Hybrid energy harvesting based on piezoelectric and electromagnetic systems

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Abstract. The aim of this paper is to boost the power output of the hybrid energy harvester effectively and to provide electrical optimization for a hybrid energy harvesting system that produces two electrical outputs from a single source of mechanical input namely vibration. Two different electrical outputs are produced by using the concept of piezoelectricity and electromagnetic induction. In this paper, an electrical equivalent is obtained for the standalone piezoelectric system and the electromagnetic system. The rectification of the piezoelectric system along with its results is discussed. Different circuits for amplification is studied and simulated to improve the voltage. All the practical experimental outputs and the different software used to gain these outputs are recorded. The various applications of the hybrid system are reviewed and discussed.

Keywords: Hybrid energy generation, piezoelectric, electromagnetic, energy, resistive load, Hybrid generation, Harmonic excitation.

1. Introduction
The energy that is lost around a system can be converted into useful energy, a power harvesting device can be used for this purpose. The most common form of energy that is lost around most machines and biological systems are the ambient vibrations present around it. Piezoelectric material can be used to harness these lost vibrations and convert them into useful electrical energy. Hybrid vibration energy harvester is a combination of a standalone PE harvester (PH) and a standalone EM harvester (EH). The former comprises of a unimorphed piezo cantilever beam with tip mass and the later comprises of a spring with magnet and copper coil. A hybrid energy harvester is a combination of a piezoelectric system (PH) and electromagnetic system (EH). The standalone piezoelectric harvester consists of a unimorphed piezo cantilever beam with a mass attached to its end and the electromagnetic system consists of a spring, a magnet and a copper coil[1]. Vibration is a mechanical occurrence wherein oscillations that is either forced or free occur about a particular point known as the equilibrium point. Vibration is desirable and is present in the movement of a tuning fork, the reed in a woodwind instrument, electronic devices etc. Vibration produces kinetic energy and thus can be converted to electricity. This concept is called a Vibration Energy Harvesting. There are a number of ways to make this possible including electromagnetic induction or Piezoelectric fibers. Piezoelectricity was discovered by French physicists Jacques and
Pierre Curie. It is basically the electric charges accumulated in elements such as crystals, ceramics and biological matter. This energy is accumulated due to mechanical stress. Piezoelectricity can be extremely useful fields like the generation and sound detection, inkjet printing, generation of voltages, microbalances, to drive an ultrasonic nozzle and ultrafine focusing of optical assemblies. It finds usage in daily life items such as; cigarette lighters, push-start propane, barbeques, time reference source in quartz watches and as amplifiers for certain types of guitars. Generation of an electromotive force through an electrical conductor in a varying magnetic field is termed as electromagnetic or magnetic induction. This has found use in electrical components such as inductors, transformers, motors and generators.

Capturing the normally lost energy and convert it into a usable form of energy for the electrical device to consume is the main aim of a power harvesting. A standard source of this energy is the ambient vibrations surrounding most machines. This energy is suitable for the piezoelectric materials. These minerals have the ability to convert mechanical strain energy into electrical energy and vice versa. The ability to generate an electric charge in response to applied mechanical stress is called piezoelectric effect. This is reversible. Similarly, combining both electromagnetic and piezoelectric effect to produce electrical energy and to improve power generated is proposed in this system. In this paper, an electrical equivalent is obtained for the standalone piezoelectric system, electromagnetic system and the results are compared with that of the proposed mechanical system. Different circuits for electrical optimization is studied and simulated to improve power.

2. Existing System

Hybrid vibration energy harvester is a combination of a standalone PE harvester (PH) and a standalone EM harvester (EH). The former comprises of a unimorphed piezo cantilever beam with tip mass and the later comprises of a spring with magnet and copper coil [1].

2.1 Analytical Modelling

The existing hybrid harvester (HH) which is shown in Fig. 1 consists of a beam, spring and mass attached to the free end of the beam. An active layer of the MFC (Macro Fiber Composite) is attached to the fixed end of the beam in a unimorph configuration. This MFC is a flexible piezoceramic and can sustain a large strain [1]. The mass attached at the free end is magnetic in nature. This moves up and down within a solenoid made of copper coil. The beam and the solenoid are connected to the same support.

