Piezoelectric Wind Power Harnessing – An Overview

Gülnihal Çevik*, Mahmut F. Akşit, Asif Şabanoviç

Sabanci University, Tuzla, 34956 Istanbul, Turkey

Abstract

As fossil energy resources deplete, wind energy gains ever more importance. Recently, piezoelectric energy harvesting methods are emerging with the advancements in piezoelectric materials and its storage elements. Piezoelectric materials can be utilized to convert kinetic energy to electrical energy. Utilization of piezoelectric wind harvesting is a rather new means to convert renewable wind energy to electricity. Piezoelectric generators are typically low cost and easy to maintain. This work illustrates an overview of piezoelectric wind harvesting technology. In wind harvesting, piezoelectric material choice is of the first order of importance. Due to their strain rate, robustness is a concern. For optimum energy harvesting efficiency resonant frequency of the selected materials and overall system configuration plays important role. In this work, existing piezoelectric wind generators are grouped and presented in following categories: leaf type, rotary type, rotary to linear type and beam type wind generators.

Keywords: wind, piezo, energy harvesting, piezoelectric materials, wind energy

1. Introduction

When some force or pressure is applied on embedded piezoelectric crystals the energy is transformed into the electrical energy which can be seen as a clean source of energy. Recently, clean renewable energy sources become popular, since the world's usable fossil energy resources are depleting rapidly. Piezoelectric generators can be embedded in any place where energy exists in the form of force or pressure like applications in highways, railways, airports, pedestrian lanes. The resulting deformation of piezoelectric material is converted into electrical energy. Though small in magnitude, the obtained energy can be stored or conveyed to direct usage areas. Apart from the applications areas listed above wind provides a natural primary source of energy to initiate this overall piezoelectric generation cycle. The wind potential is abundant and commonly available. The research on harvesting energy out of wind flow focuses on extracting maximum energy out of irregular flows as well as from low velocity wind flows.

The study done by Yan *et. all* (2009), demonstrated that by the usage of wind sources on piezoelectric materials can generate sufficient energy to use for sensors. For instance, 917 μJ energy can drive 5 words of 12 bit information for transmission period of 100 msecs [8]. Extraction of electrical energy based on piezoelectric materials involves the following steps; capturing or developing mechanical deformation of the piezoelectric material, conversion of mechanical energy to electrical energy and conveying this energy to a proper storage element or usage application. Figure 1, illustrates typical block diagram for piezoelectric generators.

In order to harvest the optimum wind energy, characteristics of the piezoelectric materials should be matched with the application areas, and designs should be tailored for different weather and operating conditions. Therefore, developing optimum design with optimum materials is regarded as key to maximum harvesting. There is a direct correlation between the harvested energy and piezoelectric material deformation. The harvested energy from piezoelectric material is also proportional to frequency and strain where maximum energy can be extracted at resonance [21].

Recently, researchers developed models, controls and devices with different topologies in order harvest energy with relatively small vibrations. Arnau [25] presented a model of a spring-mass-damper mechanical resonator with piezoelectric electromechanical coupling. The study showed that maximum power can be obtained as excitation frequency approaches the resonance frequency. Besides, the study showed that application of controllable electrical impedance to the piezoelectric device can maximize the power harvested.

This study provides an overview of current piezoelectric wind harvesting techniques. First, general information on general piezoelectric applications and piezoelectric energy harvesting methods is presented. Efficiency of the piezoelectric materials is discussed with regard to energy harvesting usage. Then, recent piezoelectric wind

E-mail: gulnihal@sabanciuniv.edu

generators such as leaf type wind generators, rotary to linear wind generators, rotary wind generators and beam type wind generators are studied. Moreover, advantages and shortcomings of these systems are discussed. The paper continues with an overview of special designs and circuit optimization methods for efficiency improvement. Finally, paper is concluded with a summary of wind harvesting designs and a discussion of future of piezoelectric wind generators.

