LOW WIND PROFILE ENERGY HARVESTER USING ROTOR AND PIEZOELECTRIC

by

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LIST OF ABBREVIATIONS

AC	Alternating Current
ANSYS	Analysis System Software
DC	Direct Current
EMF	Electromagnetic Field
FEA	Finite Element Analysis
LCD	Liquid Crystal Display
PFEH	Piezoelectric Flow Energy Harvester
PZT	Piezoelectric
RCC	Resistor Capacitor Circuit
RF	Radio Frequency
RPM	Revolution Per Unit

LIST OF SYMBOLS

B_{av}	Average Flux Density
C	Capacitor
D	Dielectric Displacement
E	Field Strength
f	Frequency
F_c	Force on Single Conductor
I_a	Armature current
L	Conductor Length
n	Revolution Number
P_{conv}	Converted Power
r	Harmonic force Frequency
R	Resistance
S	Strain
T	Torque
W	Work
ε	Permittivity of a Process in a Specific Medium

Profil Tenaga Penuai Angin Rendah Menggunakan Rotor Dan Piezoelektrik

ABSTRAK

Baru-baru ini, usaha-usaha dalam menyediakan sumber tenaga alternatif telah Banyak kajian dijalankan dengan pertimbangan untuk melanjutkan permohonan mereka mengikut ciri-ciri sumber tenaga. Walau bagaimanapun, penuaian tenaga getaran adalah antara sumber yang paling menjanjikan percuma memerangkap tenaga. Dalam perkembangan projek ini, satu sistem yang menjana kuasa dari DC generator, bagaimanapun, penjana kuasa biasanya menghasilkan sisa tenaga getaran. Oleh itu, pembangunan akhir, memberikan sebagai kaedah alternatif untuk menuai tenaga getaran sisa dan menukar tenaga getaran ini menjadi tenaga elektrik menggunakan bahan piezoelektrik. Projek ini telah dibangunkan pada MATLAB Simulink manakala fokus kajian utama mengenai kombinasi pemutar dan peranti piezoelektrik. Dalam senario ini, model mesin DC telah dipertimbangkan untuk reka bentuk rotor dan bahan Piezoelektrik (PZT) yang telah dianggap sebagai bahan piezoelektrik. Keputusan akhir menghasilkan voltan output piezoelektrik, DC voltan penjana, kesan damping sistem manakala beberapa cara yang digunakan untuk memperbaiki sistem telah dicadangkan.

Kata kunci: piezoelektrik, bahan, Generator, Getaran, Daya, Kelajuan, Frekuensi, Dam

Low Wind Profile Energy Harvester Using Rotor And Piezoelectric

ABSTRACT

Recently, efforts in providing alternative energy sources have been widely explored with the consideration of extending their application according to energy source characteristics. However, vibration energy harvesting is among the most promising source of free energy scavenging. In this project development, a system that generates power from Direct Current (DC) generator, however, power generators usually produced waste vibration energy. Therefore, the final development, providing as an alternative method for harvesting the waste vibration energy and convert this vibration energy into electricity using piezoelectric material. The project has been simulated in MATLAB Simulink while the main study concern about the combination of rotor and the piezoelectric device. In this scenario, modeling of DC machine has been considered for rotor design and the Piezoelectric (PZT) material has been considered a piezoelectric material. The final result provided piezoelectric output voltage, DC generator voltage, effects of damping of the system while few ways used to improve the system were suggested.

Keywords: Piezoelectric, Material, Generator, Vibration, Force, Speed, Frequency, Damping.

CHAPTER 1

INTRODUCTION

1.1 Background

The current efforts for providing alternative energy sources include biomass energy, wind energy, solar energy and a lot have been widely researched with the consideration of extending its application according to the characteristics of each. Wind energy, solar and vibration energy are among the most commonly used sources for certain circumstances (Cammarano, Alessandro, Petrioli, Chiara, & Spenza, Dora., 2012).

Vibration energy harvest is among the most promising source of free energy scavenging. While the major approach of scavenging this energy is the application of piezoelectric (PZT) devices. PZT device typically converts mechanical energy into electrical energy such as converting the rotation of a rotor which produces vibration into usable electricity.

However, the main concept behind the use of energy harvesting using low wind profile has been developed lately as a way for providing sufficient energy source. Thus, combining other energy methods such as PZT has been one of the well-utilized methods which mainly aim at transforming mechanical energy into electrical energy.

This is due to the ongoing needs for providing sufficient remote power electrical sensor networks. However, providing and examining such networks require substantial extraction of electrical energy from the operating environment in accordance with its settings (Krishnan, S Harihara, Ezhilarasi, D, Uma, G, & Umapathy, M, 2014). Despite this, global warming problems and related factors have raised the needs for providing a lower energy profile which as a result led to the consideration of other alternatives.

Primarily, the process associated with the consideration of certain energy harvester usually depends on the cost effectiveness and reliability of the solutions (McCarthy, JM, Watkins, S, Deivasigamani, A, & John, SJ., 2016). Thus, a number of harvesting methods were proposed in order to offer potential solutions based on the profile of solar, electromagnetism, capacitive methods and others.

This research work discusses the modelling of a system that generates power from a rotating power generating machine. Since most power generator produces waste vibration energy, project modelling focuses on the development of a system that could harvest the generator waste vibration energy and convert it into electricity.

The design and theoretical principle of a mass spring for vibration, bimorph cantilever PZT type, internal voltage generated by piezo and also discuss power generation from synchronous or induction machine.

1.2 Problem Statement

There have been many novel ideas for vibration-based PZT energy harvesters, device ideas in conjunction with design technology are likely developed but real applications of the vibration-based energy harvesters are still limited. There are different sources of vibration such as cantilever type, cymbal type, and shell type. Hence, generating sufficient vibration from rotor required any one of these vibration sources stated but the selection of the vibration source type method could also be challenging. Another concern is the usage of voltage generated from the piezo electric device. These also required some certain steps to be followed for the conversion, such as voltage rectification, voltage boosting and power analysis while all this need to be implemented as a circuit base rather than the mechanical structure base.

However, vibration harvester would also require a full and better understanding of a produced mechanical oscillation in the environment, it was set up before power output can be maximized. Using a cantilever type gives more suitable, but the choice of cantilever would also depend on the main vibration frequency of vibration energy produced by rotating rotor. Therefore, there is a good reason to analyze data collected from environmental vibration. The current issues related to the ambiguity of energy availability generated from other sources have led to the consideration of providing energy-efficient power solutions. The harvesting practices of energy sources were processed by applying sophisticated methods to generate energy intake either by using certain energy predictors. However, such practices comes with various limitations in terms of articulating the behavior of energy sources produced in short and medium periods (Carli, Davide, Brunelli, Davide, Benini, Luca, & Ruggeri, Massimiliano, 2011).

As such, the lack of gaining more insights about potential energy predictors of harvesting sources will result in an under-performing system. This includes slowing down the process related to nodes, planning in order to manage the transferred energy (Bansal A, Howey DA, & Holmes AS., 2009). On the other hand, the problem with this study is that the frequency appears to be not stable when PZT harvest the energy. This reason could be that the turbine state is changed due to certain environmental conditions. Thus, this study considered the potential of combining rotor with current properties of PZT as an efficient and practical method of harvesting energy from the wind energy.

1.3 Research Aims and Objectives

1.3.1 Aims

The rotation of the rotor can be utilized as a Direct Current (DC) power generator, the rotor also produces some waste vibration energy. Therefore, the primary aim of the project is to convert this waste vibration energy into electricity.

1.3.2 Objectives

The objectives of this study are:

1. To model the turbine generator using MATLAB Simulink environment.
2. To evaluate the effect of rotor and PZT in providing the harvested energy of low wind.
3. To harvest a waste vibration energy of a DC machine for power optimization.

1.4 Scope of Research

This study is mainly concerned with combining rotor and PZT in order to provide a low wind profile. Simulation based on MATLAB has been carried out in this study. The standard specifications of PZT have been considered in this study. The rotor was applied to the PZT when turbine began vibrate.

