21th International Conference on Renewable Energies and Power Quality (ICREPQ'23)
Madrid (Spain), 24th to 26th May 2023
Renewable Energy and Power Quality Journal (RE&PQJ)
ISSN 2172-038 X, Volume No.21, July 2023

Design, Modelling and Simulation of Hybrid Vibration Energy Harvesting System using Integration of Piezoelectricity and Electro-Magnetism

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Abstract.

In this paper, a hybrid vibration energy harvesting system based on piezoelectricity and electro-magnetic devices is modelled and simulated in a software environment. The integrated system includes harvesting devices, power electronics and the load. The converter is controlled to maintain proper voltage and current at the load side. Simulation results are provided to show the operation of each device in the integrated harvesting system.

Key words. Piezoelectricity, electro-magnetic induction, renewable, harvesting.

1. Introduction

Energy from renewable sources has zero effect on environmental pollution and hence its contribution towards climate change is non-existent. Harvesting vibration energy through piezoelectricity and electro-magnetism are two very green ways of producing energy. Ambient vibrations are considered as the energy source, which is largely unharnessed. Pedestrian movement can be targeted at first with scope of extending it to harnessing energy from the traffic movement. The working principles of piezoelectricity and electro-magnetism are combined to make one hybrid system. Factors influencing the output of piezoelectric harvesters are geometry, type of material, resonance frequency of the piezoelectric material and associated electric circuitry. These have been sought to be optimized within design constraints [1], [2]. Out of the five main types of piezoelectric materials, i.e., single crystals, piezoelectric ceramics, polymers, composites, and quartz; piezoelectric ceramics have shown to have the best overall characteristics, hence that's the choice in this work [3], [4].

In developing the piezoelectric sub-system, three different configurations were considered (parallel-series, series-parallel, and all parallel) and the one that produced the best results, which was the series–parallel configuration, is selected in the simulation of this work. The energies produced by the two distinct working principles are coupled to generate one output. This integrated mechanism is referred to as a 'Composite harvesting unit'. The energy thus generated could be put into use in remote control sensors, trickle charging of batteries, for re-charging of mobile devices in public areas and Neon sign lighting [5].

This paper presents the design, modelling and simulation of a hybrid energy-harvesting system from vibration. It will specifically elaborate the employment of a piezoelectric sub-assembly, made from multiple piezoelectric elements (discs), and an electro-magnetic device. Results for the composite energy harvester were obtained by simulating the electric circuits in the software platform MATLAB/Simulink.

2. Modeling of Vibration Energy Units

A. Piezoelectric

The relationship in a piezoelectric material, between its generated charge and the applied force on it, is given by

$$C_x = n d_{xy} F_y \tag{1}$$

where, C_x is the amount of the generated charge, in C, d_{xy} is the piezoelectric charge constant, in C/N, F_y is the applied force, in N, n is the number of piezoelectric elements, the subscript x is the direction, which is perpendicular to the plane electrodes are placed, and the subscript y is the direction in which the stress is applied.

In general, the series-parallel configuration of the piezoelectric elements provides good amount of energy and good results. All basic piezoelectric elements, in this configuration, are represented by one piezo stack when simulating the overall circuit.

B. Electro-magnetic

Electro-magnetic generators work on the principle of electro-magnetic induction which is Faraday's law of induction given by

$$\text{emf} = -\frac{d\psi}{dt} \tag{2}$$

where, emf is the electro-motive force, in V, ψ is the magnetic flux in W.

Equation (2) could also be re-written as

$$\text{emf} = -Blv \tag{3}$$

where, B is the strength of the magnetic field, in W/m^2, l is the length of the conductor, in m, and v is the speed of the moving conductor relative to the magnetic field in m/s.

The magnetic field strength in the vicinity of a cylindrical magnet could be calculated using the formula [6]

$$B = \frac{Br}{2}\left[\frac{D+Z}{\sqrt{R^2+(D+Z)^2}} - \frac{Z}{\sqrt{R^2+Z^2}}\right] \tag{4}$$

where, Br is the Remnant field (flux density), independent of the magnet's geometry, in W/m^2, Z is the distance from the pole face on the symmetrical axis, D is the thickness (or height) of the cylinder, and R is the radius of the cylinder. The unit of the length can be selected arbitrarily for all cylinder dimensions as long as it remains the same.