![Figure 1. Representation of the existing hybrid energy harvesting system](image_url)
the system is indicated as a hybrid system. The piezoelectric and the electromagnetic transductions are connected to separate external resistances, \( R_p \) and \( R_{em} \). In Figure 1, \( V_p \) represent the voltage generated by the piezoelectric transduction and \( V_{em} \) represent the voltage generated by the electromagnetic transduction. \( Y_g \) denotes the amplitude of support motion.

![Figure 2](image)

**Figure 2.** An equivalent model for hybrid energy harvesting system

The equivalent model of the hybrid system is represented in Figure 2. The equivalent mass of the cantilever beam along with the MFC and the tip mass form the first mass \( m_1 \). The second mass \( m_2 \) represents the mass of the magnet and the equivalent mass of the spring \( [2] \). \( k_1, k_2, \) and \( c_1, c_{m2} \) are the stiffness and damping coefficient of the two subunits.

### 3. Proposed System

The block diagram of the proposed system is represented in Figure 3. This system employs amplification circuits for the piezoelectric system and electromagnetic system to boost the overall output obtained [3]. The output is then used to power actuators and sensors.

![Figure 3](image)

**Figure 3.** Block diagram of the proposed system

#### 3.1 Piezoelectric System

Macro Fiber Composite (MFC) is an ideal device that offers reliability and high performance at a comparatively lower cost. When a linear load is considered the Maximum Power Point (MPP) appears at the operating point, where the load resistor matches with that of the internal resistance of the piezoelectric material. On varying the operating frequency the MMP values can be differed. In order to measure the
maximum power the external load resistance is connected with the equivalent circuit of the MFC [4-5].
The maximum power is obtained at resistance $R_p=50k\Omega$ and the maximum power obtained is $P_{\text{max}}=8.7mW$. The values from simulation tend to be equal to the practical values from experimentation.

Here MFC which is presumed as a current source ($I_{31}$) along with a capacitor ($C_{31}$) are used to frame the equivalent circuit. The capacitance and the current values are derived from the following equations,

$$S_1 = s_{11} T_1 + d_{31} E_3 \quad (1)$$
$$D_3 = d_{31} T_1 + \varepsilon_{33} E_3 \quad (2)$$

Where,
- $S_1$ = Strain in x direction
- $T_1$ = Stress (N/m$^2$)
- $E_3$ = Electric field in z direction (V/m)
- $D_3$ = Charge density (C/m$^2$)
- $s_{11}$ = Compliance coefficient
- $d_{31}$ = piezoelectric coupling coefficient

The electrical and mechanical systems can be correlated by the equations given below,

$$I_{31} = NC_m \frac{dF}{dt} \quad (3)$$

$$N = \frac{d_{31} L_2}{s_{11}} \quad (4)$$

$$C_{31} = N^2 C_m + C_0 \quad (5)$$

$$C_m = \frac{s_{11} L_1}{A_1} \quad (6)$$

$$N = \frac{A_3 \varepsilon_{33}}{L_3} \quad (7)$$

where,
- $I_{31}$ = Equivalent current source (A)
- $N$ = Coupling coefficient
- $C_{31}$ = Equivalent capacitor (F)

The simulation parameter specification for PHH is shown in the Table 1.

| S. No | Parameters      | Value       |
|-------|-----------------|-------------|
| 1.    | Input Voltage   | 54V         |
| 2.    | Frequency       | 13.7Hz      |
| 3.    | Resistor        | 80kΩ        |
| 4.    | Capacitor       | 177.07nF    |
| 5.    | Load Resistor   | 50kΩ        |
The simulation circuit of PHH is shown in Figure 4. The graph between resistance and power, resistance and voltage were shown in Figure 5 and Figure 6 respectively.

### 3.2 Electromagnetic System

As the electromagnetic circuit consists mainly of a coil, the electrical equivalent circuit consists of an inductor and resistor in series with the source [6]. The value of the resistor used is the internal resistance of the coil which is calculated as 60Ω using a multimeter. The inductance of the coil was measured using the resonance frequency in a tank circuit. The maximum power of 0.117mW is obtained at a load resistance of 60Ω. The voltage measured at the same is 0.1187V as observed from the figure. The simulation circuit of EHH is shown in Figure 7. The simulation results represented in Figure 8 and Figure 9 is equal to that of the mechanical system.
3.3 SSHI
SSHI stands for Synchronized Switch Harvesting on Inductor. SSHI circuit is presented in Figure 10. The power output of the piezoelectric transducer is increased much effectively if this circuit is used. The internal capacitor voltage is flipped by the SSHI rectifier when the PE transducer crosses the zero point [7]. At specific vibration frequencies, the energy harvesting potentials of the SSHI rectifier is moderately greater than that of a full-bridge rectifier.

