UNIVERSITY OF EDUCATION, WINNEBA

DESIGN OF PIEZOELECTRIC POWER SUPPLY UNIT FROM AIR TRAFFIC SYSTEM

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DESIGN OF PIEZOELECTRIC ENERGY HARVESTER FROM AIR TRAFFIC SYSTEM

BY

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MAY, 2022

DECLARATION

STUDENT’S DECLARATION

I, KWASI DOGBE declare that this dissertation, with the exception of quotations and references contained in published works which have all been identified and duly acknowledged, is entirely my own original work, and it has not been submitted, either in part or whole, for another degree in the University or elsewhere.

SIGNATURE: ………………………. DATE: ……………………………….

SUPERVISOR’S DECLARATION

I hereby declare that the preparation and presentation of this work was supervised in accordance with the guidelines for supervision of thesis/dissertation/project as laid down by the University of Education, Winneba.

PROF. HUMPHREY DANSO

Signature ………………………… Date: ……………………………

DEDICATION

This project work is dedicated to the Almighty God who gave strength and wisdom to come out with this dissertation.

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First to my industrious supervisor, Prof. Humphrey Danso, a competent lecturer at University of Education, Kumasi campus who made the relevant corrections, suggestions and objections on every portion of this piece of this work. His firm effort and directives made this work a success. I also acknowledge the head of electrical department University of Education, Dr. Albert Kotawoke Awopone Kumasi campus for his great immeasurable support.

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ABSTRACT

This dissertation describes an approach to harvesting electrical energy from a mechanically excited piezoelectric element. A power supply unit is designed from electrical energy generated by the piezoelectric harvester through various stages to producing significant output voltage. The stages include piezoelectric generator, voltage doubler circuit and voltage regulator circuit. The piezoelectric crystal used in this design is 'Crystal Unit – HC 49/U 80MHz which is able to generate about 7.942fv and subsequently doubled to about 14.483fv. The voltage regulator ensures the output from voltage doubler is maintained constant. Experimental results reveal that voltage from the harvester was 82% by the voltage doubler. The results indicate the viability of the piezoelectric power supply unit when compared to conventional power supply unit of the same output range in the market. A stabilize piezoelectric power supply unit with output voltage of14.483fv, and a stabilized voltage of 14.483fv has been successfully designed.

CHAPTER ONE

INTRODUCTION

1.1 Background

Renato, (2014) defined Energy harvesting or energy scavenging as the process of extracting small amount of energy from ambient environment through various sources of energy. The available energy for harvesting is mainly provided by ambient light (artificial and natural lighting), ambient radio frequency, thermal sources and mechanical sources. Globally, the world is now looking for a sustainable, reliable and environmentally friendly sources of energy, however, Adnan, Kim and Renato (2011) came out with a report that, renewable and clean energy resources have become a demanded research area due to the problems facing energy shortage and environmental concerns using fossil fuel resources, and that the world electricity demand will increase by almost 80% during the period of 2012-2040 in the International Energy Agency's New Policies Scenario. Also, the IEA believes that clean energy revolution is an essential need for the world in order to break dependence on fossil fuels. Such a revolution would enhance global energy security, promote Continuance of economic growth and tackle environmental challenges such as climate change. It would break the long-standing link between economic growth and carbon dioxide (CO_2) emissions.

In fact, Kaajakari (2010), study shows that with the rapid development of microelectronic devices in military, medical, and civil applications, a traditional bulky battery can no longer meet the needs of advanced sensing technology due to its limited service life and difficulty in replacement. Hence, much attention should be place for research and development in sustaining the power requirement for autonomous wireless and portable devices.

Consequently, the viability of other sources of renewable energy have been exploited, and a number of studies Bontempi (2012) have examined the use of piezoelectric energy harvesting technology for a variety of purposes, including sensors. Also, Roswurm et al. (2011) suggested the use of the technology for roadway lighting by embedding the piezoelectric material into bridge bearings. In addition, (Ali, 2011; Xiong, 2012; Yu, 2013), investigated the application of the technology in structural health monitoring and finally (Ali, 2011; Xiong, 2012; Yu, 2013), also suggested in their works, that the technology could be used in traffic monitoring by embedding a piezoelectric material in pavements.

Even though most concerns on piezoelectric harvesting is the minimal amount of output power generated, but Jackson (2012) published a paper which indicates that converting ambient vibrations into electrical energy is possible using piezoelectric elements and therefore the energy can be stored and used to bias low power electronic devices. In a study which set out the voltage level that could be possibly generated by piezoelectric harvester, Ambrosio, (2001) found that the maximum output power produced by the piezoelectric system was 120 mW at the operating frequency of 40 Hz across a resistive load of 70 kΩ. The useful power was capable to bias some electronic devices. With references to previous works in the later shows that, Piezoelectric Energy harvesting from ultra sound energy (from aircraft) as a sustainable clean energy will be able to generate a usable electricity depending on the vibration from the air craft. And the most disappointing aspect of this phenomenon is that valuable energy is wasted in spite of its available clean source (air plane movement). So piezoelectric components planted in walls and floors at the airports can scavenge a reasonable amount of energy that can power electrical devices like sensors.

What has not been addressed in the previous works mentioned earlier, is to embed the piezoelectric materials in the airport buildings and subsequently design a power supply unit to power sensors at the airport. So, what this dissertation seeks to address, is to design a power supply unit using piezoelectric harvesting technology embedded in the building walls of an airport to generate substantial amount of electrical energy for sensors.

1.2 Problem Statement

Due to globalization and the high demand for energy and its effect on the environment, many have resorted to the use of harmful methods of harnessing energy resources which is inimical to the environment. Nonetheless, a lot of work have been done in this regard with the use of safe methods for harnessing energy resources including the use of solar energy, wind energy, hydro energy, piezoelectric energy etc. In considering piezoelectric energy harvesting, much works has been done (Elvin, 2001) on using the idea to develop pavement electric generators, shoe generators etc. what has also been discussed are the modes of piezoelectric crystal for the design of power supply units to power electronics devices.

Many of the works in the area of energy harvesting (Wang, 2014), particularly piezoelectric harvesting looks at the literature and the possibilities of using the technology to generate electrical energy from the application of vibration effect. Studying the possibility of generating energy through power floor tiles (Elhalwagy, 2017), suggested the possibility of using high generated power floor tiles arranged in the building spaces as a power source generator that can be used to operate LED lighting system, since LEDs use far less energy than conventional (fluorescent and incandescent) bulbs. Many of those who worked on using vibration to generate electrical energy through piezoelectric materials only limited themselves on only feasibility studies (Wang, 2014), but the gap this project work intends to fill is the fact those ideas are taken to the implementation stage by designing a power supply unit using the piezoelectric techniques.

Developing a compression-based roadway harvester (Jiang, 2014) studied and proposed that a piezoelectric material can be embedded into pavement to scavenge electrical energy from traffic induced vibration. With this when cars pass over pavements the vibration caused by the moving vehicle creates time variant forces on harvesting unit which generate electrical power. Considering a design of RF energy harvester, (Potey,2014) designed a system with a clock-based generator to convert the RF energy available in the atmosphere into useful electrical energy which can be used to charge a battery which requires a voltage in the range of 4-4.2v to get itself charged.

However, most limitation in previous works in the area of piezoelectric harvesting is about the literature and the hypothesis of the processes of electrical energy generation through embedding piezoelectric materials in pavements, roads, runways, bridges etc. the overall gaps this work seeks to cover is that, firstly instead the piezoelectric material is embedded in pavements, runways, roads, shoes etc. this work considers embedding the piezoelectric materials in the walls at the airport. In view of previous literature on piezoelectric energy harvesting as later discussed in this work, and what the present study seeks to contribute to knowledge is that, acoustic energy derived from the ultrasonic sound of airplanes is to be harvested by piezoelectric materials embedded in the building’s walls situated at the airport. But what this project intends to focus and compliment, is the use of vibration obtain from air craft to generate electrical energy for the design of power supply unit to power sensor devices.

1.3 Objectives of the studies

The main aim of this study was to investigate a sustainable power source using piezoelectric material to drive sensor devices. The specific objectives of this study are:

1. To design a power supply unit from a harvested electrical energy produced by piezoelectric effect to power low voltage sensor devices at airports.
2. To determine amount of voltage in volts(V) from a microvolts (μV) piezoelectric material for the design of power supply unit.
3. To access energy required to conserve the environment and reduce CO_2 emissions produced from other fuel recourses.

1.4 Significance of Study

This study was undertaken to understand the various stages and the operations of piezoelectric energy power supply design and determining its output values. More importantly, sectors benefiting from the study includes.

The academia, who are the recipients of the output of this research and specifically are the electrical and electronic engineering students and teachers in the field of study. Any improvement of piezoelectric harvesting technique can pave the way for establishing better understanding of power supply design.

The research benefits the policy makers who are ready to guide and advice the government and stakeholders in the areas of energy saving and efficiency. As a society with scarce resources in terms energy needs, formulating policies in addressing genuine and renewable energy harnessing sources are critical and essential.

This study will be very beneficial to the government that is ready to prioritize renewable energy harnessing and utilization for the safe of the environment and the reliability of energy resources.

The research will also benefit those people who plan to rely on renewable energy as a source of energy for utilization and also conscious of the environmental benefit that will be derived from the work.

The outcome of the study is beneficial to the neither present researchers or the future researchers. This study may be one of the bases that will serve as motivation for more learning to arise.

1.5 Structure of the Research

This research comprises six chapters. The first chapter gave a general orientation of the study. This contained the introduction, statement of the problem, objective of the research, specific objectives, justifying the research work and research question. Chapter two focuses on the review of related literature, the review involves theoretical and empirical studies related to the problem under study. Chapter three dealt with the research methods employed in the study. The chapter describes the research design, the population, sample and sampling procedures, and data gathering instrument, data collection and analysis of the study. In chapter four, the main focus is the presentation of results and findings. The outcome of the research is presented and explained in this chapter. In chapter five, significant findings are identified, presented and discussed. The discussion highlights the major findings of the research and the inferences made from them in view of findings from related previous studies. Finally, chapter six focuses on Summary of Findings, Conclusions and Recommendations, it includes suggestions for future research work.

CHAPTR TWO

LITERATURE REVIEW

This dissertation reviews energy harvesting technology from mechanical vibration. Recent advances on ultralow power portable electronic devices and wireless sensor network require limitless battery life for better performance. Energy is universally around us and the most significant part in energy harvesting is energy transducer. Piezoelectric materials have high energy conversion ability from mechanical vibration. A great amount of researches have been conducted to develop simple and efficient energy harvesting devices from vibration by using piezoelectric materials. Representative piezoelectric materials can be categorized into piezo-ceramics and piezo-polymers. This study reviews key ideas and performances of the reported piezoelectric energy harvesting from vibration. Various types of vibration devices, piezoelectric materials and mathematical modeling of vibrational energy harvestings are reviewed (Kim, Erturk and Yan 2011).

2.1 Energy Harvesting

Energy harvesting is defined as capturing minute amounts of energy from one or more of the surrounding energy sources, accumulating them and storing them for later use. Energy harvesting is also called as power harvesting or energy scavenging (Kim et al. 2011).

With recent advances on wireless and MEMS technology, energy harvesting is highlighted as the alternatives of the conventional battery (Thambi and Tudor 2008). Ultra-low power portable electronics and wireless sensors use the conventional batteries as their power sources, but the life of the battery is limited and very short compared to the working life of the devices. The replacement or recharging of the battery is inefficient and sometimes impossible. Therefore, a great amount of researches have been conducted about the energy harvesting technology as a self-power source of portable devices or wireless sensor network system.

In the view point of energy conversion, (Choi and Kim 2006) indicated that human beings have already used energy harvesting technology in the form of windmill, watermill, geothermal and solar energy. The energy came from natural sources, called renewable energy, is emerged as future power source due to limited fossil fuel and nuclear power instability such as Fukusima nuclear crisis. Since the renewable energy harvesting plants generate kW or MW level power, it is called macro energy harvesting technology. On the contrast, micro energy harvesting technology is focused on the alternatives of the conventional battery. Micro energy harvesting technology is based on mechanical vibration, mechanical stress and strain, thermal energy from furnace, heaters and friction sources, sun light or room light, human body, chemical or biological sources, which can generate mW or µW level power (Choi et al. 2006).

Kim et al. (2011) mentioned in their works that ince piezoelectric material can convert mechanical vibration into electrical energy with very simple structure, piezoelectric energy harvesting is highlighted as a self-power source of wireless sensor network system.

Piezoelectricity represents pressure electricity and is a property of certain crystalline materials such as quartz, Rochelle salt, tourmaline, and barium titanate that develop electricity when pressure is applied. This is called the direct effect, on the other hand, these crystals undergo deformation when an electric field is applied, which is termed as the converse effect. Converse effect can be used as an actuator and direct effect can be used as a sensor or energy transducer. The coupled electro-mechanical behavior of piezoelectric materials can be modeled by two linearized constitutive equations.