Design and modelling was started by setting of the MATLAB environment based on the energy harvesting source. The researcher has considered a turbine model in which the wind load applied to it. By doing so, the vibratory movement of the turbine has been estimated based on the wind data collected. Then, the energy harvester was obtained by comparing it with different cases in accordance to the stiffness, mass and damping coefficient. Rotor and PZT was applied into the vibration in order to produce the low energy harvester. The design characterizes the energy output has been estimated to determine the effectiveness of the combination of rotor and PZT for providing a low wind profile based on the oscillation amplitude of the vibration as an indication of the potential energy that can be harvested.

1.5 Thesis Outlines

This thesis has five main chapters, introduction, literature review, methodology, result and conclusion.

Chapter 2: Literature Review

This chapter includes the development approach by other researchers, it also elaborates result from work done by other researchers, it is mostly content of related systems, method, result and limitation observe.

Chapter 3: Methodology

This chapter provides all idea and information regarding the system design and the functionality of the system, it comprises of design concept, mathematical equation involve and the system sustainable.

Chapter 4: Result and Discussion

This chapter provides the system model results and categorized them into three main different sections such as power generation from turbine generating machine, waste vibration generated from DC machine and conversion of waste vibration energy into useable electrical energy using PZT material.

Chapter 5: Conclusion

This chapter concludes the project, which reached the expected results of the study of the development of energy harvesting from rotor vibration in order to generate electricity. It also suggests further work needed for project improvement.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This section of the project reports evaluate different journals and works implemented by other researchers, review focus on researchers primary objective, method and result related information.

This chapter generally discusses ways that could use to generate electrical energy from generating machine and vibration. Also describe the similarities of work done by different researchers. By the end of this section, possible method has been identified and limitation observed from previous researchers work served as a key point for this project improvement.

2.2 Energy Harvest Review

Harvesting of energy to generate electricity from vibration as an alternative source or support to conventional battery is becoming an important focus for researchers, adaptation of vibration energy into electrical energy is increasing daily. However, harvesting of electrical energy for consumption from vibration can be achieved using different methods, typical examples are PZT, electrostatic or electromagnetic.

The basic understanding of energy came from the process of collecting incoming energy sources and turns them into usable since. It helps provide shows about converting the external power sources into supplying energy to various applications (Yen Bernard C & Lang Jeffrey H., 2006). Nowadays, enhancing the current techniques for extracting electrical energy from the natural sources led many researchers to consider the potential of materials such PZT to enable the current extracting techniques.

In addition, the motivation for considering such materials comes from the global warming perspectives which imposed a remarkable challenge in lowering the carbon footprint (Soliman MSM, Abdel-Rahman EM, El-Saadany EF & Mansou RR, 2008). This as a result led scholars to seek alternative energy sources that come with lower wind profile.

However, the current customization of energy sources in a harvested form can be driven by the mechanical, solar, chemical, ambient-radical or the combination of them. There are two parts where the harvest kinetic energy can be extracted from the environment, the first is known as vibration mechanical system which is usually configured by considering the environmental motion along with the motion of power generator (Liao Yabin & Sodano Henry A, 2008). However, the second part consists of conversion mechanism which is utilized in order to convert the received energy source into electrical energy.

Understanding the design of these two parts drives researchers to try out the combination of different technique in an attempt to maximize the coupling effect of the kinetic energy source.

Despite this, the key issue associated with the design of harvester system is the voltage level produced by the generator along with the regulations of the vibration level used in a circuit. This is due to the fact that a generator produces an Alternating Current (AC) voltage that requires rectifier to be operated. In addition, it is evident from the literature that current vibrations typically use higher frequencies that are appropriate for such systems since its movement value is considered somehow high enough for real life vibration sources (Lefeuvre Elie, Audigier David, Richard Claude & Guyomar Daniel, 2007). Thus, PZT materials can be used to help solve the use of higher frequencies.

2.2.1 Piezoelectric Vibration Energy Harvest

There are many ways to get energy from nature, one of the recent ways is harvesting energy through PZT, proposed project to generate energy using a piezo sensor component that is useful for multiple applications.

Study focus on the development of a model of piezo material energy harvesting device for power generation, research also investigated on the behavior of plate made from piezoceramic wafer.

In this project, they transform mechanical energy into electrical power supply with piezo material configurations in a tile, this allow the system to achieve an optimum power.

System performance and evaluation were performed from a remote section while transferring was done via a wireless transition, power supply produces an AC signal was ripple to produce a Direct Current (DC) signal with a rectification circuit while receive signal such as power was display of user for monitoring with Liquid Crystal Display (LCD) (Sowmyashree M S,Naveen R, Naveen S, Manoj V and Shashanka M K, 2015).

Another research described the development of PZT for electrical power generation as challenging due to their low current, high voltage and high impedance output.

The research proceed to describe the theoretical analysis for power generation using PZT crystal material, paper describe that, if the potential difference apply to PZT device, the deformation will occur due to strain that is generated, however, if this phenomenon is reversed by apply strain to PZT, this will produce and electric field.

A research has also overcome the weakness that is related to cantilever mounted PZT device that commonly develops to use for mobile phone, this method, to the self-actuator connected in parallel while these are turned in order to resonate the frequency range derive from am ambient vibration, this have a similarity of same vibration that will produce by human foot stepping during walking while nickel battery with 40 to 80 mAh was recharged for result demonstration at 1.4 Hz frequency.

The result generated indicated to be enough to power a device for a long time and charging of battery found to be fast enough to use the system as an alternative way for power supply using a PZT device as vibration energy harvesting technology (Anil Kumar, 2011).

A research conducted by Raunaq Shah et al (2013). Generate power under a dynamic and quasi-static condition using PZT material, research indicated that PZT for power generation is more reliable, though, using this technology result in the low voltage generation in comparison to conventional battery.

Method approach to this project is dynamic and static method for exciting PZT generator while module consists of mechanical model that allow force to apply and electrical model that consist of RC circuit for power generation.

In this development, in Quasi-Static case, stress was used to produce an output voltage result into two opposite polarity peak, one peak occur one force apply, the other peak occurs once forcibly remove and an order of 100 ms force pulse length produce while dynamic is 10 ms force pulse length. Quasi-static method produce a 4.2 V and -4.5 V when PZT material use for experimentation purpose dynamic only, result to a positive voltage of 58.4 V that decay with time (Raunaq Shah, Rahul Khandelwal, Vishnukumar A, Prof Sudha R, 2013).

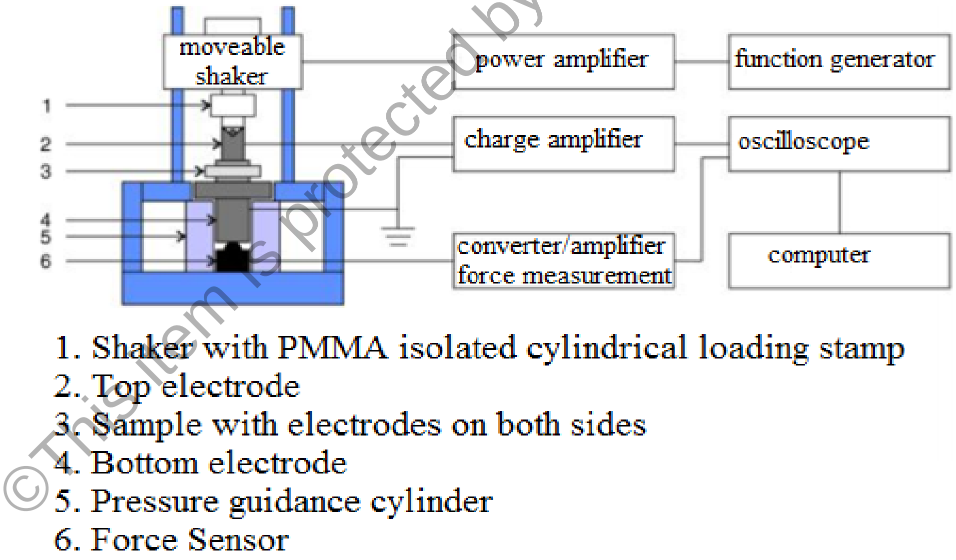

Figure 2.1: Power generating from a piezoelectric generator using piezoelectric generator. (Raunaq Shah, Rahul Khandelwal, Vishnukumar A, Prof Sudha R, 2013)

Another method develops for increasing the capability and efficiency of PZT type vibration energy harvesting, which is practically base of a cantilever beam, rather than just using the strain changes of a PZT device, it also adopts the use of a slight weight occur at the tip of the beam and hit PZT components that is located at two sides of weight. In this project, researchers illustrated that, hitting of the PZT component can result to the enhancement of this component during vibration energy harvesting.

