Performance Analysis of Maximum Power Transfer in Piezoelectric Energy Harvesting

P. Songsukthawan, and C. Jettanasen

***Abstract*—Using piezoelectric materials to harvest energy from ambient vibrations to low power required systems such as wireless and sensor for purpose of non-battery utilization, which leads to reduce production of global warming gases, has become increasingly interested. Due to rather low power output of the piezoelectric transducer and relatively high cost per watt of piezoelectric materials, simulation and performance analysis to find maximum power point of the variation of its parameters are considered. This paper presents the modeling of Lead Zirconate Titanate (PZT) employed in low frequency application using mechanical force and simulated in Capture OrCAD environment. The parametric studies are also carried out in order to identify the point that provides the highest performance allowing making decision for choosing proper piezoelectric material characteristics to match to specific tasks.**

***Index Terms*—Energy harvesting, performance analysis, piezoelectric modeling, piezoelectric parametric study, PZT**

I. Introduction

HUMAN activity is overloading globe's atmosphere with global warming gases emissions which significantly raise up planet's temperature and air pollution; this creates harmful impact on the environment and human being, thus, energy management is further concerned. Using clean or renewable energy instead of fossil fuels (not renewable), such as oil, coal, and natural gas is one of the most important strategies to reduce insidious impact on the environment. Energy from the sun, wind, water and thermal are examples.

In the growing need for renewable energy, energy harvesting from the surrounding environment is one of the interesting ways owing to several reasons, for instance, inexpensive investment, less complexity and cost of wiring, and avoidance of using energy reservoirs with limited capacities such as battery. There are many sources of energy harvesting, for example, fluid flow energy from wind or water, acoustic signal energy from loudspeaker, thermal energy from heat engine or human body, and low-level vibration energy from moving objects.

The low-level vibration energy sources are great interest to convert the mechanical energy into electricity. When moving object such as machine and human motion, it is considered as dissipated mechanical energy back to ambient, there are highly effective proposal if they are collected and utilized. Piezoelectric materials are one of the widely used as electrometrical transducers utilized to harvesting energy from low-level vibration sources with great advantages of no separate voltage source needed and no mechanical stops compared to electrostatic type and easy to integrate with electronics and microsystem with high voltage compared to electromagnetic ones; hence, it is the most popular electrometrical transducer material for low power applications, such as wireless and sensors. [1]

Manuscript received January 7, 2015.

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II. Piezoelectricity

Piezoelectricity refers to a phenomenon in which mechanical deformation (tensile or compressive forces) on crystal surface gives stress inside [2]. The positive ions gather on one side of the crystal while the negative ions are all on the other side to create electrical displacement causing a polarized state in the crystal; electric field is then created. This is called the direct piezoelectric effect, described by (1)

$$D = dT \quad (1)$$

Where d represents the piezoelectric coefficient of electric flux density D related to the mechanical stress T. Conversely, if a crystal is polarized by electric field E, strain S resulting of stresses is created. This is called the converse piezoelectric effect, described by (2)

$$S = dE \quad (2)$$

Where d represents the piezoelectric coefficient of converse piezoelectric effect, which is identical to coefficient of direct piezoelectric effect.

The piezoelectric coefficients d_{ij} are very important in piezoelectric effect, the subscript i refers to direction of applied electric field whereas j refers to direction of strains in response to an applied electric field. The Cartesian coordinate of piezoelectric material is shown in Fig. 1.

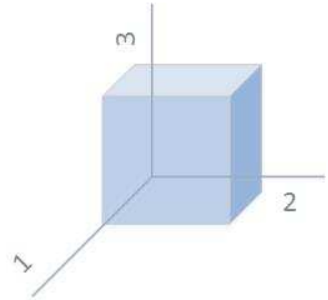
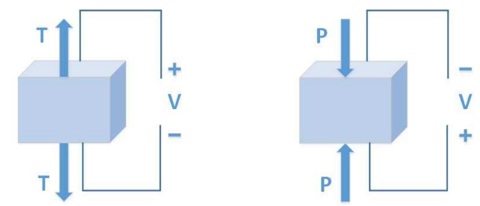
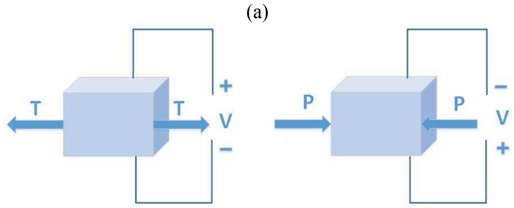


Fig. 1. Directions in a piezoceramic element, three axes are used.