Direct piezoelectric effect:

$D_{i=}e_{ij}^{\sigma} + d_{im}^{d}\,\sigma_m$

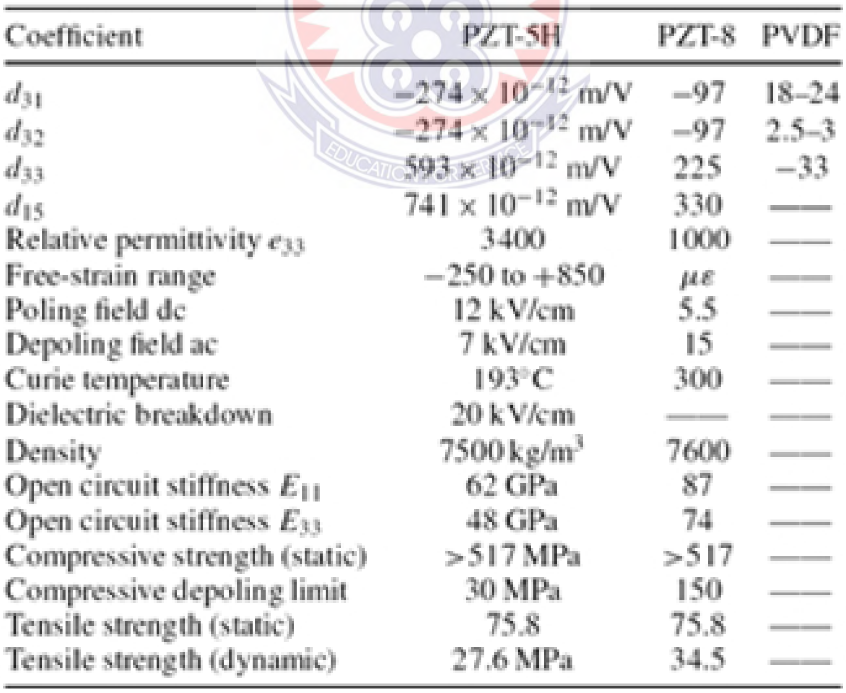
Converse piezoelectric effect:

$$\mathcal{E}_k = d^c_{jk}\, E_j + S^E_{km}\, \sigma_m$$

where vector D is the dielectric displacement in N/mV or C/m2, E_k is the strain vector, E_j is the applied electric field vector in volts/meter, and σ is stress vector in N/m2. The piezoelectric constants are the piezoelectric coefficients are d^c_{jk} and d^c_{jk} in m/V or C/N, the dielectric permittivitye^{σ}_{ij} in N/V2 or F/m, and S^E_{km} is the elastic compliance matrix in m^2/N. The superscripts c and d refer to the converse and direct effects, respectively, and the superscript σ and E indicate that the quantity is measured at constant stress and constant electric field, respectively.

Figure1. shows material characteristics of representative piezoceramics (PZT-5H, PZT-8) and piezopolymer (polyvinylidene fluoride, PVDF), Kim et al. (2011).

Table 1: Piezoelectric characteristics



Coefficient	PZT-5H	PZT-8	PVDF
d_{31}	-274×10^{-12} m/V	−97	18–24
d_{32}	-274×10^{-12} m/V	−97	2.5–3
d_{33}	593×10^{-12} m/V	225	−33
d_{15}	741×10^{-12} m/V	330	——
Relative permittivity e_{33}	3400	1000	——
Free-strain range	−250 to +850	$\mu\varepsilon$	——
Poling field dc	12 kV/cm	5.5	——
Depoling field ac	7 kV/cm	15	——
Curie temperature	193°C	300	——
Dielectric breakdown	20 kV/cm	——	——
Density	7500 kg/m^3	7600	——
Open circuit stiffness E_{11}	62 GPa	87	——
Open circuit stiffness E_{33}	48 GPa	74	——
Compressive strength (static)	>517 MPa	>517	——
Compressive depoling limit	30 MPa	150	——
Tensile strength (static)	75.8	75.8	——
Tensile strength (dynamic)	27.6 MPa	34.5	——

Representative piezoelectric materials can be categorized into piezoceramics and piezopolymers. Piezoceramics have large electro-mechanical coupling constants and provide high energy conversion rate, but they are too brittle to use general shape energy transducer. On the other hand, piezopolymers have smaller electro-mechanical coupling constants compared to the piezoceramics, but they are very flexible. Figure 1. shows material characteristics of representative piezoceramics (PZT-5H, PZT-8) and piezopolymer (polyvinylidene fluoride, PVDF).

Based on direct piezoelectricity, Tudor et al. (2006) conducted research on piezoelectric energy harvesting from mechanical vibration and came out with various types which include electrostatic, electromagnetic and piezoelectric. Figure 2. Illustrate the comparison between the three types of mechanical energy converters with respect to their energy density.

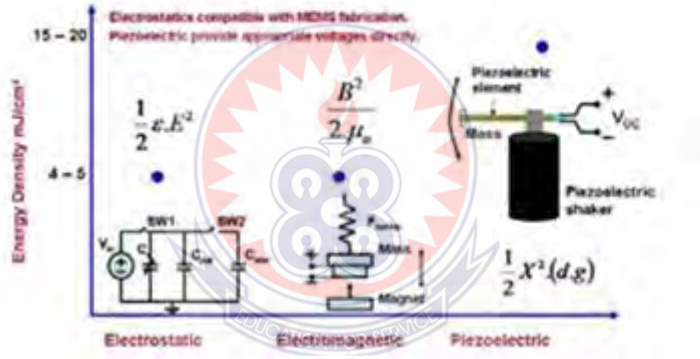


Figure 1: Comparison of the energy density for the three types of mechanical energy converters. (Tudor et al. 2006).

Yang (2009) proposed parasitic power harvesting from piezoelectric shoes using unimorph strip made from piezoceramic composite material and a stave made from a multilayer laminate of PVDF foil that periodically broadcasts a digital RFID as the bearer walks (Figure. 3). (They further explored the harnessing of parasitic energy from piezoelectric shoes and used simple mechanical structures and flexible piezoelectric materials which results a comfortable piezoelectric shoe design (Figure 3). (Shenck et al. 2001)

Figure 4. shows the compression and contraction strain along the axis of 31mode 33 mode of a PZT material. Its further explored the harnessing of parasitic energy from piezoelectric shoes and used simple mechanical structures and flexible piezoelectric materials which results a comfortable piezoelectric shoe design.

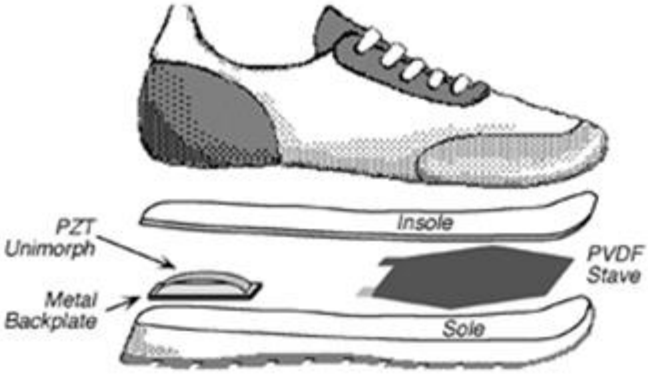
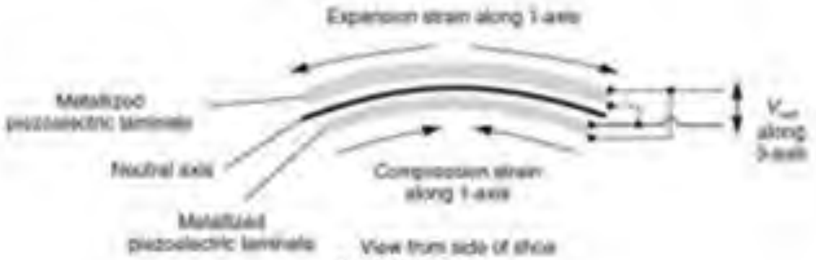


Figure 2: Exploded view showing integration of piezo shoe. (Paradiso et al. 1998)

(a) 31-Mode



(b) 33-Mode

(c) Compression strain along 3-axis

Figure 3: Conventional axis definition for a PZT material. (Shenck et al. 2001)

2.2 Types of Harvesters

2.2.1 Cantilever Type

A cantilever type vibration energy harvesting has very simple structure and can produce a large deformation under vibration. (Flynn, 2002) imposed fundamental limitations on PZT (lead zirconate titanate) material and indicated that mechanical stress limit is the effective constraint in typical PZT materials. They reported that a mechanical stress-limited work cycle was 330W/cm3 at 100 kHz for PZT-5H.

(Elvin, 2001) proposed a theoretical model by using a beam element and performed experiment to harvest power from PZT material. They showed that a simple beam bending can provide the self-power source of the strain energy sensor.

Wright, (2003) presented series of vibrational energy harvesting devices. First, they indicated low-level vibrations occurring in common household and office environments as a potential power source and investigated both capacitive MEMS and piezoelectric converters. Wright, Wan, and Elvin (2003) simulated results showed that power harvesting using piezoelectric conversion is significantly higher.

They optimized a two-layer cantilever piezoelectric generator and validated by theoretical analysis **(**Figure. 5**)** Roundy and Inman (2019). They also modeled a small cantilever-based devices using piezoelectric materials that can scavenge power from low-level ambient vibration sources and presented new design configuration to enhance the power harvesting capacity. It used axially compressed piezoelectric bimorph in order to decrease resonance frequency up to 24%.

They found that power output to be 65-90% of the nominal value at frequencies 19-24% below the unloaded resonance frequency.

Inman et al. (2006) presented more than 10 papers related to vibrational energy harvesting using PZT, bimorph Quick Pack (QP) actuator and micro fiber composite (MFC). Sodano et al. (2003) investigated monolithic piezoelectric (PZT) and MFC and estimated the efficiency of both the materials. They also investigated three types of piezoelectric devices experimentally, a monolithic PZT, bimorph QP and MFC energy harvesting devices to determine their capacity to recharge a discharged battery.

Shen et al. (2014) proposed a PZT piezoelectric cantilever with a micro machined Si proof mass for a low frequency vibration energy harvesting application. The average power and power density were 0.32 W and 416 W/cm3. Liu, Fang, Mao and Shen (2008) developed an array of power generator based on thick-film piezoelectric cantilevers in order to improve frequency flexibility and power output. They reported an improved performance of 3.98 mW effective electrical power and 3.93 DC output voltage to resistance load. Choi et al. (2006)

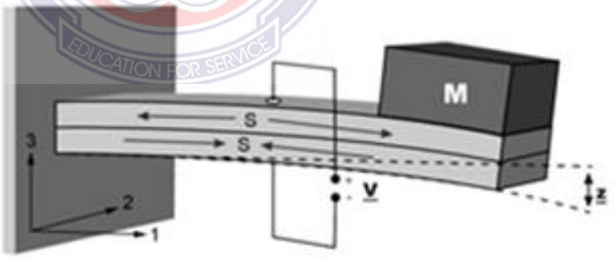


Figure 4: Two-layer bender as a cantilever. (Shen et al, 2002)

Choi, Kim and Jeon (2006) developed an energy harvesting MEMS device using thin film PZT to enable self-supportive sensors. Resonating at specific frequencies of an external vibrational energy source can create electrical energy via the piezoelectric effect. The effect of proof mass, beam shape and damping on the power generating performance were modeled to provide guideline for maximum power harvesting from environmentally available low frequency vibrations.

2.2.2. Cymbal type

Cymbal structure can produce a large in-plane strain under a transverse external force, which is beneficial for the micro energy harvesting. Kim et al. (2005) reported that piezoelectric energy harvesting showed a promising result under pre-stress cyclic conditions and validated the experimental results with finite element analysis. Li et al. (2011) presented a two ring-type piezoelectric stacks, one pair of bow-shaped elastic plates, and one shaft that pre-compresses them **(Figure. 6)**. They reported that flex-compressive mode piezoelectric transducer has the ability to generate more electric voltage output and power output as compared to conventional flex-tensional mode.

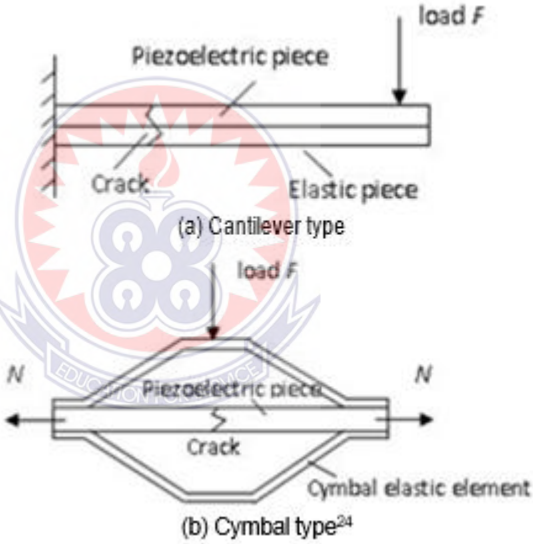


Figure 5: conventional piezoelectric energy harvester. (Li et al, 2011)

2.2.3. Stack Type

Stack type piezoelectric transducer can produce a large electrical energy since it uses d33 mode of piezoelectric materials and has a large capacitance because of multi-stacking of piezoelectric material layers. Adhikari et al. (2009) proposed a stochastic approach using stack configuration rather than cantilever beam harmonic excitation at resonance and analyzed two cases, with inductor in the electrical circuit and without inductor.

Lefeuvre, Badel and Brend (2006) proposed a synchronized switch damping (SSD) in vibrational piezoelectric energy harvesting **(Figure. 6)**. They claimed that SSD increases the electrically converted energy resulting from the piezoelectric mechanical loading cycle. This stack type can be weak under mechanical shocks.

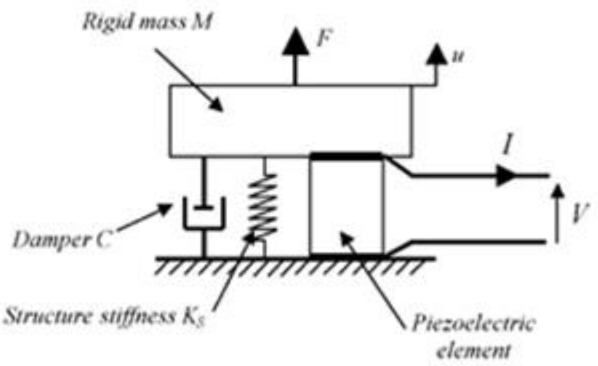


Figure 6: Model of a vibrating structure including a piezoelectric element. (Lefeuvre et al. 2006)

2.2.4. Shell Type

Since shell structure can generate larger strain than flat plate, it can improve the efficiency of piezoelectric energy harvesting. Yoon et al. (2005) employed a curved piezoceramic to increase the charge because of mechanical strain **(Figure 7.)**. They optimized the analytical model using shell theory and linear piezoelectric constitutive equations to develop a charge generation expression. Yoon et al. (2008) investigated a ring-shaped PZT-5A element exposed to gunfire shock experimentally using pneumatic shock machine. They found dependence of piezoelectric constant on load-rate, the shock-aging of piezoelectric effect, and the dependence of energy-transfer efficiency on the change in normalized impulse.

Chen et al. (2006) analyzed circular piezoelectric shell of polarized ceramics under torsional vibration to harvest electric output. The proposed structure harvested electrical energy from torsional vibration.

