Energy Capture Methods by Piezoelectric Sensors

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***Abstract*—This paper presents different energy capture methods with application to the piezoelectric sensors. The piezoelectric material elements of sensors convert mechanical energy into electrical charges due to the direct piezoelectric effect. Collecting energy from the environment is a major area of interest to the development of unconventional renewable energy sources. Electrical energy is created in a way similar to the classic one. Potential energy sources from the environment could be successfully used.**

***Keywords-piezoelectric sensor; supercapacitors; renewable energy; low-power*.**

I. INTRODUCTION

Capturing energy from the environment has shown considerable interest in recent research [1]-[4]. Piezoelectric material elements are able to convert mechanical energy into electrical charges, due to the direct piezoelectric effect. These electric charges could be used in low-power electronic circuitry that use electrically charged high-capacity capacitors. The mechanical sources could be vibrations, pulses and shocks. Piezoelectric sensors are suitable to convert small mechanical deformations directly into electricity, which can be used in small power electrical sources in applications such as: supercapacitors, battery packs, interferometric lasers, etc.

Collecting energy from the environment is a major area of interest with extensive applications in the development of unconventional renewable energy sources. This study clarifies mechanisms for converting mechanical energy into electricity in a highly efficient way. The *mechanical energy* could come from *environmental sources* such as: *wind, vibrations, shocks, rotary movements, wheel rotations, car engines, human breathing, blood flow, body movements, free or lost mechanical energy or acoustic and ultrasonic vibrations.*

This paper is organized as follows. Section II describes the piezoelectric materials and structures used. Section III discusses an overview of Energy Capture Methods in low-power electronics. Section IV presents a summary of low-power electronics. The conclusions, future work and acknowledgement close the article.

II. PIEZOELECTRIC MATERIALS AND STRUCTURES

Piezoelectric materials, usually crystals or ceramics, have the capability to generate a small amount of current, when they are subjected to mechanical pressure, such as pushing, bending, twisting, and turning. Multiple such materials placed near each other could increase the electrical energy.

The process of energy conversion in a piezoelectric material is based on the principle of the piezoelectric effect. The piezoelectric element stores the energy in two forms, as an electric field (electrical energy) and as a strain (mechanical energy). The *piezoelectric effect* exists in two domains, the first is the *direct piezoelectric effect* that describes the material's ability to transform mechanical strain into electrical charge, and the second form is the converse effect, which is the ability to convert an applied electrical potential into mechanical strain energy, as shown in Figure 1. When a piezoelectric element is mechanically stressed, it generates a charge.

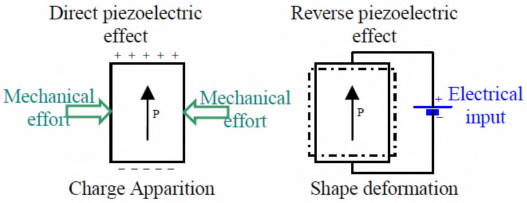

Figure 1. Electromechanical conversion via piezoelectricity phenomenon

The most common type of piezoelectric used in *power harvesting applications* is lead zirconate titanate, a piezoelectric ceramic, or piezoceramic, known as PZT. Although PZT is widely used as a power harvesting material, the piezoceramic's extremely brittle nature causes limitations in the strain that it can safely absorb without being damaged. Lee et al. [1] note that piezoceramics are susceptible to fatigue crack growth when subjected to high frequency cyclic loading. In order to eliminate the disadvantages of piezoceramic materials and improve upon their efficiency, researchers have developed and tested other, more flexible, piezoelectric materials that can be used in energy harvesting applications.

Another common piezoelectric material is *poly(vinylidene fluoride) (PVDF).* PVDF is a piezoelectric

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polymer that exhibits considerable flexibility when compared to PZT.

Mohammadi et al. [2] developed a *fiber-based piezoelectric (piezofiber) material* consisting of PZT fibers of various diameters (15, 45, 120, and 250 µm) that were aligned, laminated, and molded in an epoxy [3]. *Piezofiber power harvesting materials* have also been investigated by Churchill et al. [4], who tested a composite consisting of unidirectionally aligned PZT fibers of 250 µm diameter embedded in a resin matrix. It was found that, when a 0.38 mm thick sample of 130 mm length and 13 mm width was subjected to a 180 Hz vibration that caused a strain of 300 µε in the sample, the composite was able to harvest about 7.5 mW of power.

