International Journal of Applied Engineering and Technology ISSN: 2277-212X (Online)
An Online International Journal Available at http://www.cibtech.org/jet.htm
2012 Vol. 2 (1) January-March, pp 59-66/Upadhyay and Shanker
Research Article

PIEZOELECTRIC HARVESTER – MODEL AND PROPOSED NEW APPLICATIONS

***Kshitiz Upadhyay[1] and Anup Shanker[2]**
[1]*Research Scholar, Department of Mechanical Engineering, Maulana Azad National Institute of Technology, Bhopal (M.P), India, 462051*
[2]*Department of Electrical Engineering, Maulana Azad National Institute of Technology, Bhopal*
**Author of Correspondence*

ABSTRACT
Piezoelectric harvester provides a method, for the conversion of mechanical energy into electrical energy. Recent investigations have revealed many new applications of piezoelectric power generation. Industries and technical disciplines use piezoelectric ceramics for alarms, lasers, ink jet printing, sonar, gyros, hydrophones, and gas fired equipment such as a barbeque grill. One study used PZT wafers in shoes to convert mechanical walking energy into usable electrical energy (Platt, 2005). Also, a high energy PPG (Piezoelectric Pulse Generator) can be used for applications such as laser pumping, electron beam, rail gun, plasma research, landmine detection device, ignition, and others (*Keawboonchuay, 2003*). This paper brings a model of a piezoelectric harvester consisting of a harvester and a storage circuit, along with some new applications of piezoelectricity. Mechanical and electrical models of a piezoelectric generator are also studied in detail.

Key Words*: *Energy Conversion, Piezoelectricity, Piezoelectric Generator

INTRODUCTION
Piezoelectric harvester, basically utilizes the pressure energy from an external source, and then stores it in the electrochemical battery by converting it into electrical energy. A benefit of piezoelectric power generation is that the efficiency of power transfer is relatively high. Many investigations have been made in this field. In their recent analysis of micro piezoelectric generators, Lu *et al.,* (*2004*) represented their circuit by a resistor linked with a rectifier, and their further simplifications have excluded the nonlinear coupling, which is intrinsic to the rectification circuit, interfacing the piezoelectric harvesting structure with the energy storage device. Hu *et al.,* (*2006)* have studied the interaction between the harvesting process and the energy storage process of a harvester, through modelling the storage circuit by a simple RLC circuit, while the capacitor is applied as the energy storage element. Performance of these model energy harvesters are analysed in detail and conclusion useful for harvester design is reached. Huan *et al.,* (*2009)* developed a piezoelectric harvester using Cuk dc-dc converter into the modulating circuit.
Following sections present a detailed description of the mechanical and electrical model of a piezoelectric generator, along with the piezoelectric harvester model, and the proposed new applications of piezoelectricity.

Piezoelectricity
Certain crystals exhibit the following phenomenon: When the crystal is mechanically strained, or deformed by the application of an external stress, electric charges appear on certain of the crystal surfaces. This phenomenon is termed as the direct piezoelectric effect, and the crystals exhibiting it are classed as piezoelectric crystals. Piezoelectric generators work on the same phenomenon.
Conversely, when a piezoelectric crystal is placed in an electric field, the crystal exhibits strain, i.e. the dimensions of the crystal change. This phenomenon is termed as the converse piezoelectric effect. Piezo buzzers work on the same phenomenon.

MATERIALS AND METHODS

Piezoelectric Generator

The piezoelectric generator model consists of two parts: the mechanical model and the electrical model (*Keawboonchuay, 2003*).

1. Mechanical Model

The mechanical model of a piezoelectric generator consists of one or more PZ elements between two masses. This is called a Piezo stack. The force applied externally is parallel with the poled direction of the piezoelectric material. The applied force is assumed to be instantly and uniformly distributed throughout the device, which allows the simple spring-mass system to be used (Fig. 1).

