless sensor nodes for bridge health monitoring, ref. [32] offered unique electromagnetic bridge energy harvesters (BEHs), which have multiple resonant frequencies. The broadened frequency band increases the energy harvesting efficiency from wind surges and bridge vibrations. The created BEHs are cantilever-type devices made up of a support, an airfoil, a cantilever beam, a wrapped coil, and a permanent magnet. Harvesters are evaluated in a lab setting with varying vibration levels and air surges of varying speeds.

Many researchers have investigated mechanical frequency up-converting techniques as a means of improving the harvester's bandwidth performance. The idea behind the mechanical frequency up-converting technique is to convert a low-frequency input signal into higher-frequency signals. This has been achieved by using mechanical cantilevers, which, when excited, are vibrated at their natural frequency. This is preferable, as a high frequency will provoke more flux to be cut, or higher velocity v in Equation (2), leading to higher power output [8]. Klein and Zuo [33] constructed a harvester for the purpose of its use in nuclear power plants. Their design used a flat spring structure that was able to capture low-frequency vibrations and transform them into higher frequencies. It was able to produce a voltage of 910 mV and a power of 2 mW. Zorlu et al. [34] used a cantilever that was held by a mechanical barrier composed of a membrane. When enough acceleration was applied to the cantilever, it was able to move away from the membrane and operate at its own frequency. The device was able to turn an initial vibration of 10 Hz into 394 Hz. From theoretical analysis and prototyping investigation, it was determined that this kind of structure is a feasible design for scaling down. It was hypothesized that the power density of the device would increase with miniaturization.

Another attempt to broaden the output bandwidth of the system is a multi-stable electromagnetic harvester. In [35], Yang et al. proposed a theoretical model and dynamical analysis of a novel multi-stable energy harvester employing a geometric nonlinearity technique. The energy harvester has multiple stable potential energy functions, ranging from mono-stable to quad-stable, by varying the geometric nonlinearity parameters. Therefore, the results demonstrate that such a harvester outperforms traditional linear harvesters. In [36], Kim et al. investigated the dynamic and energetic properties of a multi-stable bimorph cantilever energy harvester that makes use of the magnetic attraction effect. The magnetic field produced by the external magnets tends to have a significant impact on the magnetic force and moment applied to the cantilever tip.

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