The last years have seen the birth of many new types of piezoelectric materials or transducers (PZT- lead zirconate titanate, PT-lead titanate, PVDF- polyvinylidene fluoride-trifluoroethylene, piezoceramic/polymer composites, Macro Fiber Composite - MFC, etc.). The schematic of the cross section of an Active Fiber Composite (AFC) actuator [5] is presented in Figure 2. If optimized geometrically, a piezoelectric generator associated with a well suited electronic is likely able to produce the standard 3 Watts required for the lighting system, with all the benefits that it provides.

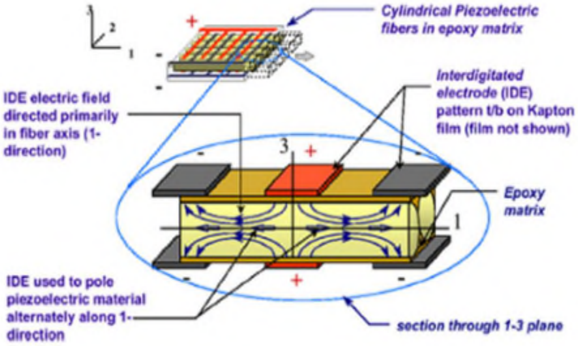

Figure 2. Schematic of the cross section of an Active Fiber Composite (AFC) actuator [5].

Piezoelectric materials exhibit the property that if they are mechanically strained, they generate an electric field proportional to the strain [6]. Conversely, when an electric field is applied, the material undergoes strain. These anisotropic relationships are described by the piezoelectric strain constant, d, which gives the relationship between applied stresses while the electro-mechanical coupling coefficient, k, describes the efficiency with which energy is converted between mechanical and electrical forms. This latter coefficient is important in determining the efficiency of a resonant generator since the overall efficiency of a piezo element clamped to a substrate and cyclically compressed at its resonant frequency is (1):

$$\eta = \frac{\dfrac{k^2}{2\left(1-k^2\right)}}{\dfrac{1}{Q}+\dfrac{k^2}{2\left(1-k^2\right)}} \qquad (1)$$

where Q is the quality factor of the resonator. As Q becomes larger, the efficiency tends towards unity but, for typically achievable Q factors, the efficiency increases significantly for higher values of k.

Lee et al. [1][7] developed a PVDF film that was coated with poly(3,4-ethylenedioxy-thiophene)/poly(4-styrenesulfonate) [PEDOT/PSS] electrodes. They compared *the PEDOT/PSS coated films* to films coated with the inorganic electrode materials, *indium tin oxide (ITO)* and platinum (Pt). When subjected to vibrations of the same magnitude over varying frequencies, it was found that the films with Pt electrodes began to show fatigue crack damage of the electrode surface at a frequency of 33 kHz. The ITO electrodes became damaged when operating at a frequency of 213 Hz. The PEDOT/PSS film, however, ran for 10 h at 1 MHz without electrode damage. One can conclude that, by utilizing a more durable electrode layer, a piezoelectric device can operate under more strenuous conditions. This may give the device the ability to harvest more power throughout its lifespan; however, the exact effect of a stronger electrode layer may vary depending on the specific application.

III. OVERVIEW OF ENERGY CAPTURE METHODS IN LOW-POWER ELECTRONICS

Piezoelectric generators are appropriate to convert the smallest mechanical deformations directly into electrical energy. This solid-state effect is free of degradation in a wide operation range. Therefore, a very high lifetime and availability can be guaranteed.

Piezoelectric materials and transducers are available commercially. Thus, new piezoelectric generators could be produced cost-efficiently in large quantities and can be easily exploited. Nowadays, it is *possible to generate renewable electricity* using piezoelectric materials and transducers placed in special structures that allow the amplification of the direct piezoelectric effect.