For example, d_{33} is coefficient representing the direction of applied stress and generated electric charge, which is the same (in third direction); we call this mode as longitudinal effect (d_{33} mode). The coefficient d_{31} always creates at the same time, we call this mode as transverse effect (d_{31} mode) related to the direction of applied in one axial (in third direction) but the electric charge is generated in perpendicular direction (in first direction) as shown in Fig. 2.



(a)



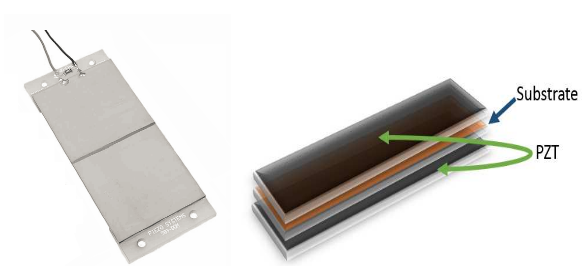
(b)

Fig. 2. The piezoelectric effect: when a pressure (P) or a tension (T) are applied to a crystal, a voltage (V) develops across the material.
(a) Longitudinal effect (d_{33} mode), (b) Transverse effect (d_{31} mode)

III. Lead Zirconate Titanate (PZT) and Its Model

PZT is poled polycrystalline ceramics of Lead-Zirconate Titanate with various compositions; it has been commercially important to the electronics industry and most have parameters useful for energy harvesting [3], such as high strain (charge) constants, permittivity, and coupling constants, high Curie temperature extending its temperature range and thermal stability, high charge output useful for sensing devices and generator elements, and high strain output useful for large displacements at modest voltages.

The basic and actual structure of double-quick-mount bending generator is depicted in Fig. 3. It comprises two layers of PZT with brass reinforced as substrate. When a mechanical force causes a suitably wired and polarized 2-layer element to bend, one layer is compressed and the other is stretched.



(a) (b)

Fig. 3. The piezoelectric structure. (a) Actual structure, (b) basic structure

Charge develops across each layer and stored in the substrate as the potential energy, when stopping applying the mechanical force, it converts into kinetic energy and oscillates with its resonance frequency, then, continuously generates electrical energy until the end of resonant period. The piezoelectric material properties are shown in Table 1.

TABLE I
PIEZOELECTRIC MATERIAL PROPERTIES

Properties	Description / Quantity
Composition	Lead Zirconate Titanate
Relative Dielectric Constant (@ 1 KHz)	1800
Piezoelectric coefficients	390 x 10-12 m/V
Piezoelectric coefficients	-190 x 10-12 m/V
Curie Temperature	350 °C
Weight	0.01 kg
Stiffness	1.9x102 N/m
Capacitance	232 nF
Rated tip deflection	2.6 mm
Rated frequency	47 Hz
Open circuit voltage	20.9 V

The electromechanical model of the PZT is illustrated in Fig. 4.

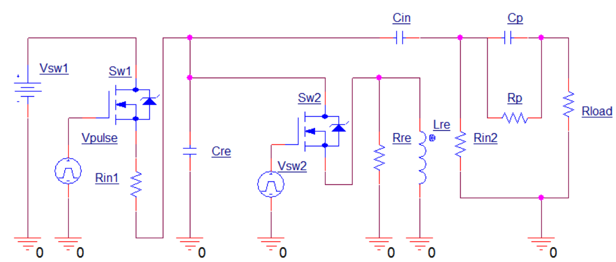


Fig.4. Schematics of piezoelectric power generation, connected directly to resistance load.