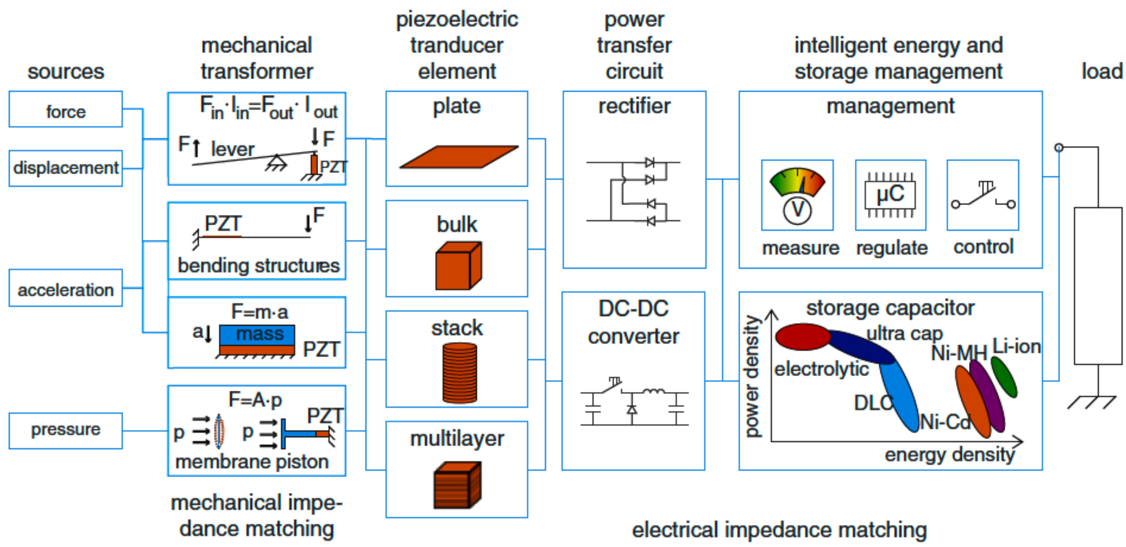

Figure 1. Block diagram for piezoelectric generators [29].

2. Piezoelectric Applications and General Energy Harvesting Methods

Since piezoelectric materials have good electromechanical coupling, these materials are suitable to use in "structural vibration control", "health monitoring" and "energy harvesting" [27]. Piezoelectric ceramics have importance for ultrasonic motors, piezoelectric and other devices [28]. ????? (PZT) materials are being used for gas igniters. The soft types are used for applications which require low-frequency, in high strain actuators and sensors with high strain actuators and sensors with high sensitivity [29]. On the other hand, hard PZT ceramics have low depolarization and low losses. Therefore, they are used for high-power ultrasound transducers, and high temperature stable sensors [29].

Piezoelectric materials make conversion of available ambient energy to electricity possible wherever vibration and pressure force is available. Lately, use of piezoelectric materials in train stations and dance floors are experimented. In a study by Rocha *et .all* [2010], integration of piezoelectric materials into shoe soles is also experimented. It is reported that the harvested energy out of human movements can be utilized to function electronics [31]. In a recent study, Kim *et. all* (2011) observed various high force and different frequency range effects on energy harvesting by placing piezoelectric materials in a bridge system [6]. Piezoelectric materials are mainly affected by the strain rate but not simply proportional. It is reported that optimum loading amplitude and frequency should be considered for maximum electric generation.

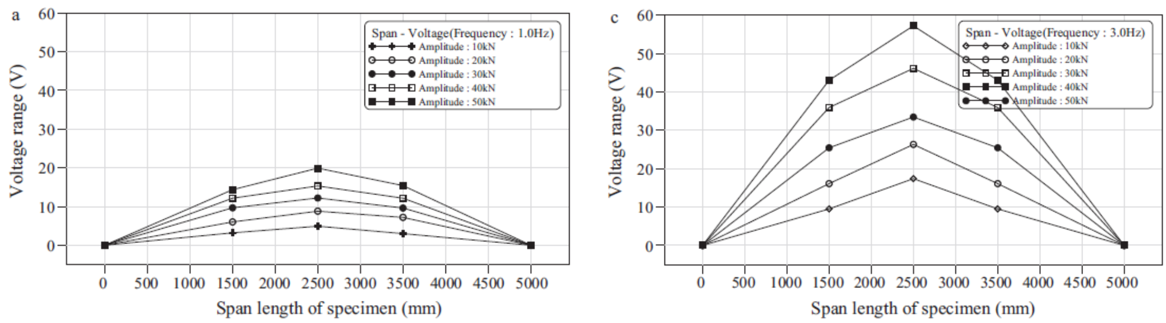

Figure 2. Generated voltage distributions with span length depending on amplitude and frequency of load. (a) Loading frequency 1.0 Hz; (c) Loading frequency 3.0 Hz.