Several techniques have been proposed and developed to extract energy from the environment. The most common available sources of energy are: wind, solar, temperature and stress (pressure). In general, *vibration energy* could be converted into electrical energy using one of *three techniques: electrostatic charge, magnetic fields*, and *piezoelectric materials*.

A number of sources of harvestable ambient energy exist, including waste heat, vibration, electromagnetic waves, wind, flowing water, and solar energy. While each of these sources of energy can be effectively used to power remote sensors, the structural and biological communities have placed an emphasis on scavenging vibrational energy with piezoelectric materials [8]. A piezoelectric material transforms electrical energy into mechanical strain energy, and likewise to transform mechanical strain energy into electrical charge [9].

As piezo energy harvesting has been investigated only since the late '90s, it remains an *emerging technology*. With the recent surge of microscale devices, piezoelectric power generation can provide a *convenient alternative to traditional power sources* used to operate certain types of *sensors/actuators, telemetry,* and Microelectromechanical systems, *MEMS* devices. Scavenging energy from ambient vibrations, wind, heat or light could enable *smart sensors* to be functional indefinitely.

Now it is necessary to develop the structures of materials with high piezoelectric coefficients and an optimal architecture for increasing the electrical efficiency of specialized devices for the production of cheap alternative energy to replace traditional energy sources.

Advances in low-power electronics and in energy harvesting technologies have enabled the conception of truly self-powered devices [10]. Cantilevered piezoelectric energy harvesters have been investigated in the literature of energy harvesting [6][16].

The concept of *"harvesting"* is recent and involves capturing the energy normally lost around a system and converting it into electricity that can be used to extend the life of the system or to provide an endless source of energy to a system [11].

IV. OVERVIEW OF LOW-POWER ELECTRONICS

The methods of accumulating and storing the energy generated, until sufficient power has been captured, is the *key to developing completely self-powered systems*. Piezoelectric transduction has received great attention for vibration-to-electric energy conversion over the last five years [12]. Future applications may include high power output devices (or arrays of such devices) deployed at remote locations to serve as reliable power stations for large systems, *wearable electronics*.

Among *challenges* is the electronic circuitry needed to capture, accumulate and store energy from energy harvesting energy sources. The circuitry must then switch the power from an energy storage device and then supply it to the application. In general, energy can be stored in a *capacitor, super capacitor*, or *battery*. Piezoelectric generators are appropriate to convert the smallest mechanical deformations directly into electrical energy. Among *alternative energy sources*, we recall, water energy, solar, wind, heat, etc. It needs to find other methods and possible ways of using energy sources such as mechanical energy converted into electrical energy.

Many conventional systems consist of a single piezoceramic in bending mode (*unimorph*) or two bonded piezoelectric in bending mode (*bimorph*), but upon the experimental, the validating model had 4.61 % maximum error [9]. Some structures can be tuned to have two natural frequencies relatively close to each other, resulting in the possibility of a *broader band energy harvesting system* [12] [13]. The energy produced by these materials is in many cases far too small to directly power an electrical device [11][14]. Recent studies present the ability to take the energy generated through the vibration of a piezoelectric material and use it to recharging a discharged battery [9].

Bimorph actuators consist of two independent flat piezoelectric elements, stacked one on top of the other. By driving one element to expand while contracting the other one, the actuator is forced to bend, creating an out-of-plane motion and vibrations [15]. *Cantilevered* piezoelectric energy harvesters have been investigated in the literature for energy harvesting [12]. An attractive configuration is to form the piezoceramic into a cantilever arrangement, as shown in Figure 3, where layers of piezoceramics are bonded to a substrate, typically made from a suitable metal. This structure allows a lower resonant frequency to be achieved while producing large strains in the piezoceramic. Where two layers of piezo material are used, the structure is referred to as a *bimorph.* In this case, the piezo layers may either be connected in series or parallel. If only a single piezo layer is used, the structure is referred to as a *unimorph* [6].

A. Piezoelectric devices

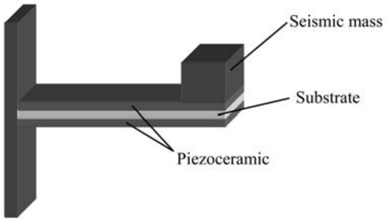

Figure 3. Piezoceramic cantilever resonator [6].