The considered model starts with studying about mechanical behavior of PZT when applying the mechanical force causing impact on the PZT and natural vibration causing converted kinetic energy with resonance frequency, then, convert the mechanical parameters from general mechanical system consisting of applied force (P), mass (M), damper (D), spring (K) and displacement (y) as expressed in (3) into electrical components consisting of current (is), capacitance (C), electric field (φ), Voltage (V_{re}), reciprocal of resistance (1/R) and reciprocal of inductance (1/L) as expressed in (4). Calculating and determining the resonance parameter in the electrical term is easier to analyze in power point of view because the internal parameters of PZT are electrical form. By using the resonance frequency of the PZT to compose the resonance circuit model, it finally consists of L_{re}, C_{re}, and R_{re} [4-6].

$$M\frac{dy^2}{dt}+D\frac{dy}{dt}+Ky=P \tag{3}$$

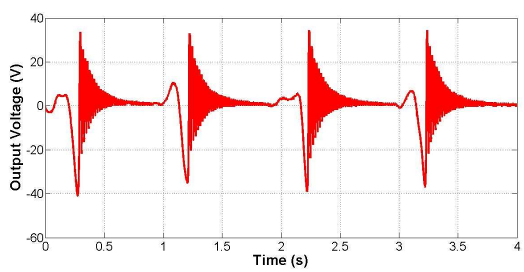
$$C\frac{d\varphi^2}{dt}+\frac{1}{R}\frac{d\varphi}{dt}+\frac{1}{L}\varphi=i_s \tag{4}$$

From the presented electrical model of PZT, the pulse voltage source V_{pulse} is represented as applied mechanical force and its frequency is set at 1 Hz, similar to the frequency of walking across the piezoelectric sheet. Other parameters are series resistor R_{in1} referring to mechanical energy loss when applying and releasing mechanical force, capacitance C_{in} and resistance R_{in} modeled as coupling energy component from output of resonance circuit to input of PZT, SW1 and SW2 are complementary work as controller of oscillation period; SW1 closes when applying mechanical force, and SW2 closes when releasing mechanical force.

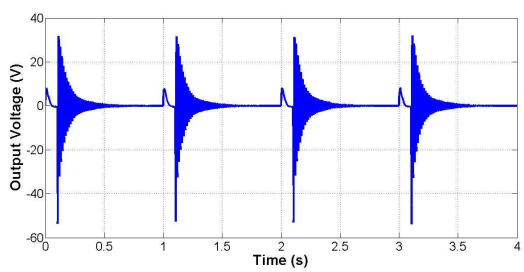
IV. Results, Parametric Studies and Performance Analysis

A. Comparison of Simulation and Experimental Results

Fig. 5 shows the output voltage curves of PZT connected directly to 50 kOhms resistive load compared to actual applying hitting force to PZT with the same mechanical force frequency at 1 Hz, so in Orcad Capture simulation software, we set period of V_{pulse} as 1 s. The simulation and experimental results are in good agreement with each other in terms of waveform shape and magnitude of output voltage signal. The peak to peak voltage is about 80 V for simulation result and about 75 V for experimental result as shown in Fig. 5, therefore, the results confirm that the PZT modeling is appropriate.



(a)



(b)

Fig. 5. PZT voltage waveforms with applying force.
(a) Experiment, (b) Simulation

Fig.5 shows result of output voltage of piezoelectric circuit connected directly to resistance load, but in practice or real utilization of piezoelectric material, it usually connects with digital devices that need DC voltage supply as the load. Therefore, utilizing full-bridge diode rectifier is required for DC voltage, as presented by schematic in Fig. 6.

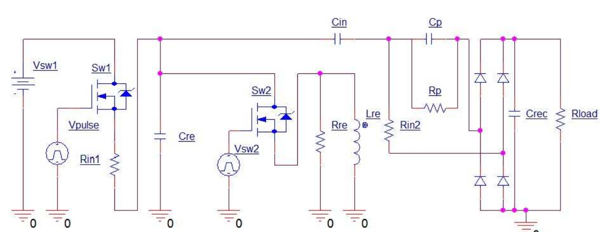


Fig. 6. Schematics of piezoelectric power generation connected to full-bridge diode rectifier with resistive load.

B. Piezoelectric Parametric Study and Performance Analysis

Fig. 7 shows performance analysis for tracking maximum output power delivered to load, the graph compares the maximum power of each resistive load value, it can be clearly seen that the maximum power is increased sharply to point of load resistance equal to about 5 MOhms and decreased gradually after this point, in contrast to the overshoot graph that the percentage of overshoot is maximum at low load resistance value, then dropped sharply at load resistance about 5 MOhms and continue to decrease but more steeply to higher load resistance value. As a result, we choose value of load resistance that achieves maximum output power and gives lowest percentage of overshoot, which is herein 5MOhms as a load for all of parametric analysis.