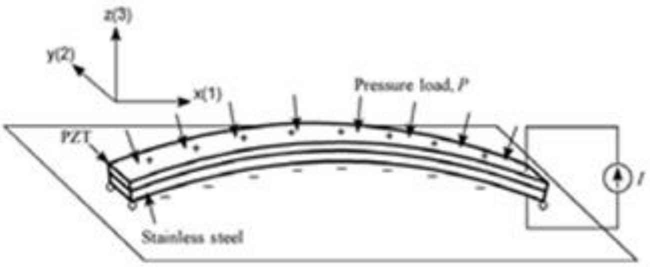


Figure 7: Curved PZT unimorth excited in d31-mode by a normal distributed force. (Chen et al. 2006).

2.2.5 Modeling and Theory

Theoretical modeling of piezoelectric energy harvesting devices should include not only its structure but also piezoelectric coupling effect as well as electrical behavior. Erturk and Inman (2008) proposed an improved mathematical model and made an attempt to correct the oversimplified issues related to mathematical formulation like piezoelectric coupling, physical modeling, low fidelity models and base motion modeling. They also proposed correction factors for single degree of freedom base excitation model and examined that the single degree of freedom harmonic base excitation relations which are commonly used by a number of researchers for harvesting energy using mechanical vibration.

They also reported a closed-form analytical solutions of bimorph cantilever configurations with series and parallel connections of piezoceramic layers. Marqui et al. (2009) presented an electromechanically coupled finite element (FE) plate model based on Kirchhoff plate assumptions that also account the effect of conductive electrodes to predict the electrical power output of piezoelectric energy harvester plates. The FEA simulation results are validated with the experimental and analytical solution for a unimorph cantilever beam. Renno et al. (2009) optimized the piezoelectric vibration-based energy harvester by using an inductor and a resistive load and it is concluded that the addition of an inductor in the circuit enhances the power harvesting capacity. Pouline, Oshman and Camara (2004) compared an electromagnetic system made of a magnet in translation within a coil and piezoelectric system which is a PZT ceramic bar embedded at one end and constrained at the other end. They predicted a strong similarity and duality in signal level. Ajitsaria et al. (2007) anticipated analytical approach based on Euler-Bernoulli beam theory and Timoshenko beam equations for the generation of voltage and power. They showed that the comparison between the experimental results and simulation were satisfactory.

Hu et al. (2007) proposed a modeling of a piezoelectric harvester as an integrated electro-mechanical system, by characterizing the interaction between the harvesting structure and the storage circuit with a nonlinear rectifier. They showed that the power density can be maximized by varying the non-dimensional inductance for a fixed non-dimensional aspect ratio together with a fixed non-dimensional end mass. Shu and Lien (2006) calculated the energy conversion efficiency under steady state condition for a rectified piezoelectric power harvester. They found that optimization criteria depend upon the relative strength of the electromechanical coupling.

Marzencki, (2009) proposed a passive, wideband adaptive system by employing mechanical nonlinear strain stiffening. They reported experimentally verified frequency adaptability of over 36% for a clamped-clamped beam device at 2 g input acceleration. They claimed that the proposed solution was perfectly suited for autonomous industrial machinery surveillance systems, where high amplitude vibrations are abundant. Dietl and Wickenheiser (2010) proposed a Timoshenko model of transverse piezoelectric beam to overcome the over predicted parameter values in Euler-Bernoulli beam models. They reported the exact expressions for the voltage, current, power, and tip deflection of the piezoelectric beam. They also optimized the shapes of beam for harvesting power using heuristic optimization code and the attributes of this optimal beam was validated with the experimental results.

Gammaitoni, (2010) modeled piezoelectric harvesting oscillator dynamics with nonlinear Gao et al. (2010) analyzed a piezoelectric unimorph cantilever with unequal piezoelectric and no piezoelectric lengths for vibration energy harvesting theoretically. They found that for a fixed vibration frequency, the maximum open circuit induced voltage occurred when nopiezoelectric-to-piezoelectric length ratio is greater than unity while the maximum power occurred when nonpiezoelectric-to-piezoelectric length ratio is unity.

Knight et al. (2011) presented a guideline to extract an optimal energy harvesting for interdigitated piezoelectric MEMS unimorph cantilever beams. They showed that poling behavior was the key factor to investigate the real losses associated with non-uniform poling. A parametric study in terms of electrode patterns, piezoelectric layer dimensions, and electrode dimensions was carried out to examine their effect on the percent poling factor.

They proposed design guidelines to help ensure that piezoelectric MEMS devices are developed to obtain optimum energy harvesting or tuning performance. Ly et al. (2011) developed a piezoelectric cantilever bending model of 31-effect under the assumption of the Euler-Bernoulli Beam Theory. The equations of motion for the global system were established by using Hamilton’s principle and solved by using the modal decomposition method. They provided the mathematical model to enhance the conversion of mechanical energy into electrical energy by using direct piezoelectric effect. They showed that second mode of resonant frequency provided the voltage and the bandwidth much larger than the first mode. Richards et al. (2004) emphasized on the efficiency of power conversion and developed a formula to predict the power conversion efficiency of different piezo generators.

2.2.6 Single Crystal

Erturk et al. (2008) analyzed single crystal piezoelectric ceramic lead magnesium niobate-lead zirconate titanate (PMN-PZT) power generation and shunt damping performance with the help of experiment and validated the results analytically. Karami et al. (2011) examined different configuration of three types of piezoelectrics (single crystal PMN-PZT, polycrystalline PZT-5A, and PZT-5H-type monolithic ceramics) in a unimorph cantilevered beam to find the best design configuration for lightweight energy harvesting devices for low-power applications. They concluded that single-crystal energy harvesters produced superior power compared with polycrystalline devices.

Rakbamrung, (2010) attempted performance comparison between two common piezoelectric compositions, PZT + 1 mol% Mn and PMN-25PT, obtained from sintering piezoelectric powders. The PMN-PT showed higher coupling coefficient than the PZT-based sample, making such a composition a better choice for energy harvesting purposes at a first glance. Although PMN-PT-based harvester effectively allowed harvesting approximately twice the power of PZT-based device when using a classical electrical interface, the use of a nonlinear approach for enhancing the conversion abilities of piezoelectric elements dramatically reduced the difference between the considered micro-generators.

Bedekar et al. (2010) fabricated piezoelectric bimorph samples using conventional piezoceramic processing methods corresponding to high energy density piezoelectric composition 0.9Pb (Zr0.56 Ti0.44) O3-0.1Pb [(Zn0.8/3Ni0.2/3) Nb2/3] O3 + 2mol% MnO2(PZTZNN) and 0.8 [Pb (Zr0.52Ti0.48) O3]-0.2[Pb (Zn1/3 Nb2/3) O3] (PZTPZN). They concluded that power harvesting largely depended upon piezoelectric strain constant and the piezoelectric voltage constant. Ren et al. (2010) presented a multilayer structure used as the resonance-based vibration energy-harvesting device based on 0.71Pb (Mg1/3 Nb2/3) O3-0.29PbTiO3 (PMN-PT) single crystal. They found a high output power of 4.94 mW and a corresponding peak voltage of 3.14 V measured at 1.4 kHz which highlighted the potential of the material for energy harvesting. Moon et al. (2009) presented the piezoelectric energy harvesting performance of a Zr-doped PbMg1/3Nb2/3O3-PbTiO3 (PMN-PZT) single crystal beam. The energy harvesting capability of a PMN-PZT beam cantilever structure under a state of vibration was calculated and compared with experimental result of frequency response of cantilever device.

2.2.7 New Materials

Jeong et al. (2011) investigated piezoelectric ceramics with microstructure texture experimentally prepared by tape casting of slurries containing a template SrTiO3 (STO), under external mechanical stress. They concluded that STO-added specimens showed excellent power over the STO-free specimen when a high stress was applied to the specimen. Elfrink et al. (2009) analyzed aluminum nitride (AlN) as a piezoelectric material for piezoelectric energy harvesters because of their high resulting voltage level. They reported a maximum output power of 60 µW for an unpackaged device at an acceleration of 2.0 g and at a resonance frequency of 572 Hz.

Tien and Goo55 analyzed a piezocomposite composed of layers of carbon/epoxy, PZT ceramic and glass/epoxy to harvest energy **(Figure 8.)**. They reported that piezocomposite have potential to harvest energy subjected to vibration after numerical and experimental validation.

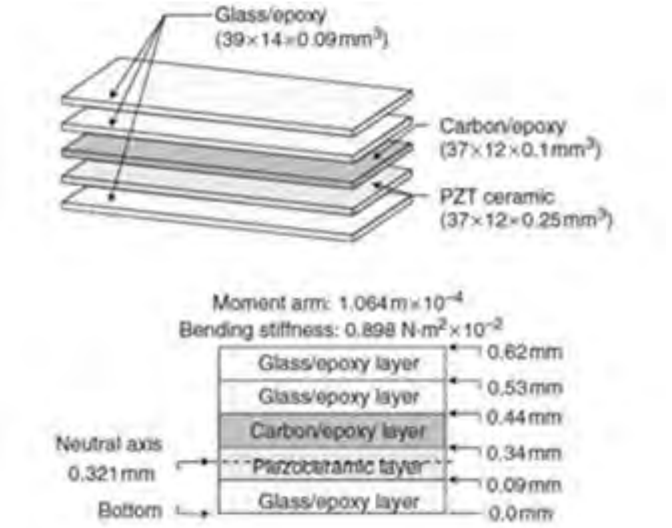


Figure 8: Geometry and position of the neutral axis of PCGE-A (Elfrink et al. 2009)

2.2.8 Others

Fang et al. (2006) proposed micro piezoelectric power generator containing a composite cantilever with nickel metal mass. They fabricated the proposed device by RIE dry etching, wet chemical etching and UV-LIGA. The proposed generator produced about 0.89V AC peak-peak voltage output to overcome germanium diode rectifier toward energy storage, and its power output was in microwatt level of 2.16 mW. Twiefel et al. (2008) investigated the piezoelectric flexural transducers for harvesting power experimentally. They employed working frequency and electrical load as boundary conditions for the development of the generator in analytical model.

Isarakorn et al. (2011) focused on the fabrication and evaluation of vibration energy harvesting devices by utilizing an epitaxial PZT thin film. The experimentally investigation and analytical calculations were compared and the epitaxial PZT harvester exhibited high power and current with usable voltage. These results indicated the potential of epitaxial PZT thin films for the improvement of the performances of energy harvesting devices.

In summary, many configurations of energy harvesting devices made with piezoceramics have been developed to improve the efficiency and power generation. Modeling of the piezoceramic energy harvesting devices is well established. Single crystal piezoelectric materials are promising for energy harvesting since it has high coupling coefficients.

2.2.9 Energy Harvesting with Piezopolymers

Mateu and Moll (2005) analyzed several bending beam structures using piezo films suitable for shoe inserts and walking-type excitation, and obtained the resulting strain for each type in function of geometrical parameters and material properties. By comparing the energy harvested, the optimum configuration can be determined. They developed piezoelectric film inserts inside a shoe based on their first work **(Figure 9.)**. Mateu et al. (2006) In their paper, they analyzed different factors, such as piezoelectric type, magnitude of excitation, required energy and voltage, and magnitude of the capacitor, to find an appropriate choice of storage capacitor and voltage intervals.

Figure 9: A piezoelectric film-based power generator. (Mateu et al. (2006)

Farinholt et al. (2007) developed a novel energy harvesting backpack that can generate electrical energy from the differential forces between the wearer and the backpack by using PVDF **(Figure. 9)**. They also proposed an energy harvesting comparison of PVDF and the ionically conductive ionic polymer transducer to examine the effectiveness of electro-mechanical conversion properties.62 Analytical models using spring-mass-damper for each material assuming axial loading and simulation results were compared with experimental results.

Figure 10: Schematic of the backpack with piezoelectric straps. (Farinholt et al. 2007)

Kuwano et al. (2011) used AlN thin films on Si substrates with diverse bottom electrode materials of Pt/Ti, Au/Cr, Al, and Ti to fabricate micro-generators by the micromachining process for converting environmental vibration energy into electric energy **(Figure. 11)**. They also studied the effect of the air damping on the vibration of energy harvesting PVDF generators in three measurement conditions. They found that the output power of generators ‘‘unpackaged in vacuum’’ was almost twice that of generators ‘‘packaged in air’’ at 0.5g acceleration. And also with the increase in vibration acceleration, the output power of generators ‘‘unpackaged in vacuum’’ rapidly increased in a quadratic relationship with the acceleration at low acceleration level, and then the increasing ratio decreased at high acceleration.

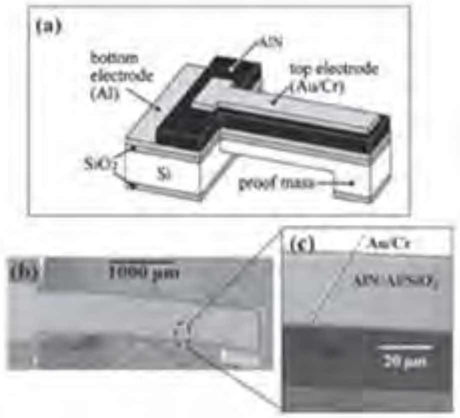


Figure 11: (a) schematic view, (b) general FE-SEM image, and (c) lateral FE-SEM image of A1N microgenerator. (Lallart et al. 2010)

Lallart et al. (2010) evaluated that energy scavenging abilities of electrostrictive terpolymer composite filled with 1 vol% carbon black poly (vinylidene - fluoride - trifluoroethylene - chlorofluoroethylene). They also demonstrated that the carbon-filled terpolymer outperformed other investigated compositions, exhibiting a figure of merit as high as 2000 times higher than pure polyurethane. They extended their work to the ac-dc conversion for energy harvesting using electrostrictive polymer P(VDF-TrFE-CFE) to make the practical application of such material for self-powered devices more realistic.66 Their theoretical and experimental analysis showed that an energy harvesting module with ac-to-dc conversion using a bias electric field of 10V/µm and a transverse strain of 0.2% is much more efficient than most of piezo-based harvesters.