The mechanical system in Fig. 1 is described by the second order equation:

$$m_{piezo}\,\ddot{x}_{piezo} + c_{piezo}\,\dot{x}_{piezo} + k_{piezo}\,x_{piezo} = F \quad ...\ (1)$$

Where m_{piezo} is the mass, c_{piezo} is damping constant, k_{piezo} is the spring constant, and x_{piezo} is the compression distance of the piezoelectric material.

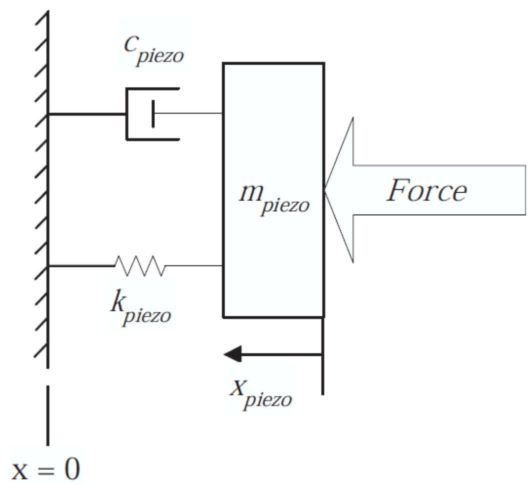

Figure 1: Spring-mass model of the piezoelectric generator (*Keawboonchuay, 2003*)

For a given displacement, the mechanical compression energy is given by:

$$W_{mech} = Fx_{piezo} \quad ...\ (2)$$

Relating (2) to the Young's modulus Y, the mechanical energy equation becomes:

$$W_{mech} = \frac{1}{2}\frac{F^2 h_{piezo}}{YA} \quad ...\ (3)$$

Where h_{piezo} is the thickness of the piezoelectric material, and A is the cross-sectional area.

2. Electrical Model

The electrical model of the piezoelectric generator is an RLC circuit, shown in Fig. 2. The piezoelectric is a metalized dielectric material which forms a capacitance C_{stack} with the usual series-connected loss resistance R_{loss}, and parallel-connected leakage resistance $R_{leakage}$. The voltage generated in the piezoelectric is represented by the stack voltage V_{stack}.

Research Article

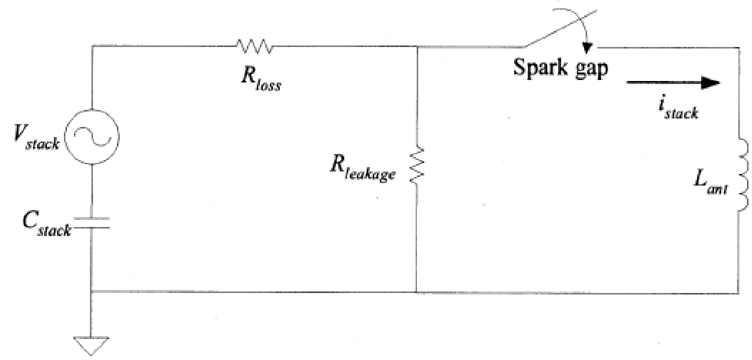

Fig. 2 – Electrical model (*Keawboonchuay, 2003*).

The capacitance of the piezoelectric material Cstack is given by:

$$C_{stack} = \frac{\varepsilon_0 \varepsilon_r A}{h_{piezo}} \quad . \; . \; . \; (4)$$

Where ε_0 is the permittivity in free space, and ε_r is the relative permittivity of the piezoelectric material.
The Piezoelectric loss resistance R_{loss} represent the internal losses and is given by:

$$R_{loss} = \frac{\tan \delta}{\omega C_{stack}} \quad . \; . \; . \; (4)$$

Where ω is the frequency and $\tan \delta$ is the dissipation factor.
The electrical energy stored in the piezoelectric as a result of compression is given as:

$$W_{elec} = \frac{1}{2} \frac{q^2}{C_{stack}} \quad . \; . \; . \; (5)$$

Where $q = C_{stack} V_{stack}$ is the electric charge. Combining the mechanical and electrical equations, Vstack can be expressed in terms of the Piezo material's properties,

$$V_{stack} = F \left(\frac{k_{33} h_{piezo}}{A} \right) (0.5 Y \varepsilon_0 \varepsilon_r)^{-1/2} \quad . \; . \; . \; (6)$$