Another study of Kim *et. all* showed that by the usage of 10 layer ceramics instead of one layer, output current can be increased by 10 times [17]. Their study showed that multilayered cymbal increased the output power 100% with the 40 times lower resistive load while current increased by 10 times. This study validated the usage of cymbal with multilayered piezoelectric layer is effective to harvest more energy.

3. Piezoelectric Energy Harvesting Materials

Piezoelectric material can mainly be divided in two: hard and soft piezoelectric material. Hard piezoelectric ceramics domain wall motion is restricted so that their piezoelectric constants are low and they have less hysteresis properties, on the other hand, soft piezoelectric are more preferable because of their high strains [8]. Polymer piezoelectric materials (PVDF) have high impact resistance and their impedance values can be matched with that of water and human body due to the fact that their acoustic impedance is comparable to a range of values in between those of piezo-ceramics and water [23]. On the other side, polymer composites (PZT) has characteristics of high resistance to depolarization, small dielectric losses in the exposition of high electric fields, high electromechanical coupling, high resistance to depolarization under high mechanical stress and great deformation ability [24]. Thunder, Active Fiber Composite, Macro Fiber Composite, Radial Field Diagram, Quickpack and Bimorphs are called as low profile transducers, since they are most used piezoelectric materials which have light weight, flexible, large response, low frequency response and low frequency operation [21].

MFC has advantages over PZT and bimorph since it has flexible, robust to damage and environmental effects and moreover it is more efficient for energy conversion, however MFC can produce low level of current which is not favorable [5]. On the other hand, PZT is more efficient; however it is vulnerable to breakage so it is less robust [5]. Their numerical analysis revealed the following efficiency formula

$$\eta = \frac{P_{out}}{P_{in}} \times 100\% = \frac{1}{m} \sum_{n=2}^{m} \frac{(V_n + V_{n-1})^2 / R}{[(F_n + F_{n-1}) \cdot (d_n - d_{n-1})] / (t_n - t_{n-1})} \times 100\% \qquad (1)$$

where η is the efficiency, V is the voltage drop across R, F is the force applied to the base of the plate, d is the displacement of the plate, t is the time increment between data points, n is the data point index and m is the total number of measured data points. Results of the efficiency study with 3 different piezoelectric material in different frequencies can be found in Table 1.

Table 1. Efficiencies of PZT, MFC and QP [5]

Signal	PZT efficiency (%)	MFC efficiency (%)	QP efficiency (%)
Resonant	4.54	1.7871	0.4662
	4.51	1.7211	0.6094
	4.2312	1.7377	0.946
Chirp 0–500 Hz	3.102	0.2927	1.6505
	3.0725	0.3033	1.2611
	3.0293	0.3368	1.492
Random 0–500 Hz	6.57	1.2103	3.097
	6.954	1.3013	2.9664
	6.8562	1.4663	3.1551

In the low frequency range, usage of bimorphs would be suitable since they have enough mechanical strength around 1-10 Hz under force of few Newton's [21]. Also, their voltage coefficient is high so the charge developed is high. However, PZT materials are more suitable than MFC, since MFC generates lower current [30]. Moreover, in the study of Kymissis et. all, the experiments resulted that in the case of displacement is low the usage of bimorphs resulted with advantageous with respect to using PZT or Thunder, since it is capable of various distribution of weights and conditions [30].

The study of Goldfarb and Jonas showed that large amount of energy stored in the piezoelectric material, so efficiency can be improved by minimizing inner energy storage [21]. In the study, oscillatory force applied on rigid mass to subtract electrical energy out of piezoelectric material revealed the efficiency formula

$$\eta = \left(\frac{1}{2}\right) \frac{k^2}{1-k^2} \Big/ \left(\frac{1}{Q_m} + \frac{1}{2}\frac{k^2}{1-k^2}\right) \qquad (2)$$

Where Qm is the mechanical quality factor and k is the coupling factor depends on system parameters [21]. Also, Umeda et. all (1996) approved that efficiency can be maximized with the increase of mechanical quality factor, mechanical coupling factor and with the decrease of dielectric loss factor [2].

It is shown that cymbal transducers have 40 times strain coefficient and usage of them would supply higher energy. Moreover, these harvesting transducers can be produced by PZT, since it has high mechanical stability and coupling factor. PVDF has lower coupling factor, so PZT would be preferable [17].

4. Recent Piezo-Wind Generators

Recently research on piezo-wind electric generators has been progressing with the increase trend on renewable energy sources. The wind energy can be converted to electrical energy via integrating piezoelectric material on leafs or converting rotary energy to linear energy to bend PE materials or PE materials can be directly utilized on rotary motion.