Shah et al. (2010) compared micropower obtained by harvesting generators using piezoelectric ceramic (PZT), PVDF (polyvinylidene fluoride) membrane and PP (polypropylene) foam polymer. They also evaluated the voltage response of ceramic based piezoelectric fiber composite structures (PFCs) and polymer based piezoelectric strips, PVDF, when subjected to various wind speedsand water droplets in order to investigate the possibility of energy generation from these two natural renewable energy sources for utilization in low power electronic devices.68 They showed that piezoelectric polymer materials can generate higher voltage/power than ceramic based piezoelectric materials and it was possible to produce energy from renewable sources such as rain drops and wind by using piezoelectric polymer materials.

Sohn et al. (2003) adopted FEM to evaluate the power harvesting capacity of piezofilm that were under the action of a blood pressure and analyzed theoretically for square and circular configuration. Hu et al. (2008) proposed a corrugated PVDF bimorph power harvester with the harvesting structure fixed at the two edges in the corrugation direction and free at the other edges. In order to keep the harvester operating at the optimal state, they adjusted the resonant frequency by changing the geometrical configuration or the span length. They reported that the adaptability of a harvester to the operating system could be improved greatly by designing the harvesting structure with adjustable resonant.

Liu et al. (2009) presented an active energy harvesting approach which used switch-mode power electronics to control the voltage and/or charge on a piezoelectric device relative to the mechanical input for optimized energy conversion. In these experiments, the active energy harvesting approach increased the harvested energy by a factor of five for the same mechanical displacement compared to an optimized diode rectifier-based circuit. Chang et al. (2010) used near-field electrospinnings to direct-write PVDF nanofibers with in situ mechanical stretch and electrical poling characteristics to produce piezoelectric properties **(Figure. 12)**. They found that under mechanical stretching, nanogenerators showed repeatable and consistent electrical outputs with energy conversion efficiency, an order of magnitude higher than those made of PVDF thin films.

Hansen et al. (2010) developed hybrid energy scavenging device consisted of a piezoelectric PVDF nanofiber generator for harvesting biomechanical and biochemical energy. They found that two type of energy harvesting worked simultaneously or individually, thereby boosting output and life time.

Miyabuchi et al. (2011) modeled the piezoelectric vibration energy harvester and found that the figure of merit was proportional to the square of the effective transverse piezoelectric coefficient e31.They measured e31 coefficient by using the substrate bending method and found that it increased with increasing strain, which was favorable for vibration energy harvesting. Chang et. al (2011) modeled and analyzed Piezo-elastic+ energy harvester in computer hard disk drives. Numerical finite element simulations and laboratory measurements showed that about 25% of the power consumed by disk drive's voice coil motor could be harvested by the proposed design. He suggested the possibility of scavenging and converting flex cable's mechanical vibrations and dynamics into electrical form for power conservation inside computer hard disk drives.

Liu et al. (2011) proposed a miniature energy harvesting device for medical microrobot devised working in blood vessel, specifically focusing on fabrication of co-axial nanofibers as converting components from a high efficient piezoelectric material PVDF. Oh et al. (2010) demonstrated an experimental investigation of a tree-shaped wind power system using piezoelectric material. PVDF was used to make the leaf element, whereas PZT was applied to the trunk portion of the tree requiring rather strong winds to generate any power.

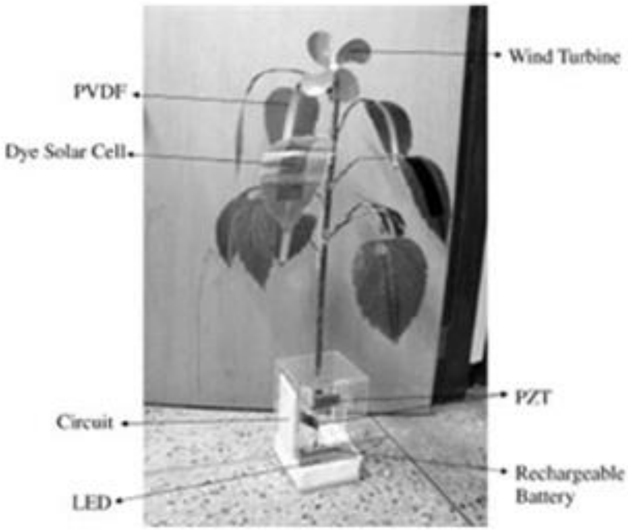


Figure 12: A prototype tree-shaped wind power system. (Li et al. 2011)

Koyama and Nakamura (2010) studied electric power generation using vibration of a polyuria thin film. The conversion efficiency from mechanical to electrical energy was calculated by using finite element analysis of the cantilever configuration. Higher conversion efficiency was obtained using a thinner and shorter cantilever configuration with increased resonance frequency. Li et al. (2011) proposed a bioinspired piezo-leaf architecture which was in dangling cross-flow stalk that converted wind energy into electrical energy by wind-induced fluttering motion **(Figure. 13)**. This kind of architecture amplified the vibration by an order of magnitude compared with conventional flow-parallel fluttering devices.

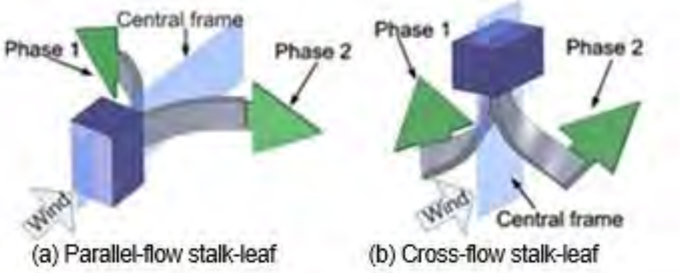


Figure 13: Motion sketch of two different structures. (Li et al. 2011)

Akaydin et al. (2010) investigated flexible piezoelectric cantilever beams placed inside turbulent boundary layers and wakes of circular cylinders at high Reynolds numbers and developed three-way coupled interaction simulation to validate the experimental results **(Figure. 14)**.

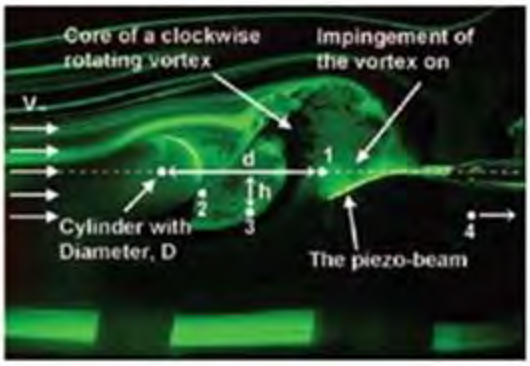


Figure 14: A schematic diagram of the piezoelectric generator in a flow field and the concept of placing an elastic beam into the vortex street to induce vibration. (Akaydin et al. 2010)

In summary, the use of piezopolymers for vibrational energy harvesting is advantageous since piezopolymers are ductile, resilient to shock, deformable and lightweight. The applications of piezopolymer based energy harvesters for wind, backpack and flower demonstrate its possibility in real life. Recently developed piezopaper based on cellulose may be another possibility for energy harvesting. Springer (2011).

2.2.9. Energy Harvesting Circuit

The optimized method of vibrational energy harvesting with piezoelectric materials is very essential to develop a scavenging energy device. In nature, vibrational piezoelectric energy harvesting devices is based on the induced power from mechanical vibrations with varying amplitude, resulting induce output voltage with alternating current (AC) from the piezoelectric elements. Early attempt to utilize the piezoelectric energy harvester, power production must be designed with a rectifier. Many different rectifiers have been suggested and studied: e.g. vacuum tube diodes, mercury arc valves, silicon based switches and solid state diodes. However, the simplest way to rectify the alternating input is to connect the piezoelectric harvester with a P-N junction diode which can work only in half input wave. Dimitrijev et al. (2006). To obtain full-wave rectification of vibrating piezoelectric device, a bridge-type with 4 diodes is required. In order to improve power harvesting circuit efficiency, there are many attempts to modify the rectifying circuit.

Using a buck-boost DC-DC converter which can track the power generator's dependence with acceleration and vibration frequency of piezoelectric device, the high efficiency of 84% was reported. Lefeuver et al. (2007). Also, to improve the conversion efficiency of the bridge-type rectifying circuit, the synchronized charge extraction technique with inductor was introduced,26 resulting the increase of the harvested power by factor 4 **(Figure. 15)**.

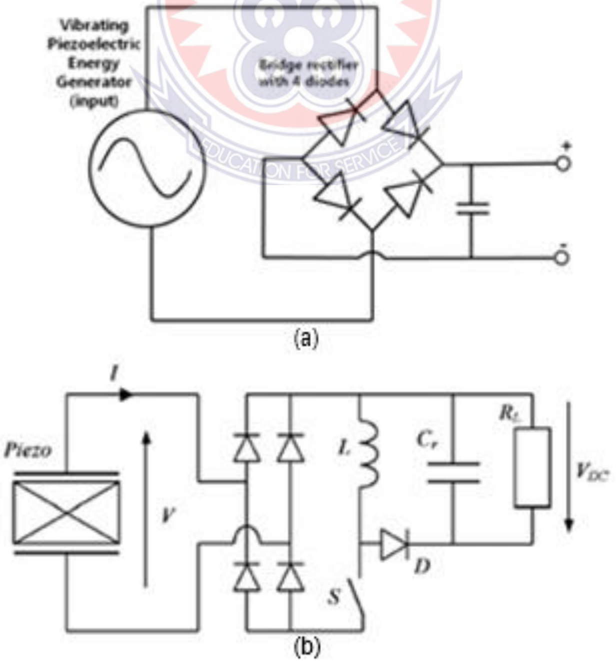
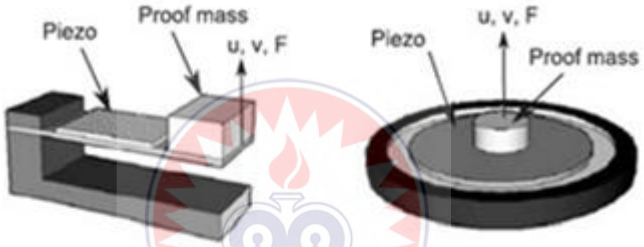


Figure 15: (a) full-wave bridge type rectifying circuit for vibrational piezoelectric energy harvester, (b) synchronous charge extraction circuit with an inductor L and a switch S. (Dimitrijev et al. 2006).

2.3.0. Synchronized Switch Harvesting on Inductor

Guyomer et al. (2009) analyzed the real energy flow that lay behind several energy conversion techniques like parallel Synchronized Switch Harvesting on Inductor (SSHI) and series SSHI for piezoelectric vibration energy scavenging and introduced pyroelectric effect which extracts energy due to temperature variation **(Figure. 16)**. Minazara et al. (2006) proposed energy generation using a mechanically excited unimorph piezoelectric membrane transducer under dynamic conditions and envisaged a new SSHI to enhance the power harvested by the piezoelectric transducer up to 1.7mW which was sufficient to supply a large range of low consumption sensors.



(a) Example of electromechanical structures

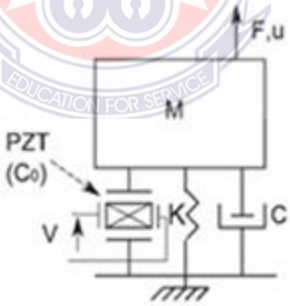


Figure 16: Electromechanical structure and model. (Minazara et al. 2006)

2.3.1. Circuits and storages

Ayers et al. (2003) conducted experiments on PZT ceramics to collect electrical energy and summarized governing equations for piezoelectric. The energy storage using both capacitor and rechargeable batteries was also investigated and findings were made for feasibility and efficiency of battery recharging. Guan and Liao (2008) investigated leakage resistances of the energy storage devices which are the most dominant factor that influences the charging or discharging phenomena. They proposed a quick test method to experimentally study the charge/discharge efficiencies of the energy storage devices using super capacitors which were suitable and more desirable than the rechargeable batteries. Wickenheiser et al. (2010) investigated the effects of varying degrees of electromechanical coupling in piezoelectric power harvesting systems undergoing base excitation on the dynamics of charging a storage capacitor. They predicted the charging behavior of the system with nonlinear simulation.

Recently, a rectifier free piezoelectric energy harvesting circuit has been suggested by Kim et al. (2008) **(Figure. 17)**. Kwon et al. (2009) The suggested circuit was a simple and scalable, which could reach 71% of high conversion efficiency. Very recently, for ultralow input piezoelectric voltage, Peters et al. (2011) suggested two stage concept including passive stage and only one active diode, resulting in successful rectification of tens of mV with very high efficiency over 90% **(Figure. 18)**. Other approach using a bias-flip rectifier with an inductor was presented in the range of µW, which is greater than 4X power extraction compared to conventional full bridge rectifier. Ramedass et al. (2011)

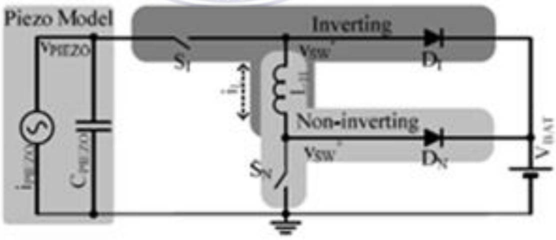


Figure 18: Rectifier-free piezoelectric energy harvesting circuit

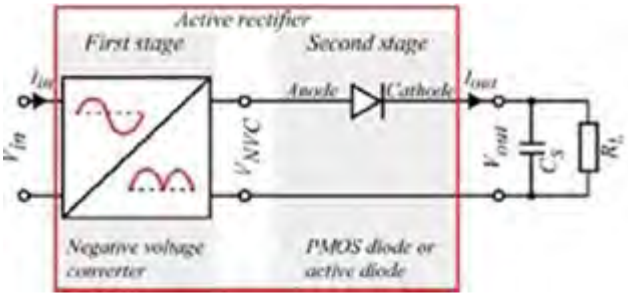


Figure 19: stage rectifying circuit for ultra-low input piezoelectric voltage. (Kim et al. 2008)

However, due to the fundamental limitation of diode type rectification, built-in voltage in diode, to minimize the voltage drop to diminish the rectified output voltage from rectifying circuit in diode is the critical issue. At room temperature, the built-in voltage of Si and Ge based P-N junction diodes are about 0.7 V and 0.4 V, respectively. Therefore, the induced vibrational input must be larger than built-in voltage of diode to scavenge the vibrational based piezoelectric input. To minimize the built-in voltage and improve the efficiency in rectifying circuit, Schottky diode with low turn-on voltage - e. g. HSMS 2822 (VF=0.34V) and Villard voltage doubler were suggested.