Project suggested a method which could be used to increase the capability of a vibration energy harvest PZT device, this include rectification circuit using capacitor and diodes in order to convert the circuit into DC and result was calculated to achieve 22.3 % of the harvested energy is wasted while another method which involve the connection of a DC voltage getting from each group of applied to different capacitors, this could result to output electrical energy of 43 NJ from spring excitation with frequency of 18.5 Hz and initial vibration amplitude of 18 mm (Hu, J., Jong, J. and Zhao, 2010).

A method also proposed to generate energy from foot step vibration using PZT sensing devices, this method utilizes the movement of the human foot step for power generation, in this development, pressure is converted into a voltage while a source of pressure result from the weight of a moving object.

Signal output generated is not stable, therefore, project went ahead to the system by converting the resulting output variable voltage into a linear type while a filter circuit design to ripple unwanted AC signal for power consumption and storage purpose. In over all, voltage monitor through LCD which read through AT89S52 microcontroller (Mr.A.Adhithan, K.Vignesh and M.Manikandan, 2015).

2.2.2 Electromagnetic Generator from Vibration Energy Harvest

A generator design proposed and developed by J. R. Amirtharajah et.al, system developed to work from induce vibration cause by human foot stepping, upon project development, result design is micro and predicted to produce about 400 uW power from a movement of 2 cm within 2 Hz frequency, in order to generate power, an electromagnetic transducer and a moving coil was used which report to produced 180 mV. However, this reported to be too small while there is also need to use transformer voltage rectification (J. R. Amirtharajah and A. P. Chandrakasan, 1998).

A small design of electromagnetic generator proposed with a practical volume of 0.15 cm^3 and component volume of 0.1 cm^3 which utilize some discrete component specifically design to optimize a vibration.

Generator designed comprises of four magnets that are arranged on an etched cantilever wound with a coil with a moving magnetic field, in this design optimization of coil parameters and magnet coil was achieved, the result produces up to 46 uW in a tested resistive load of about 4 kΩ at an experimental resonance frequency of 52 Hz.

The result achieved about 428 mV from a design generator of 2300 turns of coil, this result, profound to be sufficient enough for rectification and voltage boosting while over result given implies that, the generator was able to deliver power up to 30 % collected from an environment which tend to produce electrical energy to load (Vida Pashaei and Manouchehr Bahrami , 2013).

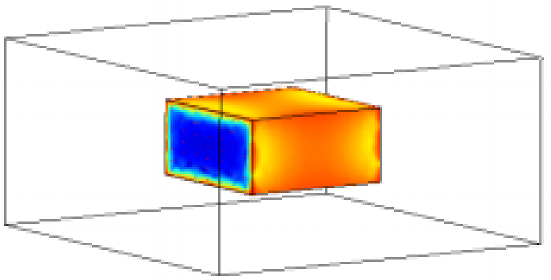

Figure 2.2: Neodymium Iron Boron magnet type with magnetic flux density. (Vida Pashaei and Manouchehr Bahrami , 2013)

Another design experiment of a rotary generator which consist of a multiplier hard magnet ring and a pattern arrangement of planner copper, size of the generator is small while the magnetic ring is made up of Neodymium Iron Boron (NdFeB) magnet, the result was optimized in this development which yield power of 7.23 mW at 4.5V rms at a rotation speed of 10000 RPM. (Lun-De Liao, P.C.-PChao, Jian-Ting Chen, Wei-Hsuan Hsu, Chi-Wei Chiu and Chin-Teng Lin, 2010).

A work also presented about harvest energy from vibration using electromagnetic phenomenon, the design comprises of a hula-hoop transformer, interface for harvesting energy and a micro generator.

Transformer design to have free movement as which is attached at the end of a rod, while the other end was hanging onto the primary mass, also consist of a mass string in a translation direction.

Configuration of the transformer allows the system to convert a linear motion to rotary ones based which has a similar concept of comparing to hula hoop motions.

However, transformer integrated to a rotating generator with integrated chips and component that serve as energy harvest circuit.

Design produces a power from the rotary generate by converting the linear motion into a rotational motion while main aim is to optimized the generator. Since design uses a linear motion technique, this is typically useful to convert vibration into electrical energy (Paul C.-P. Chao, C. I. Shao, C. X. Lu and C. K. Sung, 2011).

Another investigation was done on using an electromagnetic generator for electrical power supply, which is typically useful and can serve as vibration energy harvest technology for converting vibration into electrical energy, method was done via an analytical method using Finite Element Analysis (FEA), investigation was based on different configuration of magnets with respect to their behavior using FEA analysis. The result was able to achieve an average power that is up to 157 µW.

However, the investigation was ideally done via FEA and further analysis was based on the usage of ANSYS software (Zuraini Dahari, Wong Chin Chye, Othman Sidek and Muhammad Azman Miskam, 2011).

2.3 Rotor Power Generator

Many approaches have been established on power generator modelling such as a synchronous or asynchronous generator, however, using modelling software or simulation software for mathematical model found to be more problematic and difficult by many researchers (Spoljaric Zeljko , Miklosevic Kresimir & Jerkovic Vedrana, 2010).

Typical mathematical model of generator is usually between second order system to seventh order system, however, seventh other system is found to be more accurate, but complicated, a fifth order synchronous generator motor model approach using the simPowerSystems library in MATLAB.

Similar work for motor model describe in (K. Miklosevic, Z. Spoljaric and Z. Valter, 2009), while synchronous motor modelling also describe in (K. Miklosevic, Z. Spoljaric and Valter, 2009) while problem that usually persist on asynchronous generator model and discuss in (K. Miklosevic, Z. Spoljaric and Valter, 2009).

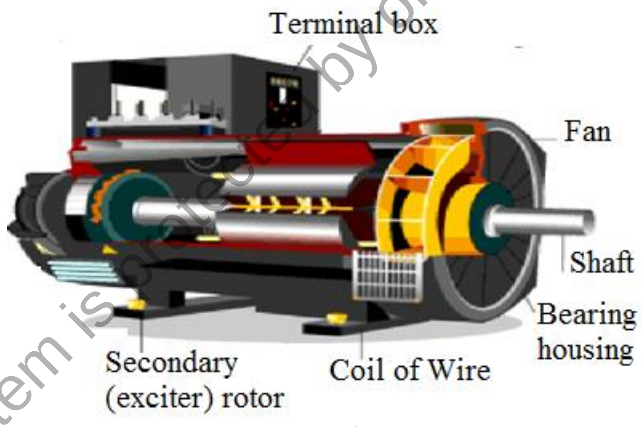

Figure 2.3: Typical view of synchronous generator.
(Spoljaric Zeljko , Miklosevic Kresimir & Jerkovic Vedrana, 2010)

However, modelling and analysis of induction generator of wind turbine, variable speed has been approached by various modelers, induction machine has been widely used for various applications as a means of converting electrical energy into mechanical energy or vis-versa, while many wind power uses induction machine due to their economic factor, reliability and ability to operate with a variable speed control system. Though it was noted that induction machine could have drawn back which required reactive power for excitation.

Problem related to current excitation and power generation is well discussed in (Ofualagba G and Ubeku E.U, 2012). Furthermore, induction machine typically made up of numerous coil and usually supply with three phase current, which combination of coil and current produces rotating magnetic field, working this in reverse pattern produced electricity which make the machine suitable for power generation.

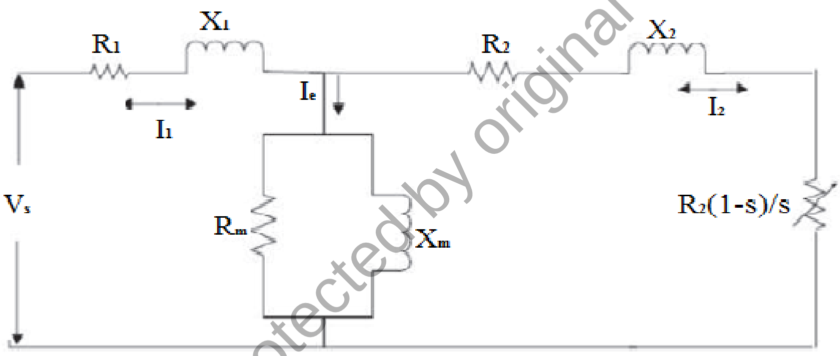

Figure 2.4: Induction machine equivalent circuit.
(Ofualagba G and Ubeku E.U, 2012)

2.4 Piezoelectric Materials

PZT materials are common sources of voltage especially when the tension is induced in accordance with the materials. The resulted frequency of 80 Hz allowed to operate different numerical calculations and trials, which also help process different power sources.