Li *et. all* (2009) proposed a novel vertical-stalk L-type design to harvest more energy which is composed of a polarized PVDF stalk, a plastic hinge and polymer leaf [1]. Vortices cause the fluctuating pressure forces which are perpendicular to motion which leads vibrations and leaf is moving through the bending force and moment of PVDF stalk. Besides, S. J. Oh *et. all* (2009) made a tree-shaped design to harvest energy by embedding PVDF's on leafs and PZT's on trunk part of the tree where the bending can be realized by strong wind. PVDF's are embedded on leafs since they are less stiff [7].

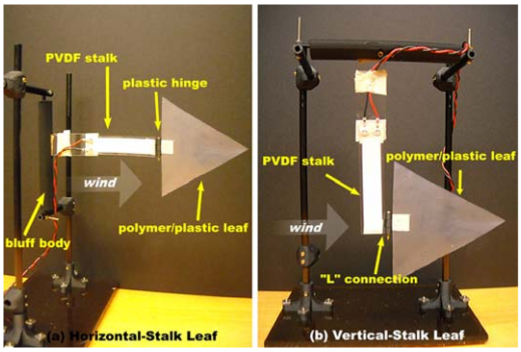

Figure 3. (a) Horizontal-Stalk Leaf, (b) Vertical-Stalk Leaf [1].

On the other side, the there have been studied rotary to linear motion wind generators. In the study of Myers et. all (2007), special designed blades are used to lead differential flow of wind [15]. While vanes rotates around a shaft with the effect of wind, crank arm attached to it supplies linear motion for nine bimorphs' deflection and in the wind speed of 10 miles/h, across 30, 0.2mW was obtained.

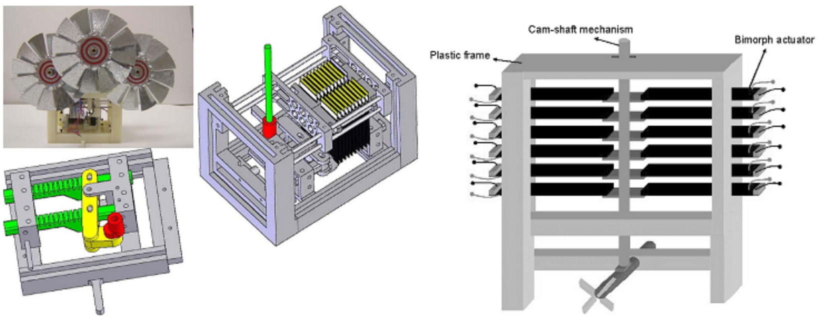

Figure 4. Optimized design of small scale windmill [15] (left), prototype of rotary to linear wind generator (right) [16].

In the design of Chen *et. all* (2007), as it can be seen in Fig.2, piezoelectric bimorphs are placed on two columns and six rows and between columns, a cam shaft mechanism with six rectangular hooks gives motion to the bimorphs [3]. By cam-shaft mechanism rotary motion obtained from fan is converted to linear motion by the height of 4 mm and at the frequency of 12 Hz, 1.2mW is obtained across 1.7 kΩ.

On the other side, rotary types of piezoelectric wind generators are developed. Priya *et. all* (2005) designed a piezoelectric windmill with ten piezoelectric bimorphs in the cantilever form, wind rotates the fan and generated torque moves windmill, so transducers oscillate between stoppers (Fig.5) [10]. At 10 mph speed, power of 7.5 mW had been obtained across optimum load 6.7 kΩ. They proofed that maximum power can be obtained at optimum load which is given at Eq.2. In another experiment of Priya *et. all* (2005), observations showed that output is proportional to pre-stress level [11]. Also, as number of bimorph is increasing, obtained output voltage is also increasing while matching load decreases.