3.4 Amplification Circuit
The different amplification circuits like AC-DC converter is analyzed and chosen for best optimization. The electromagnetic generators have size limitations which in turn produces a very low output, whereas the load requirements are typically much higher.

3.5 Nanosensors
Due to the low power output of the hybrid system, it is found that they are best suited to operate the nanosensors. Nanosensors are devices of the scale of $10^9$ and can measure physical quantities and convert them into equivalent signals that are further detected and analyzed. There are several different types of nanosensors available in the market that are manufactured by either one of the following techniques top-down lithography, bottom-up assembly or molecular self-assembly. Though the process involved in the manufacturing and development may be different they perform the same function of generating signals with the help of the bio element and processing of the signal into useful data.

To tackle the difficulties of the multi-staged power converters (here two staged) a direct ac-to-dc power converter, a basic diode bridge rectifiers [8]. A boost converter that has dual polarity is suggested for such ac-to-dc power conversion.

From the plots, the maximum power obtained at 10.19mW at a load resistance of 35kΩ and the inductor used is 250H. Since the practical realization of a 250H inductor is hard, the new circuit is proposed eliminating the losses occurred across the inductor.

4. Rectifier
Rectification can be defined as the process of converting alternating current to direct current, this can be achieved using a conventional bridge rectifier. They are commonly used inside the power supplies of about all electronic devices and capable of converting high alternating current
voltage to low direct current voltage as well. They can be fabricated with four or more diodes or other controlled solid-state switches. The simulation circuit of the rectifier is presented in Figure 11. The simulated waveforms are shown in Figure 12 and Figure 13.

![Block Diagram of Rectifier](image)

**Figure 11.** Block Diagram of Rectifier

![Voltage output](image)

**Figure 12.** Voltage output

![Current output](image)

**Figure 13.** Current output

### 5. Parallel SSHI

The overall performance of the full-bridge rectifier and parallel SSHI interfacing circuit is discussed under this topic. It is assumed that all the components are under ideal condition and the voltage drop across the diode is zero. The output power of the piezoelectric transducer is effectively improved using the SSHI circuit. When the transducer current crosses the zero point, the SSHI rectifier flips the internal capacitor voltage. From this it can be concluded that the energy harvesting capability of the SSHI rectifier is comparatively higher than that of the full bridge rectifier [9-10]. The inductor value used for the simulation is 22 mH. The Simulink model for the parallel SSHI is shown in Figure 14. The simulation results are also presented in Figure 15 and Figure 16.

![MATLAB Simulink Model of Parallel SSHI](image)

**Figure 14.** MATLAB Simulink Model of Parallel SSHI
6. Series SSHI
The series-SSHI circuit is same as the parallel-SSHI circuit. Instead of connecting the smart element in parallel it is connected in series. However, the switch control is exactly the same as that of parallel-SSHI circuit. Most of the time, the switch is open except in proximity of mechanical displacement extremums. During this instance the inversion of voltage occurs [11-13]. The Simulink model for the Series SSHI is shown in the Figure 17.

From the plots shown in the Figure 18 and Figure 19, the maximum power obtained at 10.19 mW at a load resistance of 35 kΩ and the inductor used is 250H. Since the practical realization of a 250H inductor is hard, the new circuit is proposed eliminating the losses occurred across the inductor.
7. Design of Boost Converter

\[ \text{Output Resistance} = \frac{V_o}{I_o} \] (8)

\[ \text{Duty Cycle} = 1 - \frac{V_{\text{in}}}{V_o} \] (9)

\[ C = \frac{I_o \times D}{f_s \times \Delta V_o} \] (10)

\[ L = \frac{V_s \times D}{f_s \times \Delta I_o} \] (11)

Where,
- \( V_o \) = Output voltage (V)
- \( I_o \) = Output current (A)
- \( \Delta V_o \) = Output ripple voltage (V)
- \( \Delta I_o \) = Output ripple current (V)
- \( D \) = Duty Cycle
- \( V_{\text{in}} \) = Input Voltage (V)
- \( f_s \) = Switching Frequency (Hz)
- \( C \) = Capacitor (F)
- \( L \) = Inductor (H)