The amount of researches devoted to optimizing and extending the utility of PZT energy harvesting has been extended based on the configuration of embedded energy source (Erturk, A, & Inman, Daniel J., 2009).

Typically, the PZT material remains a great emerging technology with brand new breakthrough innovations, especially after supporting non-linearity into the particular stiffness of systems. This is believed to increase the range of frequency and the quantity of energy that may be harvested (Saadon, Salem, & Sidek, Othman., 2011).

Nevertheless, the electrical pattern of a constant process can be characterized based on the field strength E and the dielectric displacement D through which the relationship is defined by the following equation:

$$D=\varepsilon E \tag{2.1}$$

Where, ε is refers to the permittivity of a process in a specific medium.

Similarly, the mechanical pattern of medium set at zero electric field can be estimated based on the value of stress began utilizing T along with the value of strain S calculated as following equation:

$$S=sT \tag{2.2}$$

Where, s is refers here to the variable compliance of the medium.

Based on these operations, the application of piezoelectricity mainly consists of the interaction usually occurred when the electrical and mechanical pattern is matched in a certain medium.

2.5 Design of Piezoelectric Energy Harvest

Presently, battery technology is utilized to give the electricity to most portable electronics devices. However, these batteries can be cumbersome for some application, furthermore, their operation is unreliable under high-acceleration situations.

Additionally, they are prone to spillage whenever they reach their maximum capacity periods. Alternative solution to energy sources such PZT energy harvester being proposed for this reason.

In this proposed project modeling and design, the electrical energy is created by harvesting the energy that is accessible from the environment (vibration energy), rather than depending on the massive batteries for the electric power. Vibration energy generated from the motor is harnessed and a PZT transducer is utilized to convert this vibration energy to electrical energy for low power supply.

This present task is to analyze and demonstrate PZT material properties, also to create a system that will permit developers to utilize these devices as an energy harvester tool. The primary objective is to produce the device simulation which can help researchers to interface PZT hardware in order to assess the performance of the devices.

PZT materials are typically a type of transducer that allows energy transformation between both mechanical and electrical sources in a predictable strategy. PZT materials can be discovered natural and they can be man-made type of material.

There are two major operational methods for the device. The first operation method is called Direct PZT Effect, is the situation where a mechanical stacking of the material utilize to create an electric field. The second operation method is called Converse PZT

Effect, is the situation where using electric field to create a mechanical deformation of the material. In this work, Direct Effect operational method the focused by converting the mechanical energy to electrical energy which can be effectively utilized or stored.

2.5.1 Piezoelectric Material

There are two major types of material that do possess PZT properties, these are Piezoceramics and Quartz. Quartz properties occur naturally, however, this can be costly and has constraints in which ways it might be utilized. Piezoceramics are more versatile in their usage and they can reconstruct it to a desired geometries.

A typical PZT material will consist some material properties like high PZT constant that used to determine the effect that occur between mechanical and electrical output, also, it describes electro-mechanical coupling coefficient of the material which can be utilized to understand and measures how efficiently the material would transform its mechanical energy to electrical energy or the other way around.

Other important parameters measurement regarding PZT material known as Curie temperature, this is the thermal point where PZT material possess the ability to free of its PZT properties. In a situation whereby, the material has a very low Curie temperature, its thermal working or operational region will be extremely limited.

2.5.2 Piezoelectric Ceramics Material

Piezo-ceramic materials are mostly made by hand in different range and type. It usually has high coupling coefficients and it is exceptionally flexible which make the material suitable for custom applications.

Another ceramic PZT material favorable aspect is that, they don't experience the scarcity like other natural material because they are man-made and crystal orientation. The material concentrated for study and modeling is lead-zitronite-titanate (PbZrO3,PbTiO3), regularly called PZT material.

PZT materials are fabricated by sintering a finely ground power blend. The powder is typically made of ferroelectrics of the oxygen-octahedral type, which are initially molded into the desired shape.

PZT ceramics consist of various ferroelectric grains, each containing domain that allow the electric dipoles to align. To legitimately illustrate PZT properties, the material must be polarize through heating method at high temperature include the application of strong electric field, for this design and modeling concept, the paper examined PZT8 or PZT5 ceramic type.

2.6 Design of Electric Machine for Turbine Power Generator

2.6.1 Operation of Electric Machine

Electric machines can be characterized into electromagnetic machines and electrostatic machines. However, electrostatic machine is not practically suitable for machines for commercial electric power, therefore, the current design focus on electromagnetic machine principle of operation.

Despite the fact that one sees an assortment of electrical machines in the business sector, the essential underlying standards of all these are the same. To comprehend, outline and utilize these machines the taking after laws must be examined.

To understand the basic working principle of electric machine, someone needs to understand four main different laws that govern these principles which are:

1) Electric circuit law, such as Kirchhoff's laws
2) A magnetic circuit law which is Ampere's law
3) Law of electromagnetic induction typically known as Faraday's law
4) Low of electromagnetic attraction which is also known as BiotSavart's Law

Whereas, the listed laws do have one or more electric circuit link that do link a common magnetic circuit. Therefore, the design of electric machine for turbine power generator focus on DC type abiding the two basic laws namely BiotSawart's Law and Faraday's law.

DC machine is sort of electromechanical energy converter, it could work as either generator or motor, that is, it can convert electrical source into mechanical likewise converting mechanical power into electrical power, these machines suitable for electrical power generation fitting them into low wind profile wind turbine system.

2.6.2 Turbine DC Generator System

In turbine generator design a static magnetic DC current is produced by a static electric field that is produced by a permanent magnet or coil carrying this DC current.

In this scenario, a coil move under magnetic field to create the change in flux linkage at the same time electromagnetic field (EMF) is induced, this emf in a conductor experiences a cyclic change in voltage as it passes under south and north pole polarity alternatively, therefore induce an emf in the conductor consequently is not a constant because there is alternate in magnitude.

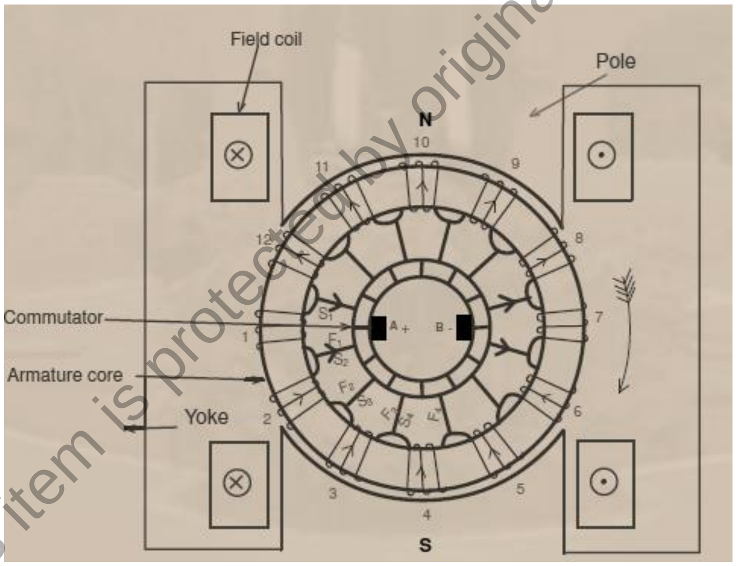

Figure 2.5: Two pole machine design concept having Gramme ring type armature.

For a constant speed or velocity of sweep, there is a proportionality between induced voltage and flux density under it moves condition, therefore, if the variation of flux density is sinusoidal in space, it will create a sine wave voltage.

This phenomenon is utilized in AC generators with respect to DC generators, the idea is to achieve a steady DC voltage at the winding terminals and not the shape of the

EMF in the conductors. This could be accomplished by utilizing an external element known as a commutator, with the winding.