The composite system oscillates as an integrated body and therefore exhibits multiple degree of freedom (MDOF) behavior [7].

C. Composite Harvester Unit: Piezoelectric and Electro-magnetic

The amount of current, generated from the hybrid harvester unit, is given by

$$I = fmMd \tag{5}$$

where, f is the number of times each harvester unit is activated per second (frequency of operation), m is the total number of harvester units operating at that frequency, M is the force presented by one footstep of a person, in N, and d is the electricity generated from a single step in C/N per composite harvester.

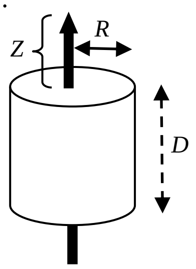


Fig. 1. Dimensions involved in calculating the flux density of a cylindrical magnet

In a tile-based energy harvester system, m could be considered as the number of tiles, s, activated per pedestrian at any given time and expressed by

$$m = sP \tag{6}$$

where, P is the total number of pedestrians over the experimental area.

It is assumed that each pedestrian has his two feet spread over two tiles, one foot over each and during busy hours the pedestrian after him would step on it soon after the previous pedestrian's foot is off it.

3. Power Conversion System

The initial rectification of the alternating output from the composite energy harvester would be done by a bridge rectifier as shown in Fig. 2. For optimization of the power transferred to the load, a DC-DC converter is used to deliver the optimal output voltage through a closed loop feedback control system to adjust the duty cycle and select the states (ON/OFF) of the converter switches based on MOSFETs. The advantage of using a buck converter is that; the inductor being placed in the load side, the ripple in the output current at the load is reduced thereby providing a smooth operation of the load since there is a capacitor to limit the ripples in the output voltage. The power flow is regulated through high frequency pulse width modulation (PWM) for switching (ON/OFF) of the MOSFETs in the circuit. The advantages of a single-phase DC-DC converter is the need of just a single MOSFET to be switched, causing small losses, and hence promoting its suitability for energy harvesting applications [8], [9].

4. Simulation of the Integrated Hybrid Energy System

The equivalent circuit of the piezoelectric sub-assembly, implemented in MATLAB/Simulink, is shown in Fig. 3. The piezo stack represents the complete piezoelectric sub-assembly. The piezoelectric sub-assembly is first tested without load, i.e, in open circuit. A saw tooth waveform has been selected for the physical input because it represents the pressure applied by the physical footsteps as closely as possible. It has a 0.5 second period (frequency of 2 Hz) and 1 Newton of amplitude.

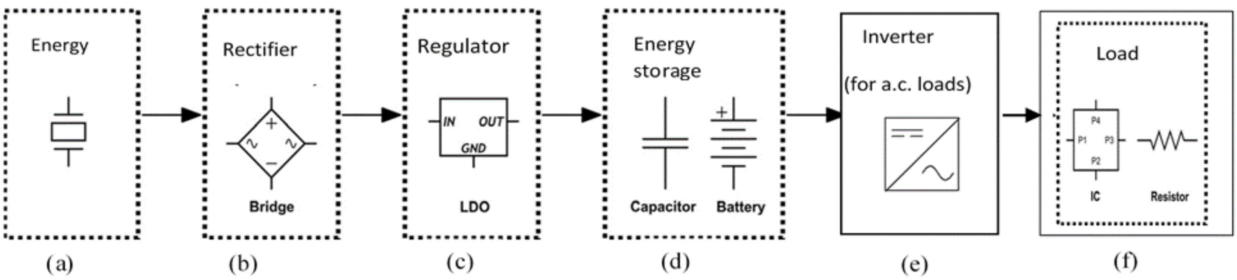


Fig. 2. Block diagram of the power electronics interface for the energy harvesting system

The ideal force source generates a force proportional to the input physical signal. The ideal translational motion sensor converts an across variable measured between two mechanical translational nodes into a control signal proportional to the velocity and the position. The translational damper represents an ideal mechanical translational viscous damper with 12 N (m/s) and the translational spring is an ideal mechanical linear spring with a value of 10 N/m. The voltage and current outputs, resulting from the simulation, are shown in Fig. 4. The equivalent circuit of the electro-magnetic sub-assembly, implemented in MATLAB/Simulink, is shown in Fig. 5. Next the composite piezoelectric vibration energy harvesting system was modelled and the related results were recorded. As previously mentioned, it consists of two parts, the piezoelectric transducer sub-assembly and the electro-magnetic sub-assembly. Figure 6 shows the MATLAB/Simulink model of the composite piezoelectric and electro-magnetic sub-assemblies together with the buck converter and Fig. 7 shows the output waveforms for the voltage and the current.