Where k_{33} is the electromechanical coefficient of the piezoelectric material. Additionally, a spark gap switch is used in the piezoelectric generator. The switch closes when V_{stack} reaches a preset level, thereby transferring electrical energy to the load, in this case the antenna coil L_{ant}.

Piezoelectric Harvester Model

Basically a piezoelectric harvester collects the pressure energy from the source, and stores it in the electric batteries. The proposed model of the piezoelectric harvester consists of two basic components: (1) A piezoelectric harvester structure for scavenging attainable energy from the energy source, and converting it into an alternating current; (2) An energy storage device, typically an electrochemical battery.

Fig. 3 shows the proposed model for the piezoelectric harvester for the proposed application conditions. A piezoelectric bimorph with a Synchronised Switch Harvesting Inductor (SSHI) L_1 in parallel is used as the harvesting structure for generating an alternating current. The SSHI is applied to raise the piezoelectric element output power by artificially extending the conducting interval of the rectifier (*Hu, 2008*). The function of the four-way rectifier bridge is to rectify the input ac current to dc current which can be fed into the electrochemical battery. C_{rect} is an energy transfer station to transport the scavenged energy from the harvesting structure to the battery.

Fig. 4 illustrates the whole harvester circuit.

RESULTS AND DISCUSSION

This proposed model of piezoelectric harvester can be use in the many new areas. The proposed new applications are:

1. The square on the Basketball back-board can be made of a piezoelectric material like PZT-5H (Lead Zirconia Titanate) wafers in a stack. The force causing pressure on the square is an impulse force caused by the collision of the ball with the board.
   If m be the mass of the ball, v_1 be its initial velocity perpendicular to the board, v_2 be the final velocity perpendicular to the board and Δt be the time of collision. Taking approximate typical values,
   m = 22 Oz = 0.62 Kg.
   $v_1 = 4$ m/s.
   $v_2 = -2$ m/s.
   Let P_1 be the initial momentum and P_2 be the final momentum, the change in momentum ΔP:
   $\Delta P = P_1 - P_2 = mv_1 - mv_2$ . . . (7)
   $\Delta P = (0.62 \times 4) - (0.62 \times (-2))$
   $\therefore \Delta P = 3.72$ Kg m/s.
   If 0.05 sec is the collision time. The average force on the back board can be calculated as:
   $F_{avg.} = \frac{\Delta P}{\Delta t} = \frac{3.72}{0.05} = 74.4\ N$
   The harvested energy can be stored in batteries which can be further used as an auxiliary source of energy to lighten up the halogen lights of the basketball court.