According to Figure 2.5 two pole machine designed, 12 different coils are turned at uniform spacing around the rotor having a junction, of all individual coils with its neighbor connected to commutator section. Every commutator section has a mica separator for protecting it from its neighbor.

Two brushes A and B are placed on the commutator that resembles a cylinder. If the connected from brush A to Brush B is trace, they're two paths located while in each path there is an additional set of voltage and the aggregate of the EMF is constant.

The magnitude of the constancy alters by a small value which is corresponding to the coil short circuited by the brush. Since the aim is to acquire an output voltage maximum value, therefore position choice will be at field neutral axis.

When an armature is turned via separation of one slot pitch, the approximate sum of EMF is seen to be constant despite the fact that an alternate set of coils partakes in the addition.

The short circuited coil has almost zero voltage induced in the same, subsequently the sum does not change significantly. This variety of the output voltage is known as the "ripple" while more quantity of coil participating in the sum lesser is known as "percentage ripple".

Another essential consideration for the working rule of the generator is that, the real flux thickness curve actual shape is not too important provided that, the integrated flux density of the rotor is held constant, which implies that for a given flux per pole, voltage remains constant even when flux density curve shapes change, that is when speed or other variable conditions remain unaltered. This is one important reason why we can take the average flux density over the whole pole pitch and flux density is thought to be rectangular.

There is much advantage of using a rectangular flux density wave form pattern in voltage derivation between brushes when relate it flux density curve, induced EMF in every turn of the armature gets to be constant and equivalent to each other.

$$E_c = B_{av}.L.v \tag{2.3}$$

$$v = 2p \times Y \times n \tag{2.4}$$

Where, L is the active conductor length m, B_{av} is the average flux density over a pole pitch Tesla, V is the sweep velocity of conductor m/sec, p is poles pair, Y is the pitch of the pole and n is the revolution number made by armature per secs.

However, in respect to the adopt design, if there is a conductor Z on the armature while this form parallel circuit b pair between the brushes via their virtual conditions, the resulting number of conductors in a series path will give:

$$\frac{Z}{2b} \tag{2.5}$$

While inducing EMF of the brushes will give:

$$E = E_c \frac{Z}{2b} \tag{2.6}$$

$$E = B_{av}.L.v \frac{Z}{2b} \tag{2.7}$$

Rearranging of equations:

$$B_{av} = \frac{\phi}{L.Y} \tag{2.8}$$

$$E = \frac{\phi}{L.Y}.L(2p \times Y \times n)\frac{Z}{2b} = \frac{\phi pZn}{b} \tag{2.9}$$

2.6.3 Production of Torque

At the point when the armature is stacked, the armature conductors convey currents while these current conveying conductors interact with the field and experience the force that is acting on the same. However, forces produce in such a direction needed to oppose their causes leading to relative movement of the field and the conductors, hence force directly oppose the motion and absorb mechanical energy.

The mechanical energy absorbed reveal itself as the electrical power that is converted. However, the generated armature electrical power delivers current *Ia* to attach load at an induced electromagnetic force resulting in electrical power generated.

$$2\pi nT = EI_a \tag{2.10}$$

Therefore:

$$2\pi nT = \frac{\phi pZn}{b} I_a \tag{2.11}$$

Which give:

$$T = \frac{1}{2\pi}\left(\frac{Ia}{b}\right)Z * \phi p \tag{2.12}$$

Where, Ia is the armature current, T is the DC machine torques N.M and E is the induced EMF.

Equation derives indicated that, torque generated are not exactly speed function, but there is a proportionality between torque, total ampere conductors, I_c and total flux results to.

$$I_c = \frac{I_a}{2b} \tag{2.13}$$

However, the amount of torque generated through the described expression can also be derived using law of attraction resulting to:

$$F_c = B.L.I_c \tag{2.14}$$

$$W_a = B_{av}.L.I_c.Z.(2pY) = \frac{\phi}{L.Y}L.I_c.Z.2p.Y \tag{2.15}$$

$$P_{conv} = \phi.I_c.Z.2p.n \tag{2.16}$$

$$A_s I_c = \frac{I_a}{2b} == \phi.Z.p.n.\frac{I_a}{b} \tag{2.17}$$

Where, F_c is force on single conductor, B is flux density, L is conductor length, W_a is work done and P_{conv} is the converted power.

2.7 Vibration Frequency for Vibration Motor

Mechanical phenomenon that oscillation does happen around an equilibrium point can be regarded as vibration. The word originates from Latin, that is vibration which means "shaking, waving". The oscillation of might is intermittent or periodic, for example, the movement of a pendulum or arbitrary, typical example is a moving tire on a gravel road.

There are many sources of vibration such as those that occur through machines, loudspeaker and other, however, a major source of vibration can be free type, force type of damped vibration.

However, vibration is sort of energy wasting such as the vibration that generate from electric generator or motor, typically this vibration could utilize by converting it into electricity. The project design interest in understanding the direction relationship between motor speed and its vibration frequency for energy harvest, therefore some certain range of frequency are needed for this reason. The project designed emphasis or understand the vibration of the motor operating at a certain frequencies such as 100 - 200 Hz. However the relationship between motor and vibration frequency is given as:

$$f_{vibration} = \frac{MotorSpeed\ (RPM)}{60} \qquad (2.18)$$

In related to the design, since motor speed can achieve from DC machine, the developer can easily examine it frequency, however, it is observed that the vibration frequency does have direct relation to the motor speed but independent of motor size or voltage and lots more. However, the motor speed is dependent of applied voltage, therefore, motor speed can vary through input voltage, however, the focus of this paper is to utilize the vibration frequency in order to provide a model for vibration energy harvest using PZT device. There are numerous caveats and limit with varying vibration frequent, these are categorized into upper frequency limit and lower frequency limit.

2.7.1 Upper Motor Frequency Limit

Common rotation of the motor shaft is typically produced by providing current through wire magnetic field, however, using the motor as a generator is vis versa and force is created. There is also a small variety of motor above 24 V while most stay within 1.5 V to 3 V, this make current become limited while problem can also overheat from excessive current. Therefore, most motors do have a speed limit which can achieve a vibration of motor that is up 312 - 401 at 17,000 revolutions per min (~283 Hz).

2.7.2 Lower Motor Frequency Limit

Slowest frequency and speed of vibration could range between 324 - 102 rated at 2800 rpm that is approximately 47 Hz, the equation that governs vibration strength of the motor can be given as:

$$f_o = m \times r \times \omega^2 \qquad (2.19)$$

Where, m is the motor mass of eccentric weight, r is eccentric weight, ω is motor angular velocity (speed) and f_o is the motor frequency vibration strength.

Therefore, frequency of vibration and amplitude of vibration is dependent on motor speed, therefore, once the speed of the motor is adjusting, this will have an effect to the frequency or amplitude of motor vibration.

2.8 Forced Vibration with Damping

The design approach a force vibration with damping and this can easily illustrate with a spring model which also varies with harmonic force, this type of force could be any form, however paper considers force generate from rotating machine (cause of imbalance). The mathematical equation of these force type describes as follows:

$$F = F_o \, sin(2\pi f t) = m\ddot{x} + cx \dot{+} kx \qquad (2.20)$$

Vibration amplitude and ration of force frequency describe as:

$$X = \frac{f_o}{K} \frac{1}{\sqrt{(1 - r^2)^2 + (2.\varsigma.r)^2}} \qquad (2.21)$$

Where, X is vibration amplitude, f is vibration frequency and r is harmonic force frequency ration.

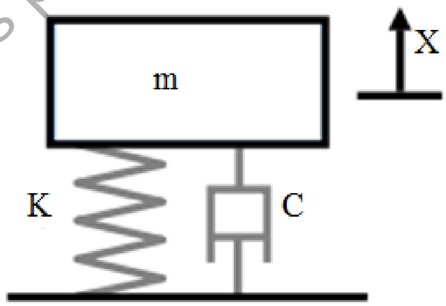

Figure 2.6: Model damper of mass spring.

2.9 Previous Works

Various studies were established to provide an enhanced low wind energy harvester using different techniques. A research proposed the design of PZT energy harvester by considering the linkage in energy resulted from the flow-induced vibration.