For a real application, using equation (5), if the time is assumed to be 1 sec to pass over two tiles, and a continuous stream of pedestrians is assumed that gives a frequency of operation 2 Hz per tile. In converting the body mass into Newton, a figure of 1/5 of gravitational acceleration g (2.5 m/s^2) is to be used [10]. If a hypothetical number of 10 tiles is assumed on either sidewalk, (total of 20), with an average body mass of 70 Kg and the charge generation coefficient per composite harvester unit being 2.5 μC/N, the current generated would be $2\times(2\times5\times2)\times(70\times2.5)\times(2.5\times10^{-6}) = 0.0175$ A. By increasing the number of tiles to a 1000 (500 on each side) the generated current would be 0.875 A (A scale up factor of 50 in the equation (5)).

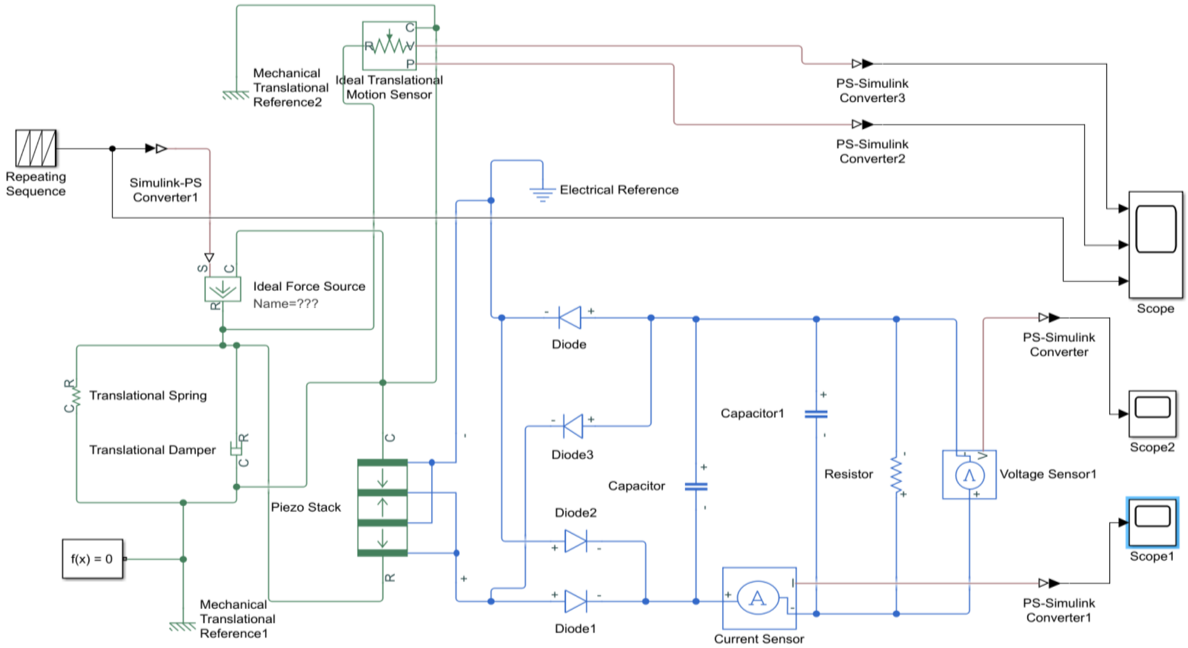
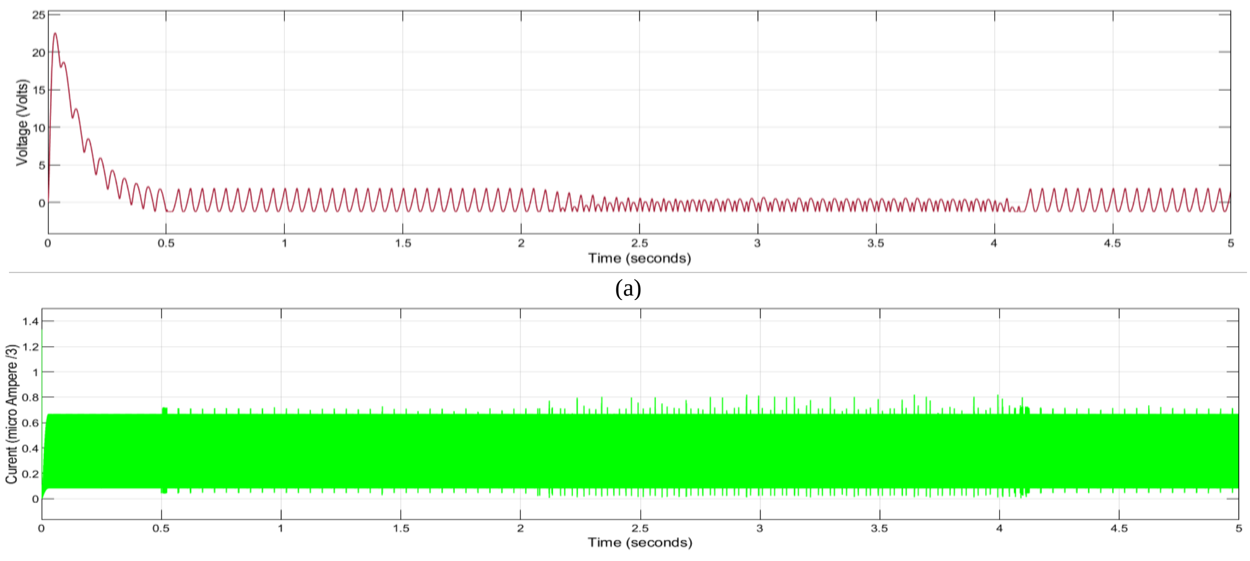