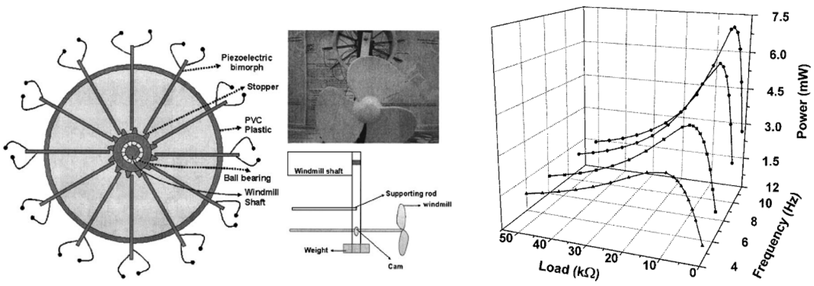

Figure 5. Schematic of piezoelectric windmill (left), variation of power with respect to frequency and load (right) [10].

$$R_{Load}^{opt} = \left| R_S + \frac{1}{j\omega C} \right| \qquad (3)$$

Results of Yoo *et. all* (1997) showed that resonance frequency has increased with the decrease of vibrating plate length [14]. So by the arrangement of the length of the plate, resonance frequency can be obtained. Deflection increases with the increase of length of piezo-ceramics and decrease of plate length. Phosphor copper shows good elastic property, high young's moduli and density.

Chen *et. all* (2007), studied the electrical power generated out of AC type wind input and simulated the vertical type wind generator outputs under residue wind flow [9]. They put the lower electrodes on copper with a piezoelectric density of 7600 kg/m^3. For characteristic area of 0.006 m^2 and in wind speed of 14 m/s, efficiency is around 60% with the resulted output 6.96 W and since 90% is mechanical loss, 0.464W could be delivered to vertical type generator. While simulations showed 10 μW output power, overall efficiency of piezoelectric generator can be calculated as 0.003%.

In the work done by Bryant *et. all* (2011), two degrees of freedom is utilized by deflection of beam and a rotation of a flap about the bearing joint which allows a modal flutter response and so on energy harvesting [4]. Experiments showed that above the flutter boundary, limit cycle oscillations are occurring which allows system to reach steady state for particular air conditions. Level of energy harvested varies according to the amplitude and frequency of the limit cycles and it also depends on the initial condition. The main contribution of this work is maximum energy can be reached when the flap and beam are deflecting with 90 degrees phase difference.

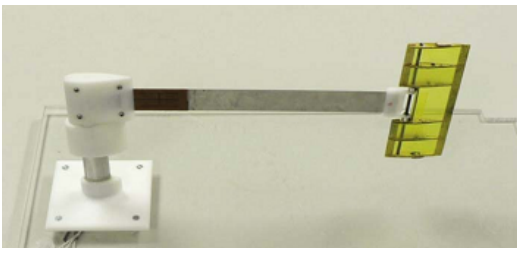

Figure 6. Two degrees of freedom beam type wind generator [4].

De Marqui *et. all* (2010), since there is a cancelation of electrical output in the coupled bending-torsion aeroelastic mode of a cantilevered piezoelectric wing generator in the continuous mode of electrodes, they proposed usage of segmented electrode [20]. This allows harvesting energy in the high frequencies where torsion modes are observed on the wing. Larger mechanical amplitudes means more energy harnessing can be observed at low damping which can be seen at flutter speed. While shunt damping effect of power generation can cause the decaying power generation can be obtained at optimum load resistance in continuous electrode case, in any load shunt damping effect can be observed in the segmented electrode case.

Many researches done in this area showed that optimum output power can be obtained at resonance frequency and studies of Yoo *et. all* (2000) showed that frequency of the vibrating plate decreases with the increase of the plate length while bimorph length kept constant [22]. So, optimum output can be realized with the proper dimensions of plate length and width at a given frequency. Relation between displacement of the plate and wind velocity is correlated. The resonance frequency of the plate is related to plate's variable as in the following

$$f_r = G\frac{t}{l^2}\sqrt{\frac{Y}{12\rho(1-\sigma^2)}} \tag{4}$$

Where ρ, σ, Y, l and t are density, Poisson's ration, Young's modulus, vibrating plate length and thickness, respectively. While G differ for different vibrating materials and can be found experimentally, for ideal fixed plates it is 0.558. Their studies showed that the best tip displacement of 35.5mm is obtained by usage of phosphor bronze plate at the length of 33 mm and S6 type bimorph with length of 31.8 mm, under a 220 V, 60 Hz electrical drive.

5. Special Designs for Improvement of Efficiency and Compensation of Deficiencies

Chang *et. all* (2010), proposed an alternative design in order to convert DC type regular wind to AC by putting a propeller in between wind and the piezoelectric bimorphs [12]. While width to length ratio kept constant as 1:5, experiments were conducted under 3.5 m/s AC wind, three times frequency of generator could obtained with three blades. With the measured speed, 42.724 Hz had been obtained and by regarding this frequency. Since the optimum power from piezoelectric bimorphs can be obtained at resonance frequency, with proper dimensions of bimorph, available frequency could be used as resonance frequency.