The main process is to convert the obtained energy into electrical energy. Such process involves imposing PZT conversion with oscillation of a PZT film. The authors also developed a way to determine the value of voltage resulted from the PZT laminate based on finite element model.

This is followed by modeling the energy harvester under certain experimental conditions where the obtained result revealed that open circuit output produced 2.2 Vpp and an instantaneous output power of 0.2 µW when experiencing frequency of 26 Hz (Wang Dung-An, & Ko Hong-Hua, 2010).

Another work proposed using the two-stage harvesting system to help provide a low wind energy profile. The use of two-stage harvesting was contributed to the characteristics of the harvesting environment that was used to estimate the primary system.

The concept was also used to provide an alternative secondary system of vibratory elements. The potential of such design was addressed to promote low and varying-speed input, especially in the event of having a constant and higher value of vibration frequency.

The authors also used PZT elements in order to harvest the frequencies of the secondary system. The validation result showed a substantial performance of the new generators that was also tested under different speed profiles.

(Moss, Scott, Barry, Alex, Powlesland, Ian, Galea, Steve, & Carman, Gregory P, 2010) investigate the use of a vibro-impact method for the aim of establishing broadband kinetic energy harvester. Theoretically, the authors put into consideration the impact could be resulted from the process of vibro when the vibration source differs in time based on the properties of the auto tuning mechanism.

The energy harvester profile produced was based on the use of a vibro - impacting oscillator along with double-sided, symmetrical, PZT bimorph-stops. The frequency range that was used for processing the harvester model was ranged between 100 - 113 Hz with an energy profile of 5.3 mW from an rms host vibration of 450 mG (Rastegar J, & Murray R., 2010).

System optimized the potential of the piezo-element to compiling the energy source of wind into stored elastic energy. The authors achieved this by identifying the configuration of geometry and dimensions which served as a medium for linking the upwind bodies.

The outcome of such utilization led to a new circuit that was named quasi-resonant rectifier. The goal of the design has been mainly to extract electric energy from the PZT frequently from the piezoelement than a conventional full-wave rectifier.

The authors also examined the potential of such design against other PZT and electrostrictive materials (Robbins William P, Morris Dustin, Marusic Ivan, & Novak Todd O., 2006).

In addition, Gao, Shih, and Shih proposed a new method named PZT flow energy harvester PZT Flow Energy Harvester (PFEH). They considered the use of PZT cantilever combined with the properties of cylindrical extension under certain environmental conditions.

They also found that the flow induced vibration of the cylindrical extension leads PZT cantilever to progressively vibrate when experiencing different frequencies. The authors illustrated that their method offers low cost, compact, and a scalable power source for small electronics by harvesting energy.

The validation result of the method was examined in laminar and turbulent air flows, which results in reliable performance based on the domination of driving mechanism in vortex shedding excitation (Gao Xiaotong, Shih Wei-Heng & Shih Wan Y., 2013).

2.10 Summary of Literature Review

Literature review summarizes different journals and works implemented by other researchers, while the focus was based on the ways to generate power from generating machine and vibration, energy harvest from vibration were detailed and several models and mode to harvest energy were discussed.

The research provides an understanding of energy coming from the process of collecting incoming energy sources and turning them into electricity, however, extracting electrical energy from the environmental sources led many researchers to consider the potential of other materials such as PZT to improve on the current extracting techniques while the motivation of considering such materials comes from the global warming perspectives which impose a remarkable challenge in lowering the carbon footprint.

Different model approaches, focused on efficiency and reliability while the source of vibration can either be a footstep, shaking and electrical power generation from PZT is challenging due to their low current, high voltage and high impedance output. The discussion proceeded to describe the theoretical analysis for power generation using the PZT crystal material.

The review also discusses system developed to work from inducing vibration cause by human foot stepping, upon project development and many approaches has been established on power generator modelling such as using a synchronous or asynchronous generator. According to information gathered, using modelling software or simulation software for mathematical model found to be more problematic and difficult by many researchers.

Various studies were established to provide an enhanced low wind energy harvester using different techniques, using the two-stage harvesting system to help provide a low wind energy profile, vibro-impact method for the aim of establishing broadband kinetic energy harvester and a new method named PZT flow energy harvester while the validation result of the method of each investigation were examined.

CHAPTER 3

METHODOLOGY

3.1 Introduction

The process associated with converting mechanical low frequency into electrical energy using PZT and rotor transducer depends on transformation energy from mechanical to electrical energy which usually done using a rectifier and DC - DC converter circuit.

In this study, the research considered trapping the mechanical properties from obtainable source, then converting the mechanical energy into electrical energy with PZT and rotor, and finally process the generated electrical energy.

As for the rotor embedment into the PZT design, Williams and Yates (1996) analyzed the method used to assess the feasibility of the design using harmonic analysis of the generator. For the analysis, the mass of the vibration source is considered much greater than the mass of the seismic mass in the generator, and the vibration source is an infinite source.

According to Figure 3.1, the project design utilizes a series of equations while these equations were used to model the entire system in the MATLAB environment. The first approach is the design and model of turbine generator for electricity production. Meanwhile, for second stage of the design is to figure out on how wind speed would affect the generated vibration of the motor and the final stage is to design and model piezoelectric device in order to harvest the generated vibration and convert to electricity.

3.2 Simulation Tools

The aim of the project is to build up a configuration device for PZT materials and DC generator as a low wind turbine representation. PZT materials consist of two different sides, these include the mechanical side and the electrical side.

Figure 3.1 presents the main phases to be followed in this study. It started with the setting of the MATLAB environment based on the energy harvesting source. The turbine model is considered in which the wind load has been applied to it.

The vibration movement of the turbine will be estimated based on the wind data collected. The energy harvester has been obtained by comparing it with different cases in accordance with the stiffness, mass and damping coefficient.

Rotor and PZT have been applied into the vibration in order to produce the low energy harvester. Moreover, the energy output also estimated to determine the effectiveness of the combination of rotor and PZT for providing a low wind profile based on the oscillation amplitude of the turbine as an indication of the potential energy that can be harvested.

However, precise or good modelling and simulation of the material would have to consolidate both electrical and mechanical of PZT material, whereas generator do consist of rotor that vibration generated is typically proportional to speed of the rotor itself.

The MATLAB coding software was utilized along with MATLAB/Simulink. This software was used to simulate and imitative the PZT material mechanical side, including environment vibration produce by DC generator.