Fig. 3. Simulation model of the piezoelectric transducer sub-assembly in MATLAB/Simulink



(b)

Fig. 4. Piezoelectric sub-assembly output at 2 Hz Frequency (a) voltage; (b) current

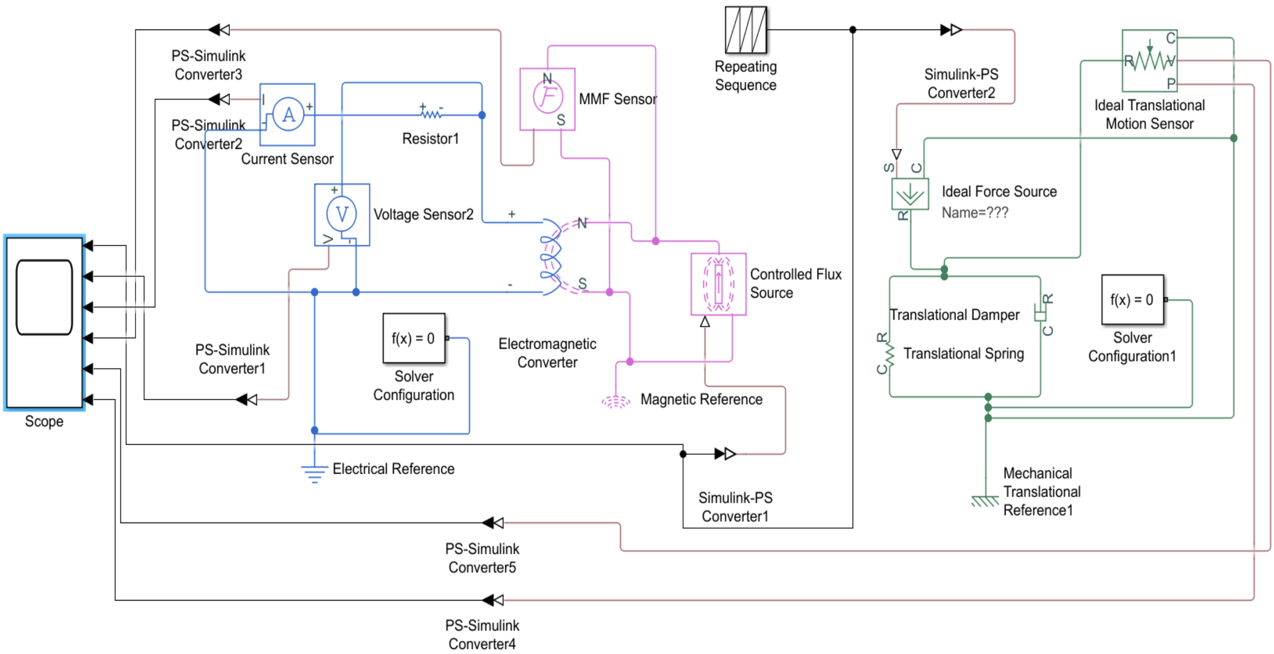