Figure 4 presents a power generator array prototype, realized by small cantilevers of different lengths, in order to obtain a larger broadband [16].

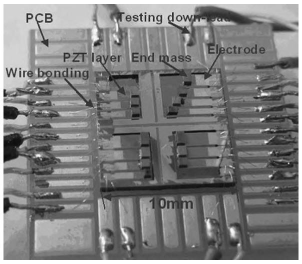

Figure 4. Picture of power generator array prototype [16].

The main steps of the fabrication process of a micro piezoelectric power generator are presented in Figure 5 and they are: (1) Functional films preparation: SiO_2/Ti/Pt/PZT /Ti/Pt, (2) functional films pattern, (3) silicon slot etching by RIE, (4) back silicon deep etching by KOH solution, (5) cantilever release by RIE, and (6) metal mass micro fabrication and assemblage [17].

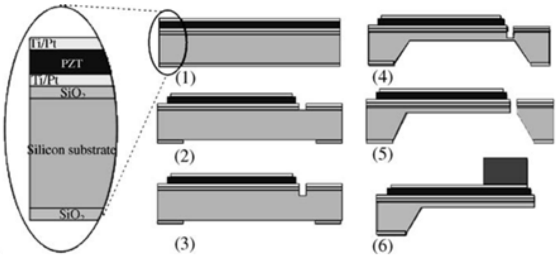

Figure 5. Fabrication process of micro piezoelectric power generator [17].

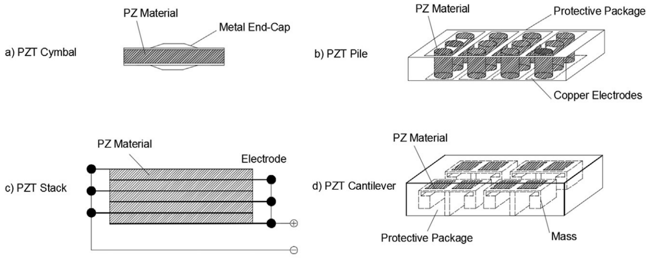

Figure 6. Types of PZT energy harvesters in pavement [18].

Studies about the piezoelectric effects for energy harvesting pavement can be found in [18], using different structures of Piezoelectric Sensors, like: PZT cymbal, PZT pile, PZT stack and PZT cantilever, as shown in Figure 6.

B. Energy harvesting piezoelectric circuitry

Piezoelectric generators are appropriate to convert the smallest mechanical deformations directly into electrical energy. This solid-state effect is free of degradation in a wide operation range. A vibrating piezoelectric device differs from a typical electrical power source in that it has capacitive rather than inductive source impedance, and may be driven by mechanical vibrations of varying amplitude, as shown in Figure 7. A PZT disc, for example, compressed between two metal surfaces, will never be able to expand in the radial direction as would a long, thin cylinder, which is only constrained at its ends and assumes a barrel shape on radial expansion. So, the way in which the material is mounted will directly affect the energy conversion per unit volume. The general rule, therefore, is to allow the PZT body some freedom to expand radially since charge generation is directly coupled to deformation.

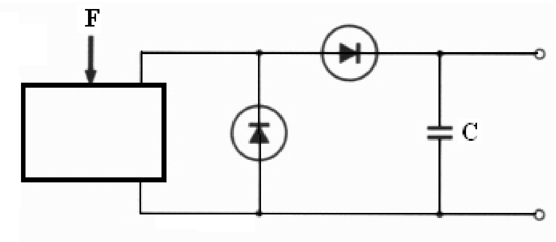

Figure 7. PZT element generator with 2 diodes as DC converter and a parallel capacitor C.

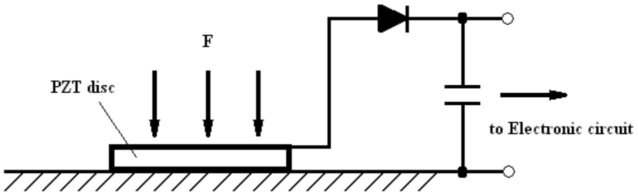

Figure 8. Electronic circuit with PZT disc strained by F force, and one diode DC converter.