The application of piezoelectric materials in energy harvesting devices contains many parameters which can be optimized to improve the efficiency such that wireless sensors and electronics can be self-powered. Salter et al. (2007)

2.3.2. Piezoelectricity of ZnO

One study by Yamin (2015), in his book titled Piezoelectric ZnO Nanostructure for Energy Harvesting, studied the structural formation of the piezoelectric material specifically ZnO crystal. ZnO is an inorganic binary compound belonging to the II–VI semiconductor material group. As most of the group II–VI binary compound semiconductors, ZnO crystallizes both in cubic zinc blende and in hexagonal wurtzite structure. As presently known, ZnO possesses three different crystallographic phases: wurtzite (B4), zinc blende (B3) and rocksalt (B1). The wurtzite structure ZnO (hexagonal) is thermodynamically stable at room temperature. The zinc blende structure ZnO (cubic) is metastable and can be stabilized only by hetero-epitaxial growth on cubic symmetry substrates. The rocksalt structure (cubic, NaCl) can be obtained applying a relatively high pressure (10–15 GPa) to the wurtzite structure; it is a metastable phase but it can persist at atmospheric pressure. Therefore, most used ZnO, natural or synthesized, have the wurtzite structure. Chen J. et al (2005) In single crystal piezoelectric solids, the piezoelectric property of the material originates in its atoms and is repeated throughout the solid due to high crystallinity. The non-symmetric distribution of positive and negative charges starts from a unit cell and repeats through the whole material; thus, a strained material results in a net polarization on the surface.

ZnO belongs to the class of piezoelectric materials and its anisotropic piezoelectric properties are due to its crystal structure which belongs to P63mc symmetry group having no center of symmetry [KON 03]. In this case, the unit cell barycenter of positive and negative charges does not overlap. Thus, an electric dipole appears within the crystal and it can be modulated by the application of mechanical stress (direct piezoelectric effect), as shown in Figure 21. The interaction of the electric dipole with an external electric field can also deform the crystal (inverse piezoelectric effect).

Piezoelectric effect in ZnO unit cell (P – dipole vector), Chen J. et al (2005) indicated the concept of piezoelectricity is based on the coupling between the mechanical properties and electrical properties of the material. These two properties are related to each other through the tensors. Strongly, the mechanical and electrical behavior of a piezoelectric material can be modeled by two linearized constitutive equations. These equations contain two mechanical and two electrical variables. The direct piezoelectric effect and the converse piezoelectric effect may be modeled, respectively, by two following constitutive matrix equations:

$$\mathrm{D} = \mathrm{d} \,.\, \mathrm{T} + \varepsilon^{\mathrm{T}} .\, \mathrm{E}$$

$$\mathrm{S} = S^{E}\ \mathrm{T} + d^{t} .\, \mathrm{E}$$

where D is the electric displacement vector, T is the applied mechanical stress vector, ε^T is the dielectric permittivity matrix at constant mechanical, E is the electric field vector, S is the mechanical strain vector, S^E is the matrix of elasticity under conditions of constant electric field, and d and d^t are the piezoelectric charge coefficients, respectively, for the direct piezoelectric effect (C.N^{-1}) and the converse piezoelectric effect (m.V^{-1}), where t denotes the transposed matrix. The piezoelectric coefficients of the direct piezoelectric effect (d) and the converse piezoelectric effect (d^t) are thermodynamically identical, i.e. d_{direct} = $d_{convers}$. Note that the sign of the piezoelectric charge D and strain T depends on the direction of the mechanical and electric fields, respectively, and the piezoelectric coefficient d can be either positive or negative.

The piezoelectric coefficient d_{ij} is the ratio of the strain in the j-axis to the electric field applied along the i-axis, when all external stresses are held constant. The piezoelectric constant d_{31} is usually a negative number. This is due to the fact that the application of a positive electric field will generate a positive strain in direction 3. There are two practical coupling modes in the piezoelectric material: the stack configuration operating in the 33 mode and the bend configuration operating in the 31 mode as shown in Figure 20. The sign convention assumes that the poling direction is always in the “3” direction. Figure 20. Illustration of two operating modes for the piezoelectric material: a) 33 mode and b) 31 mode (Chen J. et al 2005).

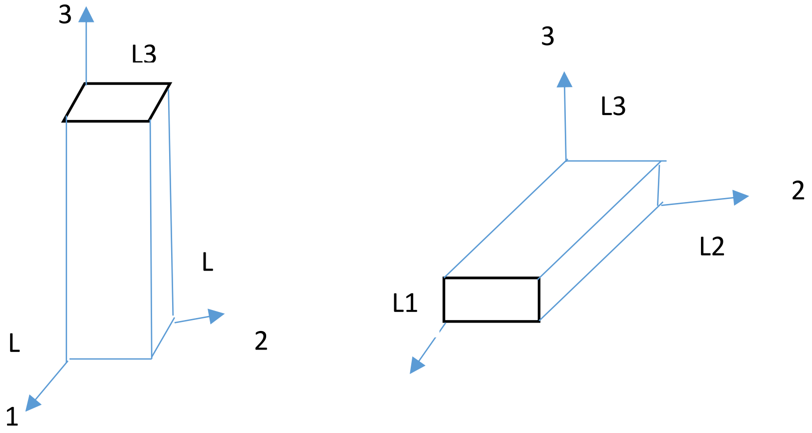


Figure 20: Operating modes for piezoelectric materials. Chen J. et al (2005)

Figure 20. Illustration of two operating modes for the piezoelectric material: a) 33 mode and b) 31 mode.

For the force applied in the direction perpendicular to the poling direction, such as bending, d_{31} will be applied; and for the force applied in the same direction as the poling direction, such as the compression, d_{33} will be applied. In d_{31} mode, the electric field is along the polarization axis (direction 3), but the strain is in the 1 axis (orthogonal to the polarization axis). In 33 mode, the electric field is along the polarization axis (direction 3) and the strain (deflection) is along the same axis. Conventionally, the 31 mode has been the most commonly used coupling mode in the energy harvesting via piezoelectric effect, but the piezoelectric coefficient d_{31} is lower than d_{33}. The ZnO crystal is anisotropic; its piezoelectric coefficients are different depending on its orientation. d_{33} = 12.4 pm/V is the accepted piezoelectric coefficient of single crystal ZnO [CHR 98], d_{31} = − 5.1 pm/V is also reported [BER 97].

It was found that the 31-configuration cantilever proved to be the most efficient under small force and in low vibration level environment; on the other hand, in large force and high frequency environment, the 33 configuration cantilever would be more efficient to generate energy. It was also found that the resonant frequency of a system operating in the 31 mode is much lower than the system operating in the 33 mode. So, the system in 31 mode is more likely to be driven at resonance in a natural environment, thus providing more power.

ZnO nanowires are more flexible than bulk materials due to their high aspect ratio (length/diameter), thus, under the same mechanical strain, the high aspect ratio nanowires can withstand larger amounts of strain to provide more mechanical energy available for conversion into electrical energy. This is why ZnO nanowires become a very promising piezoelectric material for energy harvesting (Chen J. et al 2005).

2.3.3 Principle, Characterization and Device Fabrication

Yamin (2015) conducted investigation on the Principle, Characterization and Device Fabrication of piezoelectric energy harvesting and found that mechanical energy (stress and/or vibrations) is abundantly available and can be sourced from footsteps on floors to plane engine vibrations with a large range of frequencies. Even the human body produces mechanical energy through various motions such as bodily gestures, heartbeats, blood flow, etc.

The energy harvested from these motions can supply all wireless devices, such as wireless sensor networks or bio implants, making them self-sufficient; it can also charge up the batteries of all personal smart devices. Moreover, micro/nanodevices need less energy consumption, typically from microwatts (μW) to milliwatts (mW) operating power, due to the use of advanced materials and the developments made in microelectronic technology in recent years. Piezoelectric micro/nanogenerators with an adequate active size can supply this scale of energy.

Piezoelectric micro/nanogenerators are generally composed of a mechanical support structure (rigid or flexible) on which a piezoelectric film or nanowire (NW) array is deposited. In a resonant system, using a piezoelectric film, the mechanical support is rigid and the mechanical vibrations are transmitted to film through the carrier and the converted electrical energy is maximized at the mechanical resonance of the system. Such devices generally have narrow bandwidths; thus, the resonant frequency and the source frequency must be very close.

However, this system cannot be used in the size reduced micro/nanogenerators because of the increased resonant frequency, which becomes problematic if we want to use a natural source (such as wind, water or human motions) or artificial source (such as engine vibrations from flying plane or from vehicle on roadway). These natural and artificial frequencies vary in time and are generally within a range from 0 Hz to a few hundred hertz. Therefore, the size-reduced resonant system is not suitable to harvest these surrounding energies. Nevertheless, micro/Nano-generators composed of piezoelectric NWs can overcome this problem by working out the resonance frequency via the principle of conversing mechanical stress into electrical energy.

Yamin (2015) stated nowadays that, more and more Nano-systems are present in different application fields, such as implantable biosensors, environmental sensors, as well as nanorobotics and even wearable personal electronics. They are multifunctional nanodevices with the ability to, control, communicate and actuate/respond. Another characteristic of these nanodevices is their low power consumption (typically in microwatt scale), which means that it is possible to use the electrical energy generated by harvesting the surrounding mechanical energy (even very weak) to power these nanosystems.

A nanogenerator (NG) that converts random mechanical energy into electrical energy using piezoelectric ZnO NW arrays for the self-powered system was proposed for the first time by Wang (2006). The mechanism of the NG relies on the piezoelectric potential created in the ZnO NWs by an external strain: a dynamic straining of the NW results in a transient flow of the electrons in the external load because of the driving force of the piezopotential. Because of their low stiffness, the NWs can be triggered by tiny mechanical force and the excitation frequency can range from a few hertz to thousands of hertz, which is ideal for harvesting random energy in the environment Yamin (2015)

2.3.4. Working principle of nanogenerators

The principle of the NG was introduced for the first time by Wang (2006) research group by measuring the piezoelectric properties of ZnO using a conductive tip of an atomic force microscope (AFM). As indicated from his work, the Schottky contact between the metal and semiconductor ZnO is a key factor for the current generation of the piezoelectric NG. In this pioneer work, the authors used a Pt-coated Si AFM tip (to assure a Schottky contact with ZnO NWs) which was scanned over the ZnO NW array in contact mode, and the NWs were bent consecutively.

During the scan, a constant normal force of 5 nN was maintained between the tip and sample surface. The bottom electric contact is Ohmic using silver paste for circuit measurement. The base of the NW is grounded and an external load of RL= 500 MΩ is applied, which is much larger than the resistance RI of the NW. The output voltage VL is continuously monitored as the tip scanned over the NWs without external voltage application in any stage during the experiment. Many sharp output peaks (like discharge peaks) are observed during the scan. Most of the voltage peaks are approximately 6 to 9 mV in height.

Wang (2006) indicated that approximately 40% of tip-contacted NWs are able to produce the voltage output events during the tip scan. By examining the topological profile of a NW and its corresponding output potential, a delay is observed for the output voltage signal, which means that there is no electric power output when the tip is first in contact with the ZnO NW, but a sharp voltage peak is generated at the moment when the tip is about to leave the contact with NW.

This delay is a key signature for understanding the power output process. It is also important to note that the voltage VL presented here is converted from the current flowing through the external load RL. The resonance vibration of a NW after being released by the AFM tip shows that the stored elastic energy is transferred mainly into vibrational energy after creating the piezoelectric discharge event. An overlap plot of the AFM topological image (dashed line) and the corresponding generated voltage (solid line) for a single scan of the tip across a ZnO nanowire – a delay in the electricity generation is apparent (from [WAN 06]) After some pioneering works on Wang (2003, 2006), Wang concluded that the ZnO-NW-array-based NG has the following experimental characteristics:

1) The output potential is a sharp peak that is negative referring to the grounded end of the NW.
2) No output current is received when the tip first touches and pushes the NW; and electrical output is observed only when the tip is almost leaving the NW at the second half of the contact, which means that the power output occurs only when the tip touches the compressive side of the NW.
3) Friction or contact potential plays no role in the observed output power under such configuration.

4) Output signal is observed only for piezoelectric NWs such as ZnO. No electrical output is received if the NWs are tungsten oxide (WO), carbon nanotubes (CNTs), silicon or metal.
5) The magnitude of the output signal depends sensitively on the geometric parameters of the NWs, as shown in Chapter 3 by simulation
6) Both the Schottky contact between the tip and the ZnO NW and the Ohmic contact between the ZnO NW and the grounded electrode are necessary to generate the electricity from the NG. To understand the physical principle of piezoelectric discharge energy creation, it is necessary to first understand the coupling between the piezoelectric and semiconducting properties of ZnO.

In his work, Wang proposed a simple model of a vertical and straight ZnO monocrystalline NW, which will be deflected under the AFM tip creating a strain field. In such a case, the NW has an outer surface being stretched, leading a positive strain ($\varepsilon > 0$), and an inner surface being compressed, leading a negative strain ($\varepsilon < 0$).

By the piezoelectric effect, an electric field Ez will be created inside the NW along the c-axis of ZnO crystal (z direction) with $Ez = \varepsilon z/d$. The piezoelectric field direction is closely parallel to the NW's z direction at the outer surface and antiparallel to the z direction at the inner surface. Under the first-order approximation, the electrical potential varies from Vs– to Vs+ from the compressed to the stretched side surface at the top end of the ZnO NW, where the NW experiences the maximum mechanical strain across its width. The electric potential distribution for the rest of the NW is between Vs– and Vs+ with the bottom of the NW Vs = 0 (grounded). The Vs value is determined by the relation of $Vs\ \mu = \mu 3T|Ym|/4Ld$, where T is the thickness of the NW, Ym is the maximum displacement of the NW for the top end, L is the length of the NW and d is the piezoelectric coefficient.