Fig. 5. Electro-magnetic sub-assembly modelled in MATLAB/Simulink

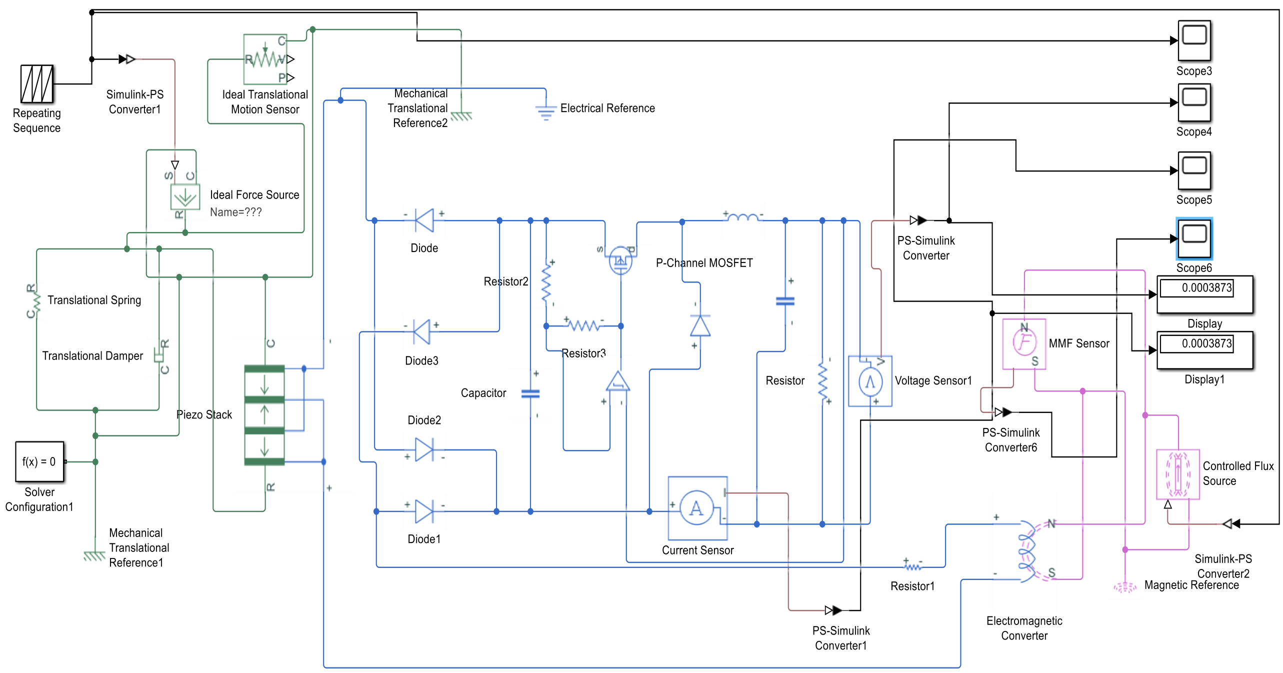
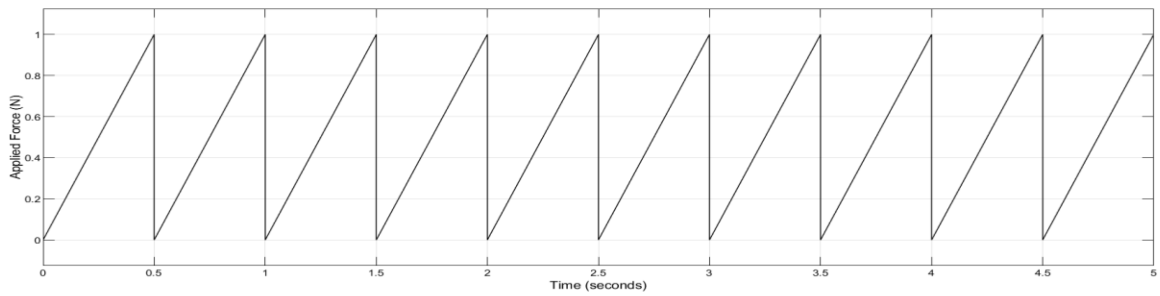
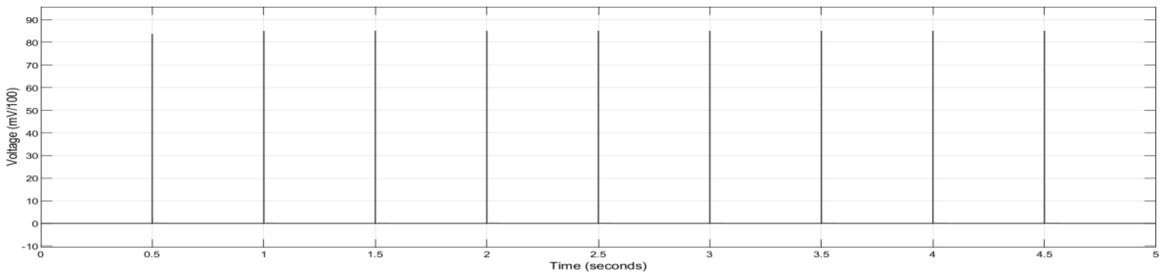