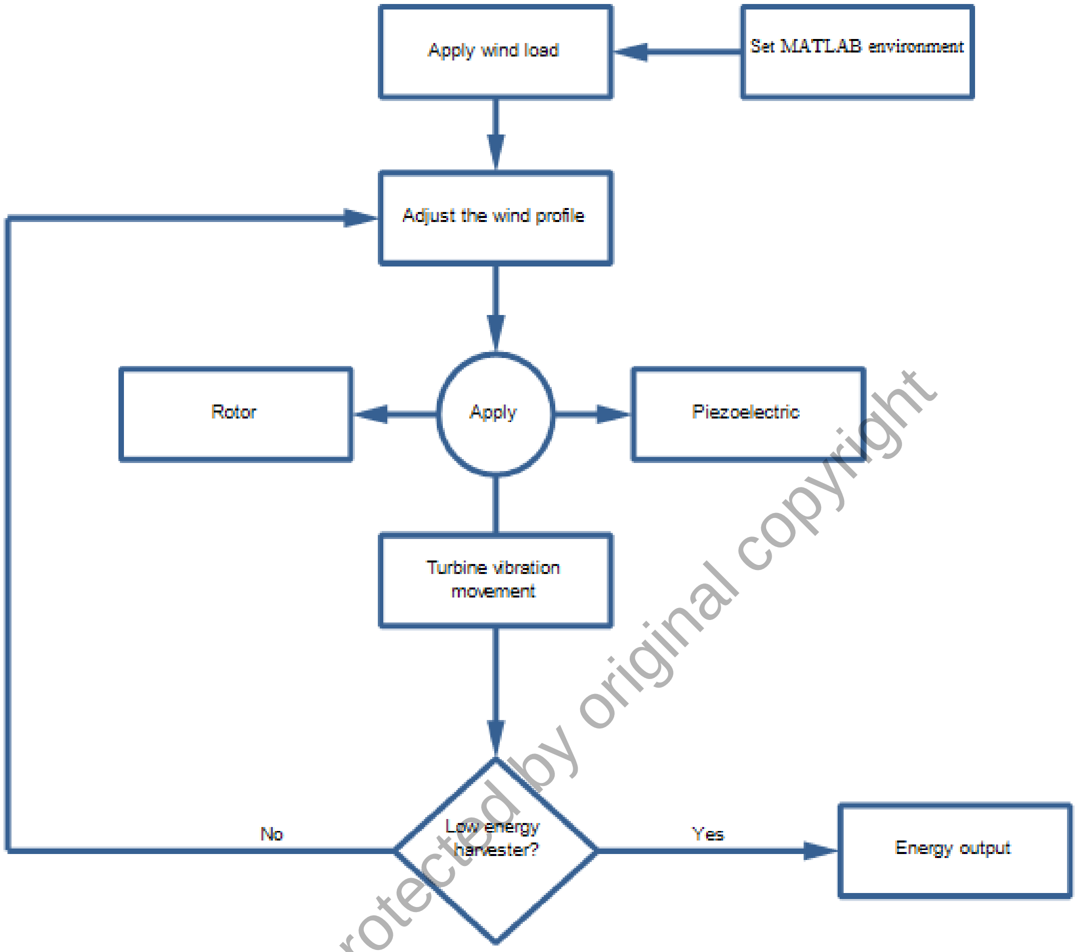

Figure 3.1: Study flowchart of the proposed system.

3.3 Modelling Rotor and Piezoelectric Energy Harvester

3.3.1 Piezoelectric Energy Harvest Resonator Model

In this model a mechanical mass-spring resonator was built to provide a solution for understanding the transfer function representation of the PZT device, mechanical system and electrical. By having this information, the mass-spring resonator is modeled as a single axis mechanical system comprises of a spring and attached mass at its free end.

The model implies that, when force is applied to the mass, this triggered the mass spring to oscillate while the PZT material is placed between the rigid attachment and the spring. It was presumed that, no presence of deviation in the PZT material, physical dimension, for example, radius, thickness and Young's Modulus.

Therefore, force that is transmitted via the PZT material can be examined by calculating the amount of force that is exerted through the spring. The method approached is by examining the spring deflection and multiplying the result of the spring constant.

3.3.2 Mechanical Model Derivation of Resonator

The first approach is the analysis of mechanical system itself. The model consider a system which consist of a housing, where by, a rectangular shape piece of PZT material is mounted. This material is to located between the mass spring unit and the housing. This allows the combination of mass-spring system to oscillate whenever a force is applied. This oscillation model is to form as a compression techniques for PZT material in order for PZT material to generate a voltage.

For the mechanical model, few assumptions were made. The model ignore the internal damping material because the contribution of the effect is typically small. It is assume that the system is one dimensional and PZT deflection was ignored.

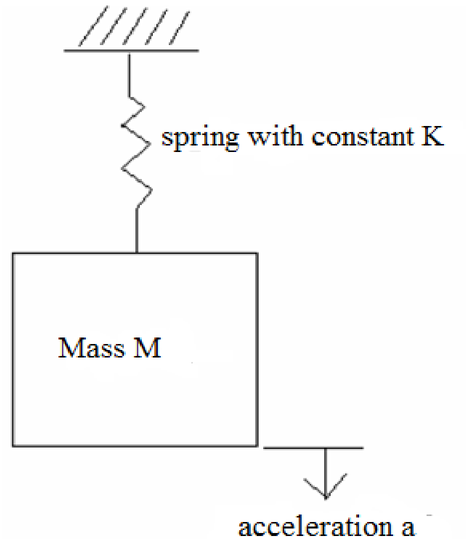

Figure 3.2: Resonator diagram for mass spring modelling.

3.3.3 Models of Piezoelectric Device

The model comprises of a simple electrical equivalent circuit that has a voltage source model to connect series with loss resistance and capacitance, however, voltage source value is directly related to two major elements, these are forces that is applied to the material and the PZT material itself.

Therefore, provided information for modelling do allow output PZT material voltage to be examined and predictable. The modeling implies that, the capacitance of the equivalent circuit calculated from PZT material relative dielectric constants, height and area of the material.

Loss resistance describes in finalize equivalent circuit illustrate the loss that travels across the regional surface of PZT material to the electrical leads while leakage resistance illustrate loss that describe the current travels through PZT material.

Usually, the loss resistance is typically small while the leakage resistance is usually high, this high or low properties of a material depends on material thickness. The loss resistance is defined PZT material loss target, the material capacitance and the operating frequency.

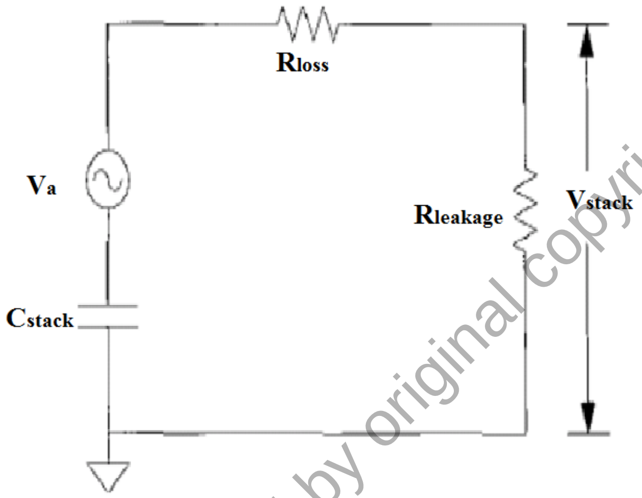

Figure 3.3: Piezoelectric material using electrical model.

$$R_{loss} = \frac{tan\,\partial}{\omega C_{stack}} \tag{3.1}$$

$$C_{stack} = \frac{tan\,\partial}{h_{piezo}} \tag{3.2}$$

3.3.3.1 Piezoelectric Theory and Physics

PZT signifies "electricity by pressure". This implies that, an electric field is created by the material when it is under mechanical deformation. When strain is applied to PZT material, this cause the material to polarize and produces an electric field as described in Figure 3.4.

As PZT material is compressed by external force, the atomic structure symmetry is disrupted, which produces poles at the atomic structure of the material and generate the field. However, the converse effect method works similarly. At the point when an electric field applies across the material, this causes the material polarize and deform the material.

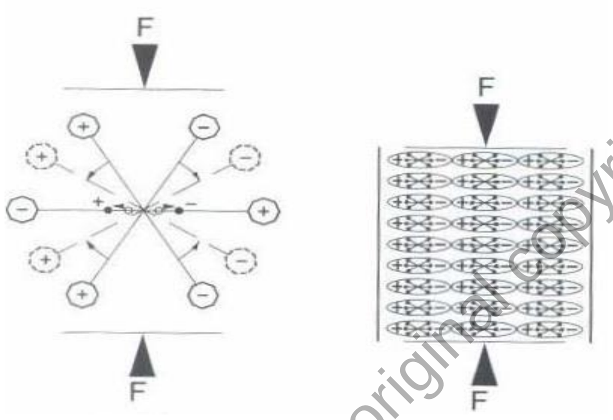

Figure 3.4: Piezoelectric material atomic distortion.
(Gautschi, Gustav, 2004)

PZT materials is termed as an anisotropic and isotropic characteristics. Isotropic material physical properties, for example, the dielectric electromechanical coupling coefficient and dielectric coefficient are uniform, regardless of the axis that material is being inspected.

Anisotropic material physical properties are most certainly not free of the physical axis inspected. When they are unloaded, they become isotropic, and along these lines, their physical properties are not subject to which axis of the material is being inspected, it will exhibit anisotropic properties at the point when the material is loaded. In this manner, it is very important to understand the direction one inspects the material.

The PZT constants are described as *Xab*, where *X* denotes the constant symbols and it is the axis required to inspect the material, electrical properties while *b* represent the required axis for inspecting the mechanical properties and in Figure 3.5 demonstrate where by all label axis are the distinctive linear direction 1, 2 and 3.

An illustration of this axis terminology is *K13*, that is, it has an electromechanical coupling coefficient where it's electrical characteristics inspect from the *X* axis and the mechanical characteristics inspect on *Z* axis, therefore the electrical output could measure at *X* if the mechanical material is being excited at *Z*.