Using the above calculated values, the boost converter for the piezoelectric system is implemented. The duty cycle of the boost converter is fixed at 50%, hence the output voltage of the converter is estimated to be boosted by twice the input. The simulation parameters for the boost converter is given in Table 2.

| S. No | Parameters     | Value |
|-------|----------------|-------|
| 1.    | Input Voltage  | 12 V  |
| 2.    | Duty Cycle     | 50%   |
| 3.    | Inductor       | 12.5 mH |
| 4.    | Capacitor      | 1 MF  |
| 5.    | Output Resistance | 100Ω |

The MATLAB Simulink model of the boost converter is shown in Figure 20. The boost converter designed manually is checked using Matlab. It includes a diode, MOSFET, inductor, capacitor, and a resistor.
The output current and voltage values are represented using the MATLAB scope image given in the Figure 21 and Figure 22. For a voltage input of $V_{in}=12V$, the voltage output can be seen as $V_{out}=24V$ and the current output $I_{out}=0.25A$ amounting to the output power of 6 Watts.

8. Combining Boost Converter and Rectifier

The rectifier and the boost converter was combined and simulated. The rectifier output was stored in a battery and the battery when charged completely is switched to a boost circuit where the voltage is amplified for practical applications [14-15]. The Simulink model of the rectifier and boost converter combination is given in the Figure 23. The simulated waveforms are shown in Figure 24 and Figure 25.
9. LabVIEW

The circuit given above experimented practically with the help of LabVIEW. The circuit diagram in the LabVIEW software is given below in the Figure 26.

![LabVIEW circuit](image)

**Figure 26.** LabVIEW circuit

9.1 Lab view Results from Rectifier

The piezoelectric beam was also vibrated using an external shaker and the output was connected to a rectifier and the output voltage was measured and is given below. The simulated waveforms are shown in Figure 27 and Figure 28. The output voltage was observed to be about 22V.

![PHH voltage with Rectifier](image)

**Figure 27.** PHH Voltage output
10. Experimental Setup

Among all the piezoelectric materials available, a MFC is chosen for its readily available flexible and durable structure. The electromagnetic energy is generated by the spring with a magnet attached to its free end moving up and down inside a solenoid made up of the copper coil. Vibrations that are produced at the free end are used for exciting the spring mass system. The hybrid circuit model is presented in Figure 29.

As per the values calculated, the circuit has been designed. This circuit also consists of the bridge rectifier that converts the AC output of the piezoelectric system into a pulsed DC output. This DC output is fed as input to the boost converter. As per the working of the boost converter, the voltage output is boosted by 50%, as the duty cycle is fixed as the same. The hardware implementation of the boost converter is shown in Figure 30.
11. Conclusion

This work is aimed at improving the output of the hybrid system. The hybrid system is studied and the electrical equivalents of the individual piezoelectric and electromagnetic systems have been derived. Different equivalent circuits have been simulated using MATLAB software and the outputs recorded. Two main amplification circuits; the SSHI and the boost converter are both designed and simulated using the MATLAB software. It can be concluded that because of the nonlinearity of the SSHI circuit, it cannot be applied to the piezoelectric system and hence the boost converter and rectifier circuit is used for amplification of the piezoelectric system output. For the electromagnetic system the output voltage is found to be very low and hence cannot be used as input to any amplification circuit. However, it is directly applied to biomedical actuators.

The final output of the piezoelectric system after passing through the rectifier, battery and then the boost converter is 24V and 0.3A amounting to a power of 7.2W. There are so many applications for the obtained power when they are stored in a battery. Some of the applications include glowing an LED, electric-motorised vehicles but particularly scale ‘toy’ models, of almost all kinds, emergency lighting in commercial buildings. The electromagnetic system has very low power with a magnitude of 0.117mW. The main applications include Pacemaker and cardioverter-defibrillator: <10 mW, Hearing aid: 100–2000 μW, Analog cochlear processor: 200 μW, Body-area monitoring: 140 μW. They are mainly found useful in applications as biomedical actuators. This paper is aimed at improving the output of the hybrid system. The hybrid system is studied and the electrical equivalents of the individual piezoelectric and electromagnetic systems have been derived.

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