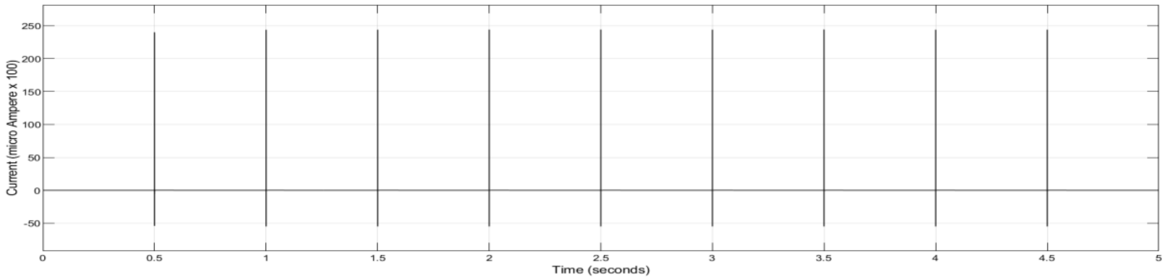
Fig. 6. MATLAB/Simulink model of the complete energy system (piezoelectric, electro-magnetic, converter and load)



(a)



(b)



(c)

Fig. 7. Waveforms results for the complete vibration energy system. (a) Applied force, (b) Output voltage, and (c) Output current.

5. Conclusion

Piezoelectric materials could transform mechanical strain energy into an electrical charge. The amount of the generated energy depends on the volume of the traffic (Human/Vehicular) and the number of piezoelectric elements placed under the surface. Foot traffic that moves fast and a vehicle that moves slowly appears to generate slightly more energy. Further research is necessary to tap the potential of piezoelectricity as a viable alternate power generation system. It has tremendous scope for future energy solutions and provides an impetus towards providing greener and sustainable energy with creating a healthier environment as an equally valuable result. The electro-magnetic sub-assembly attached to the conventional piezoelectric assembly proved to enhance the electricity production rather than when employing only piezoelectricity.

Acknowledgement

This research is supported in part by funding from the Natural Sciences and Engineering Research Council of Canada (NSERC), Discovery Grant number: 2018-05381.

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