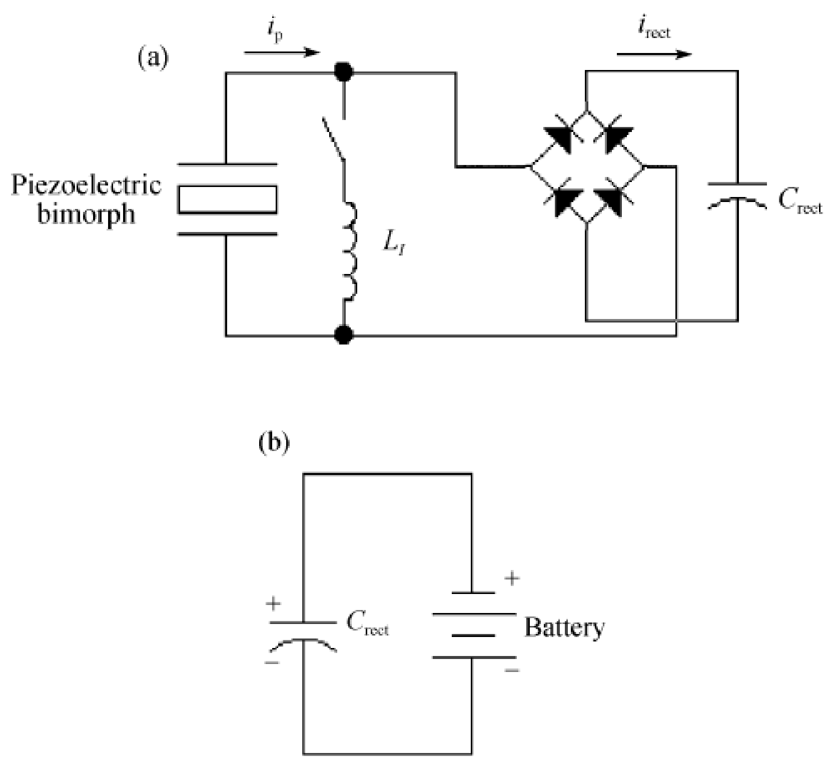

Figure 3: (a) A schematic illustration of a piezoelectric harvester structure (*Huan, 2009*); (b) A schematic illustration of the storage circuit

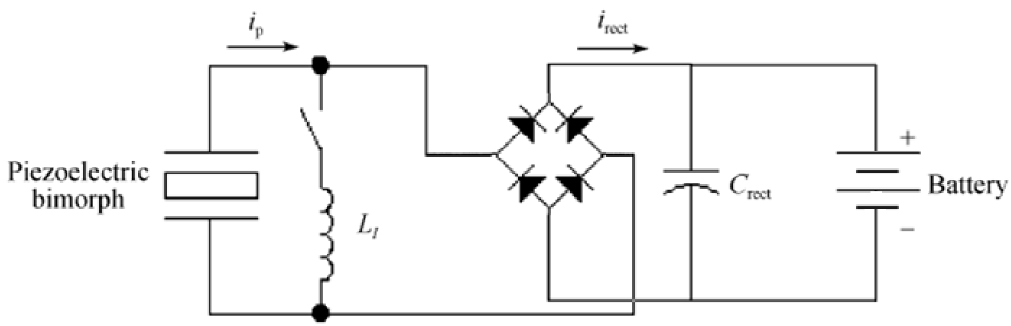

Figure 4: Proposed circuit diagram of the complete piezoelectric harvester

2. Steps in the railway stations where frequent movement is expected. Thousands of people pass daily through the steps, thus imparting a force more than their actual weights due to their momentum. If 60 Kg be taken as the average mass of a person, the weight would be 588.6 N. From eq. 6, we can see that the output voltage is proportional to the force applied. Pinkston C S et al. investigated through experiments and presented a linear relation between force applied and the output voltage.

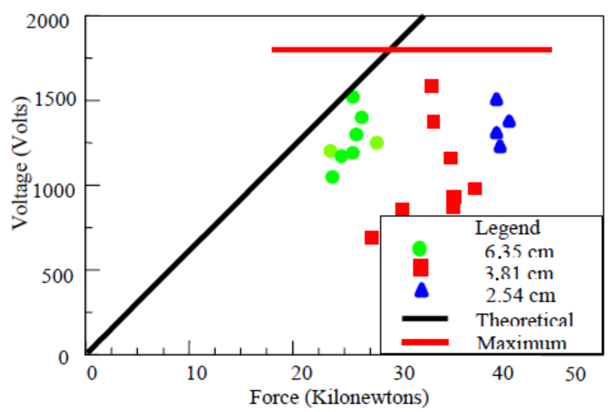

Figure 5: Actual results obtained by Pinkston et al. taking different thickness of PZT-5H (*Pinkston, 2006*)

The voltage produced will charge up the capacitance which in turn, will discharge to charge the battery. The voltage must be produced for a time greater than the time constant of the capacitive circuit so that the capacitance may be charged.