The principles of charge generation by a PZT disc to an electronic circuit performance are the shape of the PZT transducer, the manner in which the transducer is mounted and, of course, the nature of the electrical load, as shown in Figure 8.

Typical energy harvesting circuitry consists of voltage rectifier, converter and storage, as shown in Figure 9.

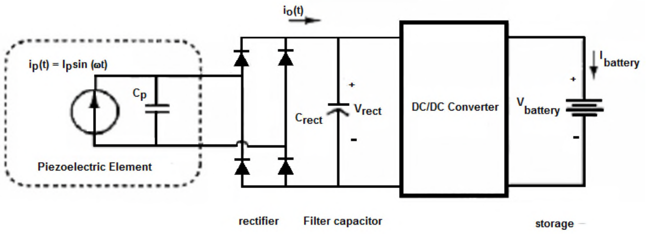

Figure 9. Typical energy harvesting circuitry

Energy harvesting sources that generate power from ambient sources present problems in generating a predictable flow of electricity for the operation of electronic circuits. At times, these sources generate zero power. At other times, they generate trace amounts of power that are unusable. Then, there are times when the power generated is so great that a charge from an energy harvesting source could burn out the circuitry. Therefore, electronics with energy harvesting intelligent piezoelectric transducer should be used. In Wireless Sensor Networks (WSNs), one of the major hurdles is the limited battery power that is unable to meet long-term energy requirements. Energy harvesting, conversion of ambient energy into electrical energy has emerged as an effective alternative to powering WSNs [19].

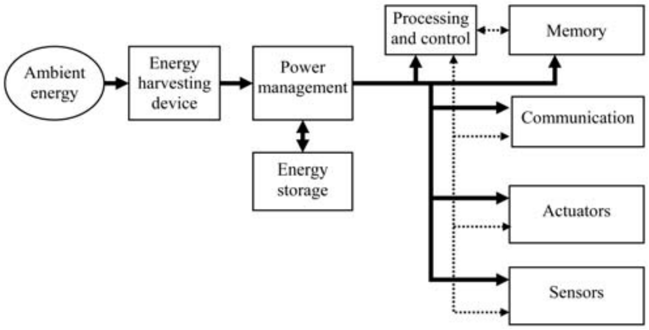

Figure 10. A generic sensor network node with energy harvesting device [6].

The idea of harvesting ambient energy from the immediate surroundings of the deployed sensors is to recharge the batteries and to directly power the sensor nodes. The power consumed by a network node can be split between the various functions it has to perform, as shown in Figure 10.

V. CONCLUSION AND FUTURE WORK

Collecting energy from the environment is a major area of interest with extensive applications in the development of unconventional renewable energy sources. This study clarifies mechanisms for converting mechanical energy into electricity with a high efficiency conversion rate.

Energy harvesting is an attractive concept because so many energy sources such as light, heat, and mechanical vibration that exist in our ambient living could be converted into usable electricity. The technical progress in the *field of extremely low energy electronics* opens up the chance to use *harvested energy* from the environment. Most piezoelectric electricity sources produce power in the order of milliwatts, too small for system application, but enough for hand-held devices such as some commercially available self-winding wristwatches. The methods of accumulating and storing the energy generated, until sufficient power has been captured, is the *key to developing completely self-powered systems*.

WSNs are crucial in supporting continuous environmental monitoring, where sensor nodes are deployed and must remain operational to collect and transfer data from the environment to a base-station. Further development of such energy circuitry and piezoelectric materials with various structures will facilitate the progression of power harvesting methods from a research topic to a useable technology in practical devices.

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REFERENCES

[1] C. S. Lee, J. Joo, S. Han, J. H. Lee, and S. K. Koh, “Poly(vinylidenefluoride) transducers with highly conducting poly(3,4-ethylenedioxythiophene) electrodes,” Proc. Int. Conf. on Science and Technology of Synthetic Metals, 2005, vol. 152, pp. 49–52.

[2] F. Mohammadi, A. Khan, and R. B. Cass, “Power generation from piezoelectric lead zirconate titanate fiber composites,” Proc. Materials Research Symp. 2003, pp. 736.