Wang (2006) indicated that the voltages Vs+ and Vs– are produced by the piezoelectric effect in the ZnO wurtzite crystal structure due to the relative displacement of the Zn2+ cations with respect to the O2– anions under the external mechanical strain applied on the NW. Thus, these ionic charges can neither move freely nor recombine as long as the external strain is applied. The output current can be produced, while the external strain is released. In this case, the output electric current will suddenly increase, producing the electron flow across the metal–semiconductor interface from the n-type semiconductor ZnO side to the metal tip side. Due to this oppositely biased Schottky barrier, the ZnO-NW-based NG can preserve the piezoelectric charges and later produce the discharge output.

From wang (2006) study, he estimates that it is possible to power nanodevices with the ZnO-NW-array-based NG. If the density of NWs is 20/µm2, the output power density is approximately10 pW/µm2. By choosing a NW array of size 10 µm × 10 µm, the power generated may be enough to drive a single NW/nanobelt/nanotube-based device [HUA 01, BAC 01, CHE 05]. Furthermore, if the energy produced by acoustic waves, ultrasonic waves or hydraulic pressure/force could be harvested, the electricity could be generated by ZnO NW arrays grown on solid substrates or even on flexible polymer films [XU 10]. The principle of the ZnO-NW-array-based NG demonstrated in his work could be the basis for new self-powered micro and nanodevices using surrounding energy for large application fields such as implantable biomedical devices, wireless sensors and portable electronics.

2.3.5. Aircraft Vibration Level Analysis

In the analysis to ascertain the vibration levels of aircrafts and its frequency ranges, (Russell et al. 2002) analyzed the Flight vibration data for the NASA F-15B/Flight Test Fixture II test bed. Understanding the in-flight vibration environment benefits design and integration of experiments on the test bed. The power spectral density (PSD) of accelerometer flight data is analyzed to quantify the in-flight vibration environment from a frequency of 15 Hz to 1325 Hz. These accelerometer data are analyzed for typical flight conditions and maneuvers. The vibration data are compared to flight-qualification random vibration test standards. The PSD levels in the lateral axis generally are greater than in the longitudinal and vertical axes and decrease with increasing frequency. At frequencies less than approximately 40 Hz the highest PSD levels occur during takeoff and landing. Peaks in the PSD data for the test fixture occur at approximately 65, 85, 105-110, 200, 500, and 1000 Hz. The pitch-pulse and 2-g turn maneuvers produce PSD peaks at 115 Hz. For cruise conditions, the PSD level of the 85-Hz peak is greatest for transonic flight at Mach 0.9. From 400 Hz to 1325 Hz, the takeoff phase has the highest random vibration levels.

From greater than 40 Hz to approximately 300 Hz, the Mach 0.9, transonic flight PSD levels were greatest. Random vibration levels were larger for transonic flight than for subsonic or supersonic flight. From approximately 300 to 1325 Hz, the takeoff produced the largest random vibration levels. Significant vibration levels were also encountered during sideslip maneuvers and landing, possibly because of vortex shedding from the nose wheel landing gear door impinging on the FTF-II (Russell et al. 2002). In conclusions the frequency between 300 to 1325Hz is appreciable enough to generate a substantial amount of voltage when subjected to piezoelectric material. Since the piezoelectric material requires ambient vibrations below 1kHz.

2.3.6. Energy Harvesting with Piezoceramics

In this section, vibrational energy harvesting with piezoceramics are reviewed. Various types of vibration devices, single crystal piezoelectric materials and mathematical modeling of vibrational energy harvestings are described in the followings. Priya (2009), provided a review of a comprehensive coverage of the piezoelectric energy harvesting using low profile transducers and the results for various energy harvesting prototype devices. He also gave a brief discussion on selection of piezoelectric materials for on and off resonance applications. According to his theoretical calculation, the energy density of piezoelectric energy harvesting devices is 3-5 times higher than electrostatic and electromagnetic.

2.3.7. Summary and outlook

Piezoelectric energy harvesting technologies from vibration were reviewed in this work. Principles of piezoelectric energy harvesting, various types of piezoelectric harvesting devices and piezoelectric materials were investigated. Vibrational energy harvesting technology is highlighted as a permanent power source of portable electronic devices and wireless sensor network. There have been many novel ideas for vibration-based piezoelectric energy harvesters. Device ideas in conjunction with design technology are at far advanced stages in the field of study. Though real applications of the vibration-based energy harvesters are still limited. There are three issues that limit the broad technological impact of the vibration-based piezoelectric energy harvesters. Firstly, development of high coupling coefficient piezoelectric materials is essential to improve the performance of piezoelectric energy harvesters.

Once the coupling coefficient is twice increased, then the energy conversion efficiency can be four times improved. Thus, the advent of new piezoelectric materials with high coupling coefficient will bring a new era of piezoelectric energy harvesters. Secondly, the energy harvesters should be able to sustain under harsh vibrations and shocks. Fatigue and crack of the energy harvesting devices are crucial for real application. Thus, development of flexible and resilient piezoelectric materials is Necessary.

Thirdly, development of efficient electronic circuitry for energy harvesters is necessary. Since the obtained electrical energy from vibration is small, rectification and energy storing circuits should be able to activate in such a low power condition. Vibration is everywhere, and vibration-based energy harvesters will come to our real life. Kim et al. (2011).

CHAPTER THREE

RESEARCH DESIGN AND MODELLING

3.1 The Study Area

Students, teachers, in the field of electrical/electronic engineering studies offers the opportunity to addressing the scarce energy resources available for electricity generation and the determination to maximize the minimal power generated by electrical devices to handle portable electronic devices. Moreover, stake holders in the field of renewable energy resources and environmental protection practitioners with key interest in the reduction of carbon emission production which results in global warming are also covered by this work.

3.2 Research Approach

Mixed type approach was conducted in the execution of this work which has help to addressing the key research objectives, this research work obtained its data from literatures of published journals and research papers on piezoelectric energy harvesting and its related study areas as acknowledged in previous chapter. Most of the information on the type of components required for the design and of the piezoelectric power supply unit was obtained from published research papers and journals. (Kim et al., 2011) etc.

3.3 Design Process

The design process commenced with the idea from previous literatures that electrical energy could be generated through mechanical pressure exerted on certain electronic components made of materials like lead zirconate (PZT), Barium titanate, Lithium niobate and Quartz. However, most of the piezoelectric materials generate minimal amount of voltage when pressure is exerted on them, in that regard other components are required to increase the voltage level to a significant value to be able to power sensor devise.

With respect to power supply unit, a lot of circuits come together to ensure a desired output voltage is achieved. However, in terms of alternating inputs, rectification circuit is needed to ensure d.c voltage is obtained from a.c input. Also, to ensure smooth d.c output, filter circuit is desired to keep pure d.c output. Additionally, with the effect of fluctuation in the input supply and an anticipated system noise, stabilization circuit is required to ensure that output voltage is always kept constant irrespective of over voltage or over current in the system. Furthermore, considering a significant output required for the loads, voltage doubler circuit is needed to ensure output voltage is increased to a significant level.

The model of this work is based on bringing together various components that makes up the power supply unit design using piezoelectric source. First of all, the design process illustrates the first component of the power supply unit which considers the piezoelectric harvester as the main source of supply.

3.4 Circuit Modeling

The circuit design is organized as follows, the first section discusses the piezoelectric model and the details of the harvesting unit, which include the operations of the piezoelectric crystal, secondly the voltage doubler circuit and thirdly the voltage regulator circuit.

3.5 Piezoelectric Circuit Model

With the improved small-deflection model Tabesh et al (2008) derived the components of this model. The static charge equation for a deflected piezoelectric beam is

$\mathrm{Q} = Q_{u + C_{pV_p}}$ (1)

where u is the deflection of the beam at the tip and vp is the voltage across the piezoelectric electrodes. The coefficients θ and C_p are the coupling and capacitance coefficients of the piezoelectric beam, respectively. They are functions of the piezoelectric properties and the beam geometry as elaborated in Tabesh et al (2008) Using (1) and considering the sign convention in Figure. 22 (b), the load current (i = −dQ/dt) is given by

$$i(t) = -\frac{dQ}{dt} = -\theta\frac{du}{dt} - Cp\frac{dvp}{dt} \qquad (2)$$

A sinusoidal excitation u = Um cos(ωt), under a steady-state condition, generates a sinusoidal load current as

$$i(t) = (-)\omega Umsin(\omega t) - \frac{Cydvp}{dt} \qquad (3)$$

Figure. 22(c) shows an equivalent circuit for the piezoelectric beam based on the load current in (3). In this circuit, the vibrating beam is represented with a capacitance Cp and a sinusoidal current source ip (t) = Ip sin(ωt), where the peak current Ip = $\Theta\omega U_m$ is proportional to the maximum tip deflection Um and the vibrating frequency of the beam ω.

B. Rectifying Circuits and Optimal Power Flow in **Figure**. 22 shows two configurations for rectifying circuits: FB and VD diode rectifiers. For each configuration, the filter capacitor (CF) is designed such that, for a specific load, the fluctuations of the filter voltage (VF) are limited to a narrow band (typically less than 5% of the nominal dc voltage). For the FB configuration, the maximum rectified voltage occurs under no-load condition, and it is ideally equal to the peak open-circuit voltage at the piezoelectric terminals. This peak value based on the equivalent circuit in **Figure**. 21 (c) is Voc = Ip /ωCp = ΘUm /Cp, which is proportional to the maximum deflection Um.

When the rectifier is connected to a load, the piezoelectric maximum voltage is limited to the filter voltage (i.e., vp (t) < VF). Ottman et al., (2001) have analytically shown that, for an FB configuration, the maximum average power extracted from a piezoelectric device occurs when the rectifier voltage is one-half of the peak no-load voltage, and the maximum average power is

$$(P_{FB})_{max} = \frac{Cp\omega V^2oc}{2\pi} \text{ at } V_F = \frac{Voc}{2} \qquad (4)$$

where PFB is the instantaneous extracted power and (-) denotes its average value. Herein, the theory of maximum power flow for the VD rectifier is developed. In the VD rectifier, the negative piezoelectric current passes through the diode D1, and this diode does not allow v_p to become negative. Thus, only the positive piezoelectric current can charge up C_p starting from zero voltage (v_p (0) = 0). Under a no-load condition, the piezoelectric current totally charges up C_p, and the no-load peak voltage of the piezoelectric is

$$v_p\left(\frac{T}{2}\right) = \frac{1}{C_p}\int_0^{\frac{T}{2}} I_p \sin(\omega t)\, dt + \overbrace{v_p(0)}^{=0} = \frac{2I_p}{C_p\omega} = 2V_{oc}. \qquad (5)$$

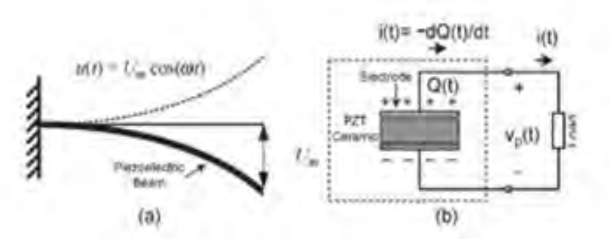


Figure 21: (a) Schematic diagram of a vibrating piezoelectric beam (cantilever), (b) Electrical connection of the beam to a load.

In the design of the harvester, cantilever type is selected based on its considerable features obtained from the data sheet (www.digikey.in). Nominal Frequency Range is from 10 to 80MHz and 30 to 60MHz, Vibration Mode is Fundamental (AT) and 3rd Overtone (AT). Frequency Tolerance @25°C is ±20, ± 30 or ±50ppm, Temperature Stability is also ±30 or ± 50 ppm, Operating Temperature Range -20°C to +70°C Storage Temperature Range -30°C to +80°C, Load Capacitance 8pF to 32pF or series, Shunt Capacitance 7pF max, Drive Level 100µW max, Insulation Resistance 500M Ω min @ 100VDC, Aging ±5ppm per year.

3.6 Piezoelectric Crystal

The piezoelectric crystal used in this design is 'Crystal Unit – HC 49/U 80MHz which have the following features obtained from the data sheet (www.digikey.in). Nominal Frequency Range is from 10 to 80MHz and 30 to 60MHz, Vibration Mode is Fundamental (AT) and 3rd Overtone (AT). Frequency Tolerance @25°C is ±20, ± 30 or ±50ppm, Temperature Stability is also ±30 or ± 50 ppm, Operating Temperature Range -20°C to +70°C Storage Temperature Range -30°C to +80°C, Load Capacitance 8pF to 32pF or series, Shunt Capacitance 7pF max, Drive Level 100µW max, Insulation Resistance 500M Ω min @ 100VDC, Aging ±5ppm per year.