Keawboonchuay *et al.* (2003) investigated about the voltage produced when pressure is applied on a piezoelectric crystal. There can be two possible cases: (1) The quasi static case; and (2) The dynamic case.

In the quasi static case, the forces are applied for the duration of the order of 100 milliseconds. Two voltage peaks are obtained in either direction for about 2 seconds when the experiment is performed using PZT-5H and PZT-5A with an input quasi static force of 490 N.

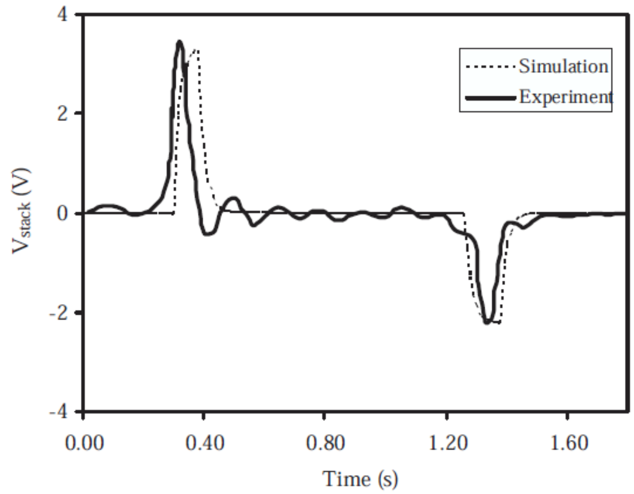

Figure 6: Output Voltage, V_{stack} under quasi static stress [*Keawboonchuay, 2003*]

In the dynamic stress case, only one peak of voltage will be obtained, higher than that obtained in the quasi-static stress case. This is due to the inability of the capacitance of the piezoelectric crystal to charge. This is due to the reason that the time constant of the PZT-5H crystal (15 ms) is greater than the duration of the application of force (<10 ms).

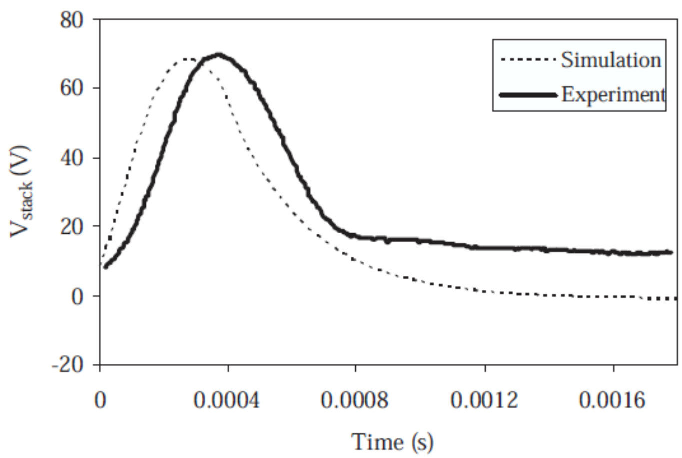

Figure 7: Output Voltage, V_{stack} under dynamic stress condition [*Keawboonchuay, 2003*]

3. Floor of the metal detectors in malls, airports, temples etc. All people have to pass through the metal detector, thereby making it a zone where constant trespassing is there. The stored energy can be used as an auxiliary source to lighten up these places, or can be used in some other area as an auxiliary source, wherever energy is needed.
4. Jogging arena can be made of a floor of piezoelectric material. While jogging, a force greater than the human weight is imparted on the floor, making in a good site for energy generation using piezoelectric harvester.
5. One interesting application area of the piezo harvester is the seed crushing area in villages in India, where heavy bullocks, tied to the centre pole move and crush the oil seeds to extract oil. An average bullock weighs 360 Kg, thereby applying 3532 N force, which is able to produce a high voltage. The stored energy can be used to lighten up the crushing area at night. It can also be used up in the village

houses where electricity is not there, or as an auxiliary source for running some of the farming machines.