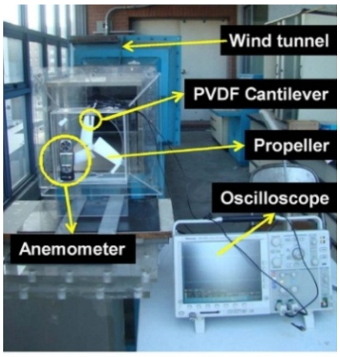

Figure 7. Experimental setup of PVDF wind generator with propeller integration [12].

Ting *et. all* (2010), proposed a nozzle accelerator to increase the wind speed five times more and correspondingly to increment the drag force in order to vibrate the piezoelectric bimorph more in order to harvest more energy [13]. Nozzle accelerator consists of flow guided mechanism, nozzle, duct and closed mechanism which is increasing the force on PVDF cantilever type mechanism and so maximum output voltage 1.313 V had been obtained.

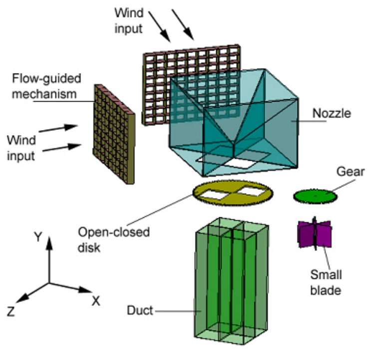

Figure 8. Wind collector design with the integration of nozzle [13].

Clair *et. all* (2010), used the flow induced self-excited oscillation to generate electricity [18]. They used a chamber to let increase of pressure, and so the beam would be bended by pressure and aperture area increases.

By the increase of aperture, pressure decreases and restoring forces lead the motion back. By the forth and back motion of bender, after a while, energy consumed balances the energy produced so system undergoes self-sustained oscillations. This design does not necessitate external vibration source to eliminate the bandwidth issues and size of design does not influence the efficiency.

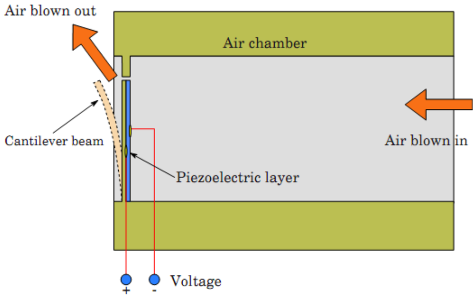

Figure 9. Modal of scalable flow induced self excited wind power generator [18].

Robbins *et. all* (2006) harvested energy by using flag-like membrane with piezoelectric materials which is attached to anchor rod [19]. Wind leads flapping of the membrane and the periodic stress occur on bimorph generates voltage across electrodes. Flag positioned parallel to the length of the flag. Since the generated stress gets larger as thickness is getting larger in the same given amplitude, optimum should be considered since too thick material generates little strains. Kelvin-Helmholtz instability shows that at the calculated wind velocity, flag can flap tremendously.

$$U_{crit} = (2.5\ \mathrm{L})(2\pi \mathrm{f}_1) \tag{5}$$

Where L is length of bimorph, f_1 is the mechanical resonant frequency. The membrane produces increased amplitude vortices when shedding frequency ($\mathrm{f}_s = 0.2\ \mathrm{U/D}$) matches with flapping frequency and so increase of energy generation would be observed. Furthermore, addition of optimum mass to the end of the flag increases the output voltage and so the generated power. They observed that usage of a MFC which is stronger piezoelectric material generates 25 times more power compared to PVDF bimorphs under same conditions.

6. Energy Maximization and Required Circuit Designs for Piezoelectric Generators

In energy harvesting systems to satisfy the appropriateness of voltage to energy storage elements an electric interference is needed [27]. Most known electric interface is AC-DC rectifier and most commonly used one is classic interface and can be seen in Fig.1.

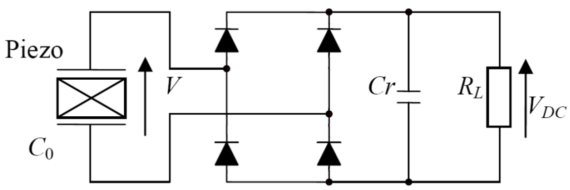

Figure 10. Classic Interface [27].