[3] A. A. Bent, N. W. Hagood and J. P. Rodgers, “Anisotropic actuation with piezoelectric fiber composites,” J. Intell. Mater. Syst. Struct., vol. 6, pp. 338–349, 1995

[4] D. L. Churchill, M. J. Hamel, C. P. Townsend, and S. W. Arms, Strain energy harvesting for wireless sensor networks,” Proc. Smart Struct. and Mater. Conf., Proc. SPIE 5055, 2003, pp. 319.

[5] W. K. Wilkie et al., “Low-cost piezocomposite actuator for structural control applications,” Proc.7th Int. Symp., 2000.

[6] J. M. Gilbert and F. Balouchi, “Comparison of Energy Harvesting Systems for Wireless Sensor Networks,” International Journal of Automation and Computing, vol. 05(4), pp. 334-347, Oct. 2008.

[7] C. S. Lee, J. Joo, S. Han, and S. K. Koh, “Multifunctional transducer using poly(vinylidene fluoride) active layer and highly conducting poly(3,4-ethylenedioxythiophene) electrode: actuator and generator,” Appl. Phys. Lett., vol 85, pp. 1841–3, 2004.

[8] S. R. Anton and H. A. Sodano, “A review of power harvesting using piezoelectric materials (2003–2006)”, Smart Mater. Struct., vol. 16, pp. R1–R21, 2007, doi:10.1088/0964-1726/16/3/R01.

[9] H. A. Sodano, D. J. Inman, and G. Park, “A Review of Power Harvesting from Vibration using Piezoelectric Materials,” The Shock and Vibration Digest, pp. 197-205, May 2004.

[10] M. Lallart, S. Priya, S. Bressers, and D. J. Inman, “Small-scale piezoelectric energy harvesting devices using low-energy-density sources,” Journal of the Korean Physical Society, vol. 57(41), pp. 947-951, Oct 15 2010.

[11] H. Sodano and D. Inman, “Generation and Storage of Electricity from Power Harvesting Devices,” Journal of Intelligent Material Systems and Structures, vol. 16(1), pp. 67-75, Jan. 2005, doi: 10.1177/1045389X05047210.

[12] A. Erturk and D. J. Inman, “An experimentally validated bimorph cantilever model for piezoelectric energy harvesting from base excitations,” Smart Mater. Struct., vol. 18, pp. 025009 (18pp), 2009, doi:10.1088/0964-1726/18/2/025009.

[13] A. Erturk and D. J. Inman, “A Distributed Parameter Electromechanical Model for Cantilevered Piezoelectric Energy Harvesters”, J. Vib. Acoust, vol. 130(4), pp. 041002 (15 pages), June 2008, doi:10.1115/1.2890402.

[14] N. M. White, P. Glynne-Jones, and S. P. Beeby, “A novel thick-film piezoelectric micro-generator,” Smart Materials & Structures, *10*(4), pp. 850-852, 2001.

[15] I. Chilibon, C. Dias, P. Inacio, and J. Marat-Mendes, “PZT and PVDF bimorph actuators,” Journal of Optoelectronics and Advanced Materials, vol. 9**,** Issue 6, pp. 1939-1943, Jun 2007, ISSN: 1454-4164.

[16] J-Q. Liu et al., “A MEMS-based piezoelectric power generator array for vibration energy harvesting,” Microelectronics Journal, vol. 39, pp. 802–806, 2008.

[17] H-B Fang et al., “Fabrication and performance of MEMS-based piezoelectric power generator for vibration energy harvesting,” Microelectronics Journal, vol. 37, pp. 1280–1284, 2006.

[18] L. Guo and Q. Lu, “Potentials of piezoelectric and thermoelectric technologies for harvesting energy from pavements,” *Renewable and Sustainable Energy Reviews*, vol. 72, pp. 761-773, May 2017, doi: 10.1016/j.rser.2017.01.090.

[19] K. Singh and S. Moh, “Comparative Survey of Energy Harvesting Techniques for Wireless Sensor Networks,” Advanced Science and Technology Letters, vol.142, pp. 28-33, GDC 2016, http://dx.doi.org/10.14257/astl.2016.142.05.