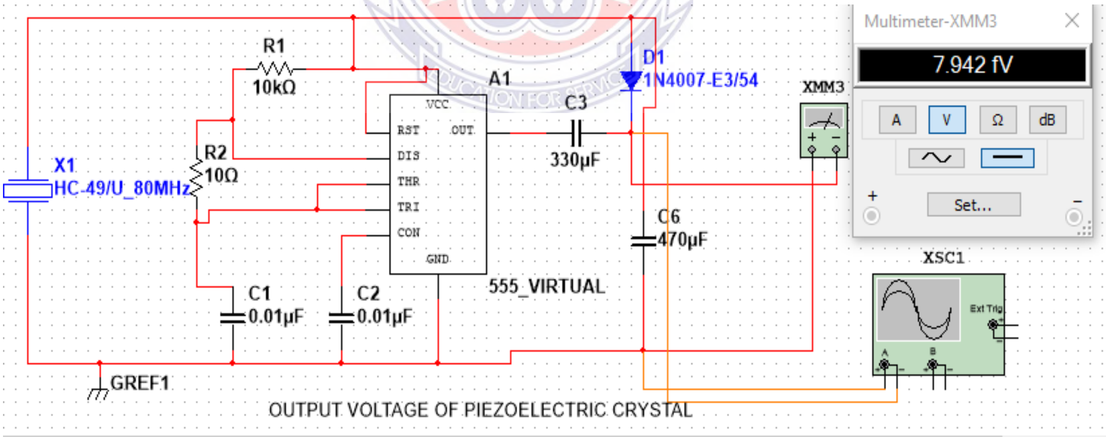
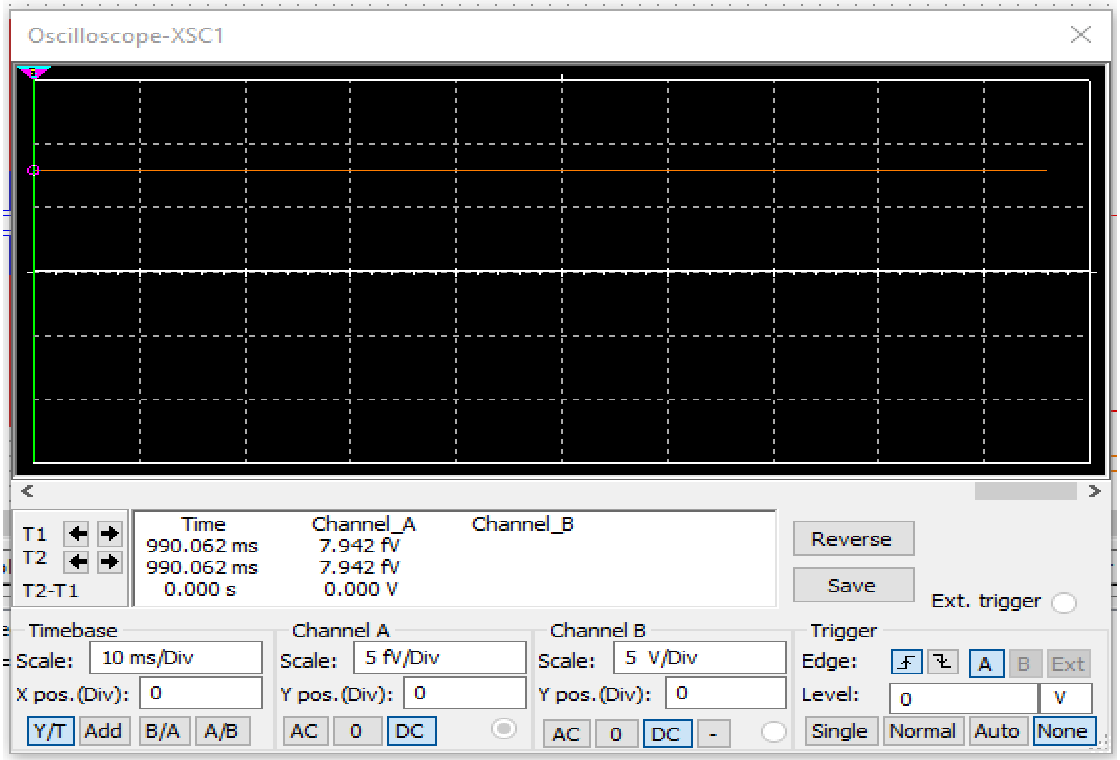


Figure 22: Output voltage of the piezoelectric crystal



	Time	Channel_A	Channel_B
T1	990.062 ms	7.942 fV	
T2	990.062 ms	7.942 fV	
T2-T1	0.000 s	0.000 V	

Timebase
Scale: 10 ms/Div
X pos.(Div): 0

Channel A
Scale: 5 fV/Div
Y pos.(Div): 0

Channel B
Scale: 5 V/Div
Y pos.(Div): 0

Trigger
Edge:
Level: 0 V

Figure 23: D.C output characteristics of the piezoelectric crystal

3.7 Voltage Doubler Circuit

The second stage requires that the output of the harvester circuit needs to be scaled up or increased to a significant value, and so voltage doubler circuit was needed to perform such functions. Upon consideration, Villard voltage doubler circuit was selected due its simplicity and effectiveness. The simplest voltage doubler circuit is a half-wave doubler, and it is nothing more than a series capacitor with a reverse biased diode to GND. This is also called a Villard circuit, named after its inventor.

The voltage doubler circuit is a circuit in which the outputs DC voltage is twice the peak value of the AC input voltage, without using a transformer. There are many electrical design situations where an AC voltage signal is available (or can be created), but a larger DC voltage is needed for the circuit. These situations include energy harvesting, high voltage flashers, or ion generator applications. Transformers are often considered first when it comes to multiplying voltage, but a well-designed voltage doubler circuit can be the better solution in many cases. The simplest voltage doubler circuit is a half-wave doubler, and it is nothing more than a series capacitor with a reverse biased diode to GND. This is also called a Villard circuit, named after its inventor. The capacitor enables AC current to pass through it, but the diode only allows current to flow in one direction. This creates a peak output voltage of 2*Vpk across the diode. It is worthy to note that a voltage doubler is the first-order form of a voltage multiplier. Voltage multipliers can be stacked together to triple a voltage, quadruple a voltage, and so on.

The output voltage ripple depends primarily on the characteristics of the capacitors used and the load on the output. Capacitor selection is very key in the designing of voltage doubler circuits. The Selected capacitors of the circuit should have good energy density and capacitance-voltage (CV) while remaining cost-effective. The capacitors must be selected to provide the current required by the load. Aluminum electrolytic capacitors are an obvious choice, providing excellent energy density, CV, and have a long life at elevated temperatures, making them ideal for voltage doubling applications. However, there are a number of factors that was taken to consideration. The load supplied by the output is another critical item for a voltage doubler because the output is poorly regulated. Hence there is the need for voltage regulator to ensure constant voltage at the loads.

The work herein develops and demonstrates a viable adaptive piezoelectric energy-harvesting circuit based on a voltage doubler (VD). The proposed circuit is suitable for low power (0.5-5 mW) applications and overcomes the aforementioned limitations of the existing adaptive circuits. The circuit consists of two diodes, resistors and capacitors which allows stand-alone operation of the energy harvester circuit.

As will be shown, the total power consumption of the controller unit is less than 0.05 mW, and the overall efficiency of the circuit prototype reaches 60%. The circuit improves the amount of extracted power from a piezoelectric generator independent of its operating frequency, vibration amplitude, and its geometry (capacitance). This feature of the circuit is of utmost importance for adaptive energy-harvesting devices that tune their resonant frequency to track the source vibrations. The limitations of the proposed energy-harvesting circuit are the following:

1) For a power range less than 0.5 mW, the circuit is not efficient mainly due to the control circuit's power loss, and
2) The VD rectifier of the circuit requires a filter capacitor with higher voltage level. This can limit the applications of the circuit for high voltages since the size and cost of a high-capacity storage are rapidly increased with voltage.

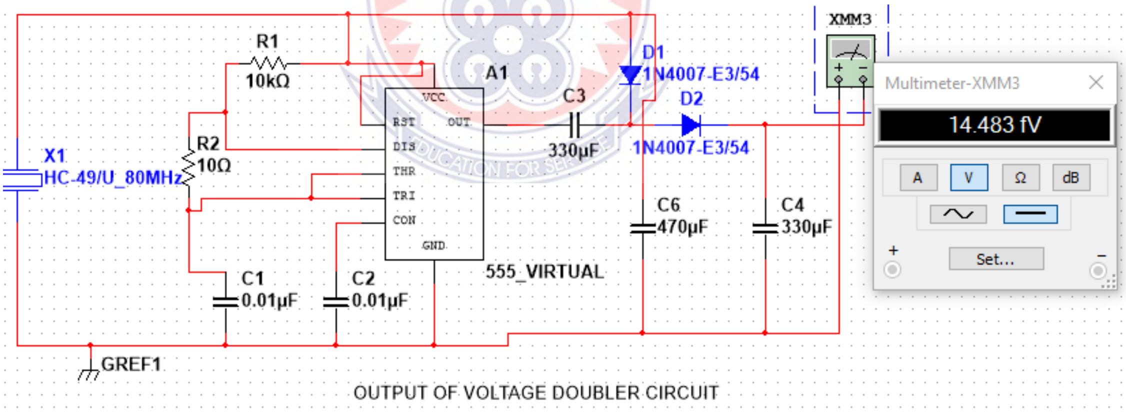


Figure 24: Output voltage of the voltage doubler.

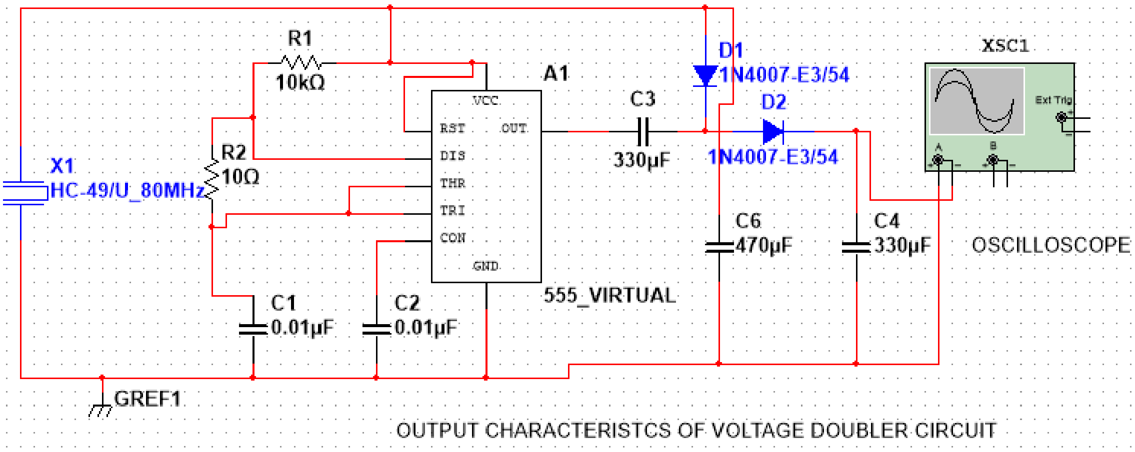
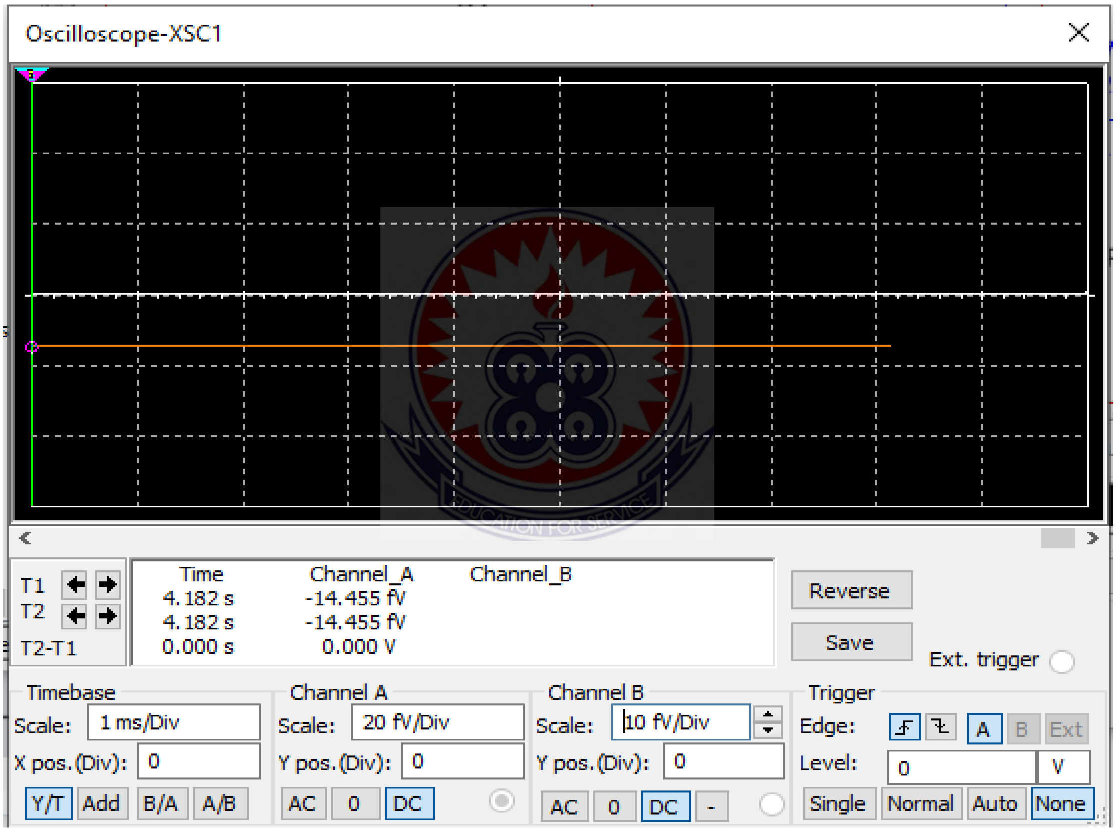


Figure 25: Output characteristics of the voltage doubler



	Time	Channel_A	Channel_B
T1	4.182 s	-14.455 fV	
T2	4.182 s	-14.455 fV	
T2-T1	0.000 s	0.000 V	

Timebase
Scale: 1 ms/Div
X pos.(Div): 0

Channel A
Scale: 20 fV/Div
Y pos.(Div): 0

Channel B
Scale: 10 fV/Div
Y pos.(Div): 0

Trigger
Edge:
Level: 0 V

Figure 26: Graph of Output Voltage.

3.8 Voltage Regulator

The third stage also requires that the circuit gives smooth and stable output, but due to imperfection of the electrical systems and other circumstances, electrical circuit may not be stable and therefore makes it unreliable. The electrical circuit instability also occurs as a result of fluctuation of the supply and the variable loads that may be connected to the circuit. However, a voltage regulator circuit is required to perform to ensure stable and smooth operations of the power supply. Therefore, in selecting the voltage regulator, IC LM1084 was considered due to its availability and efficiency.