In the study of Tianze et. all (2009) , it is deduced that greatest amount of energy can be subtracted can be obtained when circuit of transducer reaches impedance matching [28]. Also, they proposed dynamic tuning match for transducer since resonant frequency changes with the load power, temperature and humidity.

For the optimum energy extraction, Tan et. all proposed synchronous charge extraction circuit with flyback transformer (Fig.1) and its maximum efficiency is found that 63.5% [26]. According to experimental and simulation results, the maximum They proposed that efficiency can be increased with the advancement in flyback transformer.

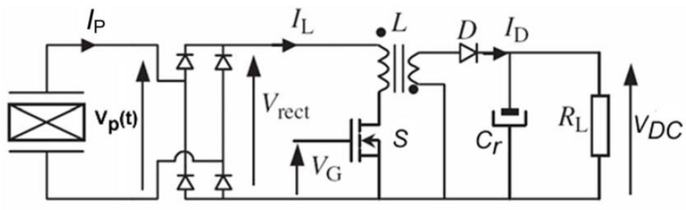

Figure 11. Synchronous charge extraction circuit with flyback transformer [26].

8. Discussion and Conclusion

In order to get the optimum efficiency more research should focus on optimization and combination of existing researches. Also, since the most of the energy lost realized at storage elements, circuit designs should be advanced.

Piezoelectric energy harvesting can be seen as a future of self-powered systems source. Although, the efficiencies are not sufficient the meet to requirements of minimum energy for devices, the desired electricity could be obtained with the advancements of piezoelectric materials and the storage elements.

Acknowledgements

Author[1] was supported by Faculty of Engineering and Natural Sciences Master Program at Sabanci University.

References

[1] Li S., Lipson H., (2009) " Vertical-Stalk Flapping-Leaf Generator For Parallel Wind Energy Harvesting", *Proceedings of the ASME/AIAA 2009 Conference on Smart Materials, Adaptive Structures and Intelligent Systems*, SMASIS2009.
[2] Umeda, M., Nakamura, K., and Ueha, S., “Analysis of Transformation of Mechanical Impact Energy to Electrical Energy Using a Piezoelectric Vibrator,” *Japanese Journal of Applied Physics*, Vol. 35,Part 1, No. 5B, 3267–32731996,.
[3] Ping-Ho Chen, Sheam-Chyun Lin, "Wind-Powered Piezo Generators", *Industrial Electronics Society, 2007. IECON 2007. 33rd Annual Conference of the IEEE* , pp.2163-2168, 5-8 Nov. 2007
[4] Matthew Bryant, Ephrahim Garcia, “Modeling and Testing of a Novel Aeroelastic Flutter Energy Harvester*”, J. Vib. Acoust.* 133, 011010 (2011)
[5] Sodano, H. A., Inman, D. J. and Park, G., 2005, “Comparison of piezoelectric energy harvesting devices for recharging batteries” *J. Intell. Mater. Syst. Struct.,* 16 799–807.
[6] Sang-Hyo Kim, Jin-Hee Ahn, Ha-Min Chung and Hyung-Won Kang, “Analysis of piezoelectric effects on various loading conditions for energyharvesting in a bridge system”, *Sensors and Actuators A: Physical*, Volume 167, Issue 2, June 2011, Pages 468-483 Solid - State Sensors, Actuators and Microsystems Workshop
[7] Oh, S. J., Han, H. J., Han, S. B., Lee, J. Y. and Chun, W. G. (2010), “Development of a tree-shaped wind power system using piezoelectric materials”, *International Journal of Energy Research*, 34: 431–437.
[8] Tan, Y.K., Panda, S.K, Novel Piezoelectric Based Wind Energy Harvester for Low-power Autonomous Wind Speed Sensor", *Industrial Electronics Society, 2007. IECON 2007. 33rd Annual Conference of the IEEE*, pp.2175-2180, 5-8 Nov. 2007
[9] Schmidt, V.H.; , "Piezoelectric energy conversion in windmills", *Ultrasonics Symposium, 1992. Proceedings., IEEE 1992* , pp.897-904 vol.2, 20-23 Oct 1992
[10] Priya, S., “Modeling of Electric Energy Harvesting using piezoelectric windmill”, *Appl. Phys. Lett.* 87, (*2005)*
[11] Priya, S.; Chen, C.; Fye, D.; Zahnd, J.; “Piezoelectric Windmill: A Novel Solution to Remote Sensing”, *Jpn. J. Appl. Phys. 44 (2005),* pp. L104-L107
[12] Hyung-Kwan Chang, Daejoong Kim, Jungyul Park, "Design and analysis of portable loadless wind power source for ubiquitous sensor network"*, 2010 The 2nd International Conference on Computer and Automation Engineering (ICCAE)*, vol.5, pp.93-96, 26-28 Feb. 2010
[13] Yung Ting, Chi-Yuan Chang, Gunawan, H., "Circuitry design for direct wind energy harvest system" *, 2010 IEEE International Symposium on Industrial Electronics (ISIE)*, pp.694-699, 4-7 July 2010
[14] Ju Hyun Yoo; Jae Il Hong; Chang Yub Park; , "Characteristics of piezoelectric fans using PZT ceramics" *, Proceedings of the 5th International Conference on Properties and Applications of Dielectric Materials, 1997*, vol.2, pp.1075-1081 vol.2, 25 -30 May 1997