6. Below the keypad of mobiles and laptops. The harvested energy can be used as an auxiliary source in charging the main battery. This can increase the battery backup of these devices, as charging will continue even when the device is not connected to the power source.
7. The proposed system can be installed in the gyms where rigorous muscular work is there. For example, below the treadmill in the gym. The harvested energy can be used to run the treadmill. Also, the system can be installed inside the punching bag of the boxers. The energy collected can be used for various purposes like using as an auxiliary source for lighting up the gym.
8. Fancy doormats can be made using piezoelectric wafers below the doormat layer. These doormats can give a flash of coloured light when a person walks over it. There is no storing of energy as this works on the principal of piezoelectric flash generator.
9. In the gaming zones in malls. For example, the hammer games, in which points are given on the basis of the impact on the bed. Piezoelectric wafers can be installed below the bed, thereby harvesting energy, which can be used to run the game. The stored energy can also be used as an auxiliary source of power supply for the gaming zone, where very much of fancy lighting is there.
10. Steps in houses where frequent trespassing is expected. This can serve as an auxiliary source of energy in the house.

Conclusion

Energy generated by a piezoelectric harvester is a renewable source of energy, thus would be able to cater the needs of the future generations, where energy crisis is sure to occur. The piezoelectric harvester can become a good auxiliary source of energy for various energy requirements due to its compactness and high efficiency. The harvester is able to collect the mechanical energy from the impact forces in various areas, which otherwise gets converted into non useful energy forms like vibration energy, sound energy etc. The proposed new applications of piezoelectricity include areas like railway stations, malls, villages, jogging parks, houses, gyms, and also in devices like laptops and mobile phones. The harvested energy can be used further as a supplementary source to cater various useful needs.

ACKNOWLEDGEMENTS

We would like to thank Pradeep Yadav, Department of Electrical Engineering, MANIT Bhopal and Ankita Prasad, Department of Information Technology, JEC Jabalpur for their helpful inputs on the topic.

REFERENCES

Keawboonchuay C (2003). *Maximum Power Generation in a Piezoelectric Pulse Generator,* IEEE Transactions on Plasma Science **31**(1) 123-128.

Hu YT (2008). *Nonlinear Interface between the Piezoelectric Harvesting Structure and the Modulating Circuit of an Energy Harvester with a Real Storage Battery,* IEEE Trans Ultrasonic Ferroelectric Freq Control **55**(1) 148-160.

Hu YT (2008). *On the Interaction between the Harvesting Structure and the Storage Circuit of a Piezoelectric Energy Harvester*, International Journal of Applied Electromagnetism Mech. **27**(4) 297-309.

Huan XUE (2009). *An Improved Piezoelectric Harvester Available in Scavenging Energy from the Operational Environment with either Weaker or Stronger Vibration Levels,* Science in China Series G: Physics, Mechanics & Astronomy **52**(2) 218-225.

Pinkston CS (2006). *Maximum Charge Generation in a Piezoelectric Generator,* Power Modulator Symposium, IEEE edition 1-4244-0019-8/06, 518-521.

Platt S (2005). *On Low-frequency Electric Power Generation with PZT Ceramics,* IEEE Trans. Mechatronics **10**(2), 240-245.

Keawboonchuay C (2003). *Electrical Power Generation Characteristics of Piezoelectric Generator under Quasi-Static and Dynamic Stress Conditions,* IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control **50**(10), 1377-1382.
Keawboonchuay C (2003). *Investigation and Optimization of a Piezoelectric Pulse Generator*, Doctor's Dissertation, University of Missouri- Columbia.
Lu F (2004). *Modelling and Analysis of Micro Piezoelectric Power Generators for Micro-electromechanical System Applications*, Smart Mater Struct **13**(1), 57-63.