These units stabilize and control the variation of the output voltage within the specified voltage range as

shown in figure below. The IC LM1084 stabilizes the output voltage to a very stable one. The LM1084 has known ground terminal, it adjusts v_{out} to maintain a constant of 1.25v from the output terminal to the adjusted terminal. (**Ariyo et. al, 2014).**

The regulator puts 1.25v across R1, so 70mA flows through it. The adjustment terminal draws very little current

(50–100A). The output voltage does not depend on the input voltage and it is given by

$$\boldsymbol{vout = 1.25(1 + R2v/R1)volts}$$

Since R2 and Rv are connected in parallel they act as one resistor with resultant resistance given by

$R_{T=}(R2\ Rv)\ /\ (R2 + Rv)_{=}$ 1*1000/(1+1000)= 0.99Ω

therefore, the output current, I =14.43-1.25/0.99 =13.3A

the output power P_o= 1.25*13.3= 16.6w

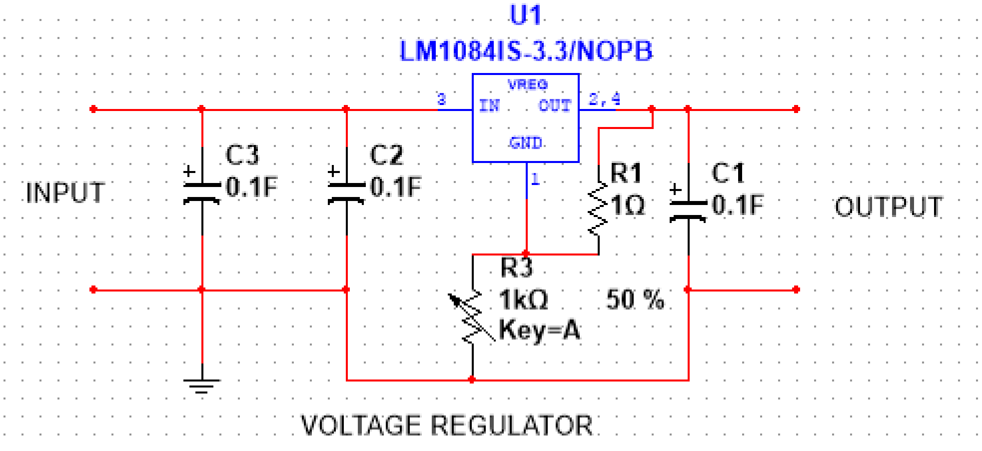


Figure 26: Voltage regulator circuit

3.9 Power Supply Unit Design

The proposed power supply unit considered in this work contain various components that make up the system and these include the piezoelectric crystal, the voltage doubler circuit, and the regulator. Piezoelectric crystal is able to produce power when it is subjected to vibration, the large deformation due to stress of the crystal material is enough to generate some amount of electrical energy.

The voltage doubler is designed to multiply or increase the level of voltage generated by the crystal material since the voltage produced is insignificant to meet the voltage requirement of a sensor device.

However, all power supply circuits must be designed to optimize both line and load regulation requirements within the needs and constraints of the system. This means that the regulator must have the ability to maintain the voltage output at a constant value even as the current demand (load) changes.

The line regulation abilities or limitations of a controller are usually part of the controller specifications such as 3-5v + 10%, -15%. The degree of load regulation involves the end-to-end accuracy and repeatability, and is usually not explicitly stated as a specification for controllers.

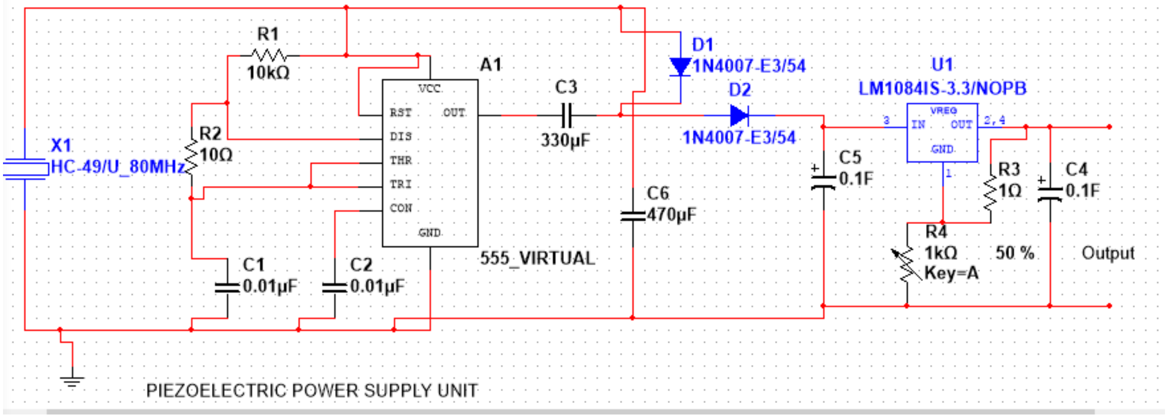


Figure 27: Piezoelectric power supply unit

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Voltage Output by Power Supply Unit

A significant amount of 14.483fv was obtained by the piezoelectric power supply unit and it is illustrated in Table 2. An initial voltage of 7.942fv was obtained from the piezoelectric crystal circuit as indicated in figure 23. This was transmitted to the voltage multiplier circuit and the voltage multiplier circuit doubled the voltage obtained from the crystal to a significant value of 14.483fv as illustrated by figure 25. The V_{out} maintained a constant voltage of 1.5v when resistors R1 and R2 was varied. A piezoelectric power supply unit with an output voltage of about 14.48fv, has been obtained. Table 1 indicates the voltage levels at each stage of the power supply unit design. Percentage increase **(%) =[V_2-V_1/V_1]*100%**

Table 2: Shows voltage levels and Percentage increase at each stage of power supply unit

No.	Stages	Voltage output (v_o)	Percentage (%) increase
1	Harvester	7.942fv	-
2	Voltage Doubler	14.483fv	82.4%
3	Load Voltage	14.483fv	82.4%

4.2. Power Supply Design

The design of the piezoelectric power supply is made with the help of multism application software, which was able to give result in each of the stages in the design process. In each of the design stages, significant output values were recorded indicating the achievement and the successful design of the piezoelectric power supply unit. Figure 29 illustrate the circuit diagram and design of the proposed piezoelectric power supply unit.

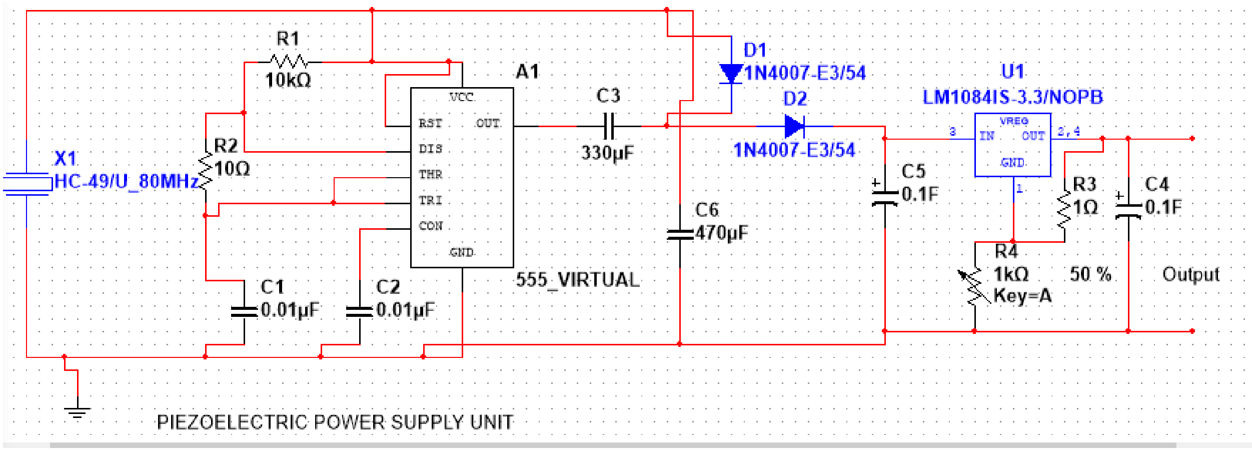


Figure 28: Piezoelectric power supply unit

4.3. Energy Accessibility

The accessibility of the piezoelectric crystal is largely relied on the availability of materials like Tomalin, quartz etc. which only use stress exerted by a radiant energy from vibration to generate an electrical energy. From all indications piezoelectric energy harvesting is an inventive prospect for clean and renewable energy production and one of the benefits of using the piezoelectric generator is that it can be used to charge and store energy in secondary batteries as a means of energy conservation in small sensor devices. The results indicate the viability of the piezoelectric power supply unit when compared to conventional power supply unit of the same output range in the market.

4.4. Observation

It is observed from figure 30, that piezoelectric crystal at different frequency ranges, generated almost the same output voltage.

Table 2, shows the characteristic of a stabilized standard power supply voltage and its output voltage is always constant. Furthermore, figure 31, Shows the relationship between various piezoelectric crystal frequencies and the corresponding voltages.

The text caried out indicate that the output from the voltage doubler was almost two times the input voltage obtained from the piezoelectric crystal. figure 3. It was also observed that the piezoelectric crystal generated a voltage of the region of fuzy level and that with little improvement of the design, substantial amount of voltage could be realized. The output waveform from figure 27, indicate the quality of the smooth nature of the output voltage which indicate the costant nature of the d.c voltage.

Table 3: Output of piezoelectric crystal at different frequency ranges.

No.	Frequency (MHz)	Output voltage (fv)
1	80	14.7
2	25	14.47
3	15	14.83
4	11	14.82
5	14.63	1.5
6	14.78	20

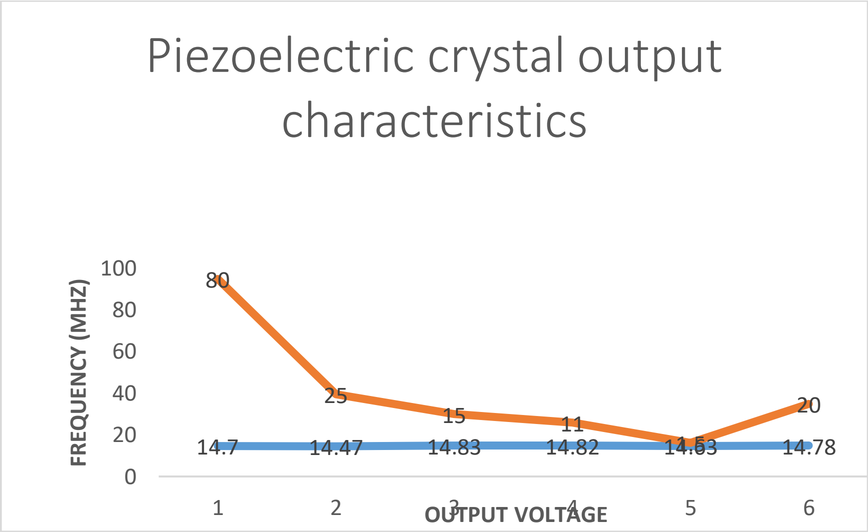


Figure 28: Frequency/voltage characteristics of piezoelectric crystal.

4.4. Discussion

This study was conducted in order to design a power supply unit from a harvested electrical energy produced by piezoelectric effect to power low voltage sensor devices at airports, as well as solving a short run-time for a device or battery life and also to determine amount of voltage in volts(V) from a microvolts (µV) piezoelectric material for the design of power supply unit. Finally, to access energy required to conserve the environment and reduce CO_2 emissions produced from other fuel recourses.

Previous studies have been done to show that piezoelectric harvesters have been used to generate electrical energy in footwear (Farinholt et al. 2007), further in pavements where piezoelectric harvesters are embedded in walkways (Jiang et al. 2014). Studying the possibility of generating energy through power floor tiles, (Elhalwagy et al. 2017), suggested the possibility of using high generated power floor tiles arranged in the building spaces as a power source generator that can be used to operate LED lighting system, since LEDs use far less energy than conventional (fluorescent and incandescent) bulbs.

The study is also aimed to show that power supply unit could be built by using piezoelectric material embedded in the building walls at the airport. Moreover, it intended to determine significant amount of voltage generated by the power supply unit and to also to ensure that energy is conserve in the utilization of the power supply unit for the safety of the environment.

The result of this study do support the previous studies and subsequently suggest that, using piezoelectric harvester as a means of energy source to design a power supply unit for low voltage devices is feasible and is directly contributor to students' knowledge in the field of electrical and electronic engineering.

The difference between this study and that of the previous works are that, they are mostly limited to the literature and the hypothesis of the processes of electrical energy generation through embedding piezoelectric materials in pavements, roads, runways, bridges etc**.** The results of this study point to the fact that with the improvement in the design process, piezoelectric power supply unit could replace the traditional energy sources.

The overall gaps this work seeks to cover is that, firstly instead the piezoelectric material is embedded in pavements, runways, roads, shoes etc. this work considers embedding the piezoelectric materials in the walls at the airport.

But what this study intends to focus and compliment, is the use of vibration obtain from air craft to generate electrical energy for the design of power supply unit to power sensor devices.

CHAPTER FIVE

SUMMERY OF FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary of findings

This study sort to investigate a sustainable power source using piezoelectric material to drive sensor devices.

The first objective was to design a power supply unit from a harvested electrical energy produced by piezoelectric effect to power low voltage sensor devices at airports. The power supply was designed and the finding revealed an amount of voltage recoded at the output.

The objective two was to determine the amount of voltage in volts(v) from a microvolts (µv) piezoelectric material for the design of power supply unit. However, the study discovered that an output voltage of 7.942fv and14.483fv was recorded from the power supply designed. The output of the various stages shows that voltage generated by the harvester was increased by the voltage doubler circuit by 82.4%.

The final objective was to access the energy required to conserve the environment and reduce CO2 emissions produced from other fuel sources. The study indicated that piezoelectric materials have the tendency of producing electrical energy to power low voltage sensors without depending on other harmful sources of energy.

5.2 Conclusion

The purpose of this study was to investigate a sustainable power source using piezoelectric material to drive sensor devices.

The finding revealed that power supply unit can be design with piezoelectric material installed at the air ports. And that the output voltage is significant to power sensor devices.

Additionally, piezoelectric materials have the properties of generating substantial amount of electrical energy.

5.3 Recommendation

Therefore, I recommend that, further research work needs to be conducted by the academia and policy makers to improve on this study so that it can be implemented at the airport.

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