[15] Myers, R., Vickers, M., Kim, H., Priya, S., "Small scale windmill", *Applied Physics Letters*, vol.90, no.5, pp.054106-054106-3, Jan 2007

[16] Chih-Ta Chen, Islam, R.A.; Priya, S., "Electric energy generator", *IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control*, vol.53, no.3, pp.656-661, March 2006

[17] Hyeoungwoo Kim; Priya, S.; Stephanou, H.; Uchino, K.; , "Consideration of Impedance Matching Techniques for Efficient Piezoelectric Energy Harvesting," Ultrasonics, Ferroelectrics and Frequency Control, IEEE Transactions on , vol.54, no.9, pp.1851-1859, September 2007

[18] So-Nam Yun, Young-Bog Ham, Jung-Ho Park, "Energy harvester using PZT actuator with a cantilver" *ICCAS-SICE, 2009* , pp.5514-5517, 18-21 Aug. 2009

[19] Robbins, W. P., Morris, D., Marusic, I., and Novak, T. O., 2006, “Wind-Generated Electricity Using Flexible Piezoelectric Materials”, *Proceedings of IMECE 2006*, Vol. 71, pp. 581–590.

[20] De Marqui, C., Jr., Erturk, A., and Inman, D. J., 2010, “Piezoaeroelastic Modeling and Analysis of a Generator Wing With Continuous and Segmented Electrodes”, *J. Intell. Mater. Syst. Struct.*, 21, pp. 983–993.

[23] Uchino, K., 1996 Piezoelectric Actuators and Ultrasonic Motors (Deventer: Kluwer)

[24] Arnau, A., 2003 Piezoelectric Transducers and Applications (Springer)

[25] Cheng Luo, Hofmann, H.F., "Wideband energy harvesting for resonant piezoelectric devices," *Energy Conversion Congress and Exposition (ECCE), 2010 IEEE*, pp.4171-4178, 12-16 Sept. 2010

[26] Tan, Y.K.; Lee, J.Y.; Panda, S.K.; , "Maximize piezoelectric energy harvesting using synchronous charge extraction technique for powering autonomous wireless transmitter", *IEEE International Conference on Sustainable Energy Technologies, 2008. ICSET 2008.*, pp.1123-1128, 24-27 Nov. 2008

[27] Qiu, J.H.; Ji, H.L.; Shen, H.; , "Energy harvesting and vibration control using piezoelectric elements and a nonlinear approach," *ISAF 2009. 18th IEEE International Symposium on the Applications of Ferroelectrics, 2009.*, pp.1-8, 23-27 Aug. 2009

[28] Li Tianze; Zhang Xia; Jiang Chuan; Hou Luan; , "Analysis of the characteristics of piezoelectric sensor and research of its application," *ISAF 2009. 18th IEEE International Symposium on the* , *Applications of Ferroelectrics, 2009.* vol., pp.1-4, 23-27 Aug. 2009.

[29] Rödig T., Schönecker A., “A Survey on Piezoelectric Ceramics for Generator Applications”, J. Am. Ceram. Soc., 93 [4] 901–912 (2010).

[30] Sodano H. A, Inman D. J. and Park G., 2004, “A review of power harvesting from vibration using piezoelectric materials” *Shock Vib. Digest* 36 197–205.

[31] Rocha, J.G.; Goncalves, L.M.; Rocha, P.F.; Silva, M.P.; Lanceros-Mendez, S.; , "Energy Harvesting From Piezoelectric Materials Fully Integrated in Footwear," *IEEE Transactions on Industrial Electronics*, vol.57, no.3, pp.813-819, March 2010.