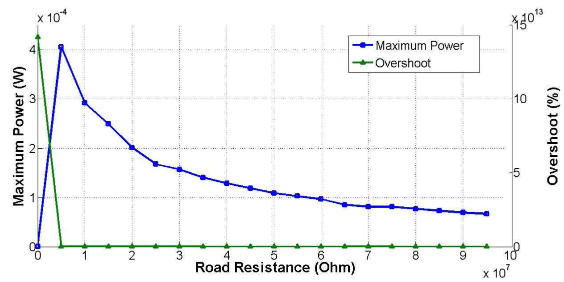


Fig. 7. Performance analysis of maximum power and overshoot with variation of load resistance.

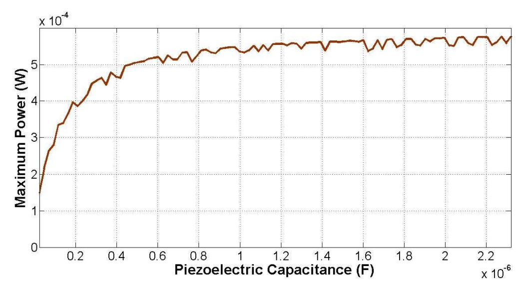


Fig. 8. Performance analysis of maximum power with variation of piezoelectric capacitance C_p.

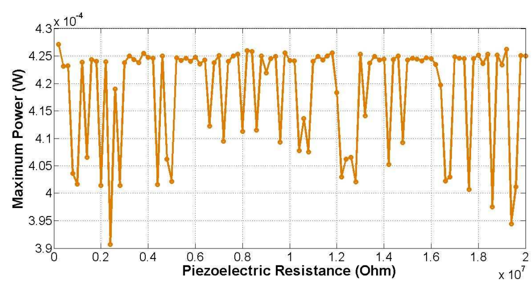


Fig. 9. Performance analysis of maximum power with variation of piezoelectric resistance R_p.

For further parametric studies and performance analysis respecting to maximum output power, the variations of piezoelectric resistance, piezoelectric capacitance and frequency of applied mechanical force are carried out. In Fig. 8, when C_p is varied, the maximum power increases significantly in the range of the value of piezoelectric capacitance less than 600 nF and continues to increase gradually with more capacitance value. In Fig. 9, it is unclear pattern for the variation of piezoelectric resistance to be defined; it seems to be fluctuation in majority of data. In Fig. 10, we can clearly notice that lower period of hitting force gives higher maximum power.

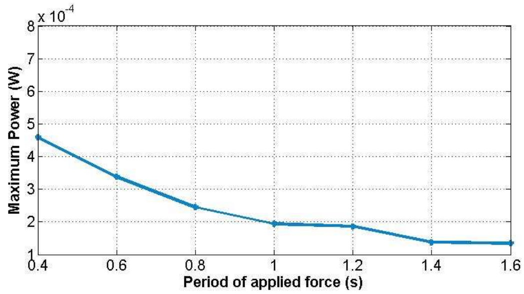


Fig. 10. Performance analysis of maximum power with variation of piezoelectric period (or 1/frequency) of applied mechanical force.

V. Conclusion

This paper has presented the PZT model and investigated on parametric studies and performance analysis in terms of maximum power achievement. The simulation and experimental results are satisfactorily agreed. The parametric studies by varying piezoelectric capacitance, piezoelectric resistance, and piezoelectric frequency of applied mechanical force showed that more piezoelectric capacitance was high more maximum output power was high. However, it is difficult to interpret the trend of the obtained maximum output power when piezoelectric resistance is varied. Furthermore, when applying higher mechanical force frequency, it gives higher maximum output power because the higher mechanical force frequency is closer to the resonance frequency (the point that impedance is minimized, highest current flows, then, highest power transfer) of the PTZ material that is mentioned in data sheet with value around 47 Hz.

Parametric studies and performance analysis are indeed very important to make decisions and identify the characteristics of materials that are matched to specific tasks.

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ISBN: 978-988-19253-9-8
ISSN: 2078-0958 (Print); ISSN: 2078-0966 (Online)