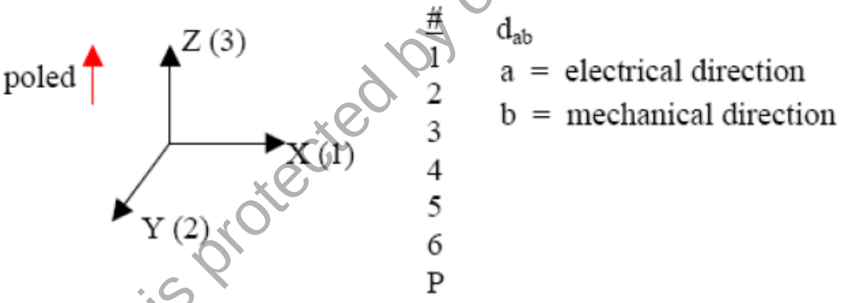

Figure 3.5: Electro-Mechanical constant axis notation.

(Phillips, James R, 2005)

Most PZT devices found to govern by one particular equation known as PZT equation. This equation relates compressive force per unit area, that is pressed to the electric displacement. This is the simple equation utilized as a part of the analysis of PZT devices (Phillips, James R, 2005).

$$D_i = d_{ij} \times \sigma_j = d_{ij} \frac{F}{A} \tag{3.3}$$

Where, D_i is electric displacement, σ_j is mechanical stress, F is force, A is area and d_{ij} is PZT constant.

However, PZT effect is typically linear in nature, therefore, the electric field created is directly proportional to the stress to which the material is subjected. There is link between the PZT strain coefficient to these two properties. This same coefficient is used to create a converse PZT effect.

Equivalent circuits in Figure 3.6 is the modelling concept electrical properties of PZT materials, which include a simple configuration capacitive and resistive components, therefore PZT material exhibit electrical resonance and characterized resistance, capacitance, inductance. These properties have a direct relationship with the PZT modulus "e" and area.

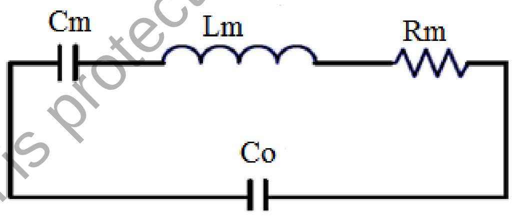

Figure 3.6: Equivalent circuit of piezoelectric material model.

Therefore, PZT materials using the electrical equivalent circuit equations at electromechanical resonance derive as follows:

$$R_m = \frac{\eta l}{Ae^2} = K_R\eta \tag{3.4}$$

$$L_m = \frac{\rho_s l^2}{2Ae^2} = K_L\rho_s \tag{3.5}$$

$$C_m = \frac{Ae^2}{cl} = K_c \frac{1}{C} = K_s S \tag{3.6}$$

$$C_o = \frac{\varepsilon A}{l} \tag{3.7}$$

Where, C is elastic constant, η is viscosity, ρ_s is surface mass density, s is compliance coefficient, e is PZT stress constant, A is area and l is height of the material.

3.3.4 Modeling of Piezoelectric Device Voltage Source

The PZT material mechanical model is based in mass-spring-damping system as described above in this paper, this provides a resulting force equation given as follows:

$$F = m_{Piezo}\ddot{x}_{piezo} + c_{Piezo}\dot{x}_{piezo} + k_{Piezo}x_{piezo} \tag{3.8}$$

Where, m_{Piezo} is the PZT material mass, c_{Piezo} is PZT material internal damping and x_{piezo} PZT material spring constant.

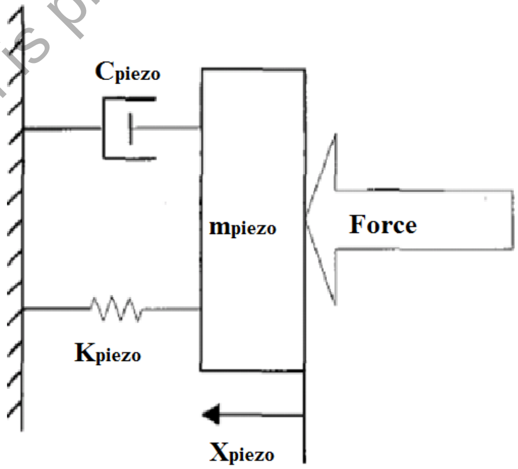

Figure 3.7: Piezoelectric material mechanical representation.

For any applied compression, the system store mechanical energy while the equation can be written by relating the young's module to the spring constant. The resulting equations are given as:

$$W_{mech} = Fx_{piezo} \tag{3.9}$$

$$Fx_{piezo} = \frac{1}{2}\frac{F^2 h_{piezo}}{YA} \tag{3.10}$$

Then the next phase of the model is to determine the amount of electrical energy generated in the PZT device, this is described in Equation 3.11, therefore by equating the mechanical energy equation in an electrical energy equation will provide a possible solution for calculating the internal voltage is generated by PZT devices.

$$W_{elec} = \frac{1}{2}\,\frac{q^2}{C_{stack}} \tag{3.11}$$

Therefore, solve for internal voltage is:

$$V_a = \frac{K_{33}F\,h_{piezo}}{A}(0.5Y\varepsilon)^{\frac{-1}{2}} \tag{3.12}$$

3.3.5 Modeling of DC machine

The model is a complete separately excited DC generator model which comprises of different blocks as per derived equation using MATLAB/Simulink, however, the major component of the model is DC machine model which consist of four major terminals include field terminals, armature terminals, torque input terminal and measurement terminal, however measurement terminal is connected to a bus demuxer block, this terminal is where speed, armature current, field current and torques is measured and record as a reference to speed requires for vibration energy harvest modeling and simulation.

In the model, field terminal ($F+$, F-) allow the model to work as either series connected DC machine or shunt connected DC machine while the armature model comprises of resistor Ra and inductor La have a counter electromotive force which is proportional to machine speed and there is also a proportionality between voltage constant K - E and field current I - f. This can be expressed with the given equation:

$$E = K_E \omega \tag{3.13}$$

$$K_E = L_{af} I_f \tag{3.14}$$

Where, E is electromotive force or output voltage, K_E is the generator voltage constant, L_{af} is field armature mutual inductance and I_f is the field current.

However, in this model, electromechanical torques of the DC machine have a direct proportionality to armature current while torque constant is equivalent to voltage constant.

$$T_E = K_T I_a \tag{3.15}$$

$$K_T = K_E \tag{3.16}$$

3.3.6 Force Response of Single Mass System

The model present the usage of MATLAB for vibration analysis based on rotor excitation, the behavior of vibration is considered as a single degree of freedom, therefore these effects of vibration are assumed to cause by the rotation effect of the machine that is mounted on a flexible floor.

This scenario also assumes that, rotor crack having a small mass rotating as a certain angular velocity causing the mass to vibrate, this mass could be added with any external mass, in these scenarios, we are adding PZT device material which model to harvest the free vibration when vibration forces model through vibration frequency apply to apply to this device.

The model focus on forced response of a single degree of freedom system governs by the following equation:

$$F_o\, cos(2\pi f t) = m\ddot{x} + cx \dot{+} kx \tag{3.17}$$

3.3.7 Using Model

The complete separately excited DC generator model represent similar power generator that can utilize for low wind profile turbine power generating system, machine model to have an external load and generate the machine or rotor speed, torque and current analysis using MATLAB/Simulink. However, the motor speed is then used to compute the physical properties of free vibration generated from the machine.

The computed free vibration is analyzing to generate an input compressive force by relating it to the mechanical resonator model while the electrical properties and the material physical properties and the use to compute the harvested voltage waveform. However, the modeling of electrical model written in MATLAB use to calculate the voltage that is generated by PZT material.

However, due to two major parts of PZT model apply, that is mechanical and electrical part, the code uses impingent force and material property to convert the mechanical energy into electrical energy while only the voltage generated are account and description for this MATLAB code.

3.4 Summary of Methodology

The process in this chapter is associated with converting mechanical low frequency into electrical energy using PZT and rotor transducer depends on transformation energy from mechanical to electrical energy.

This chapter provides all the idea and information regarding the system design and the functionality of the system, it comprises of design concept, mathematical equation involve and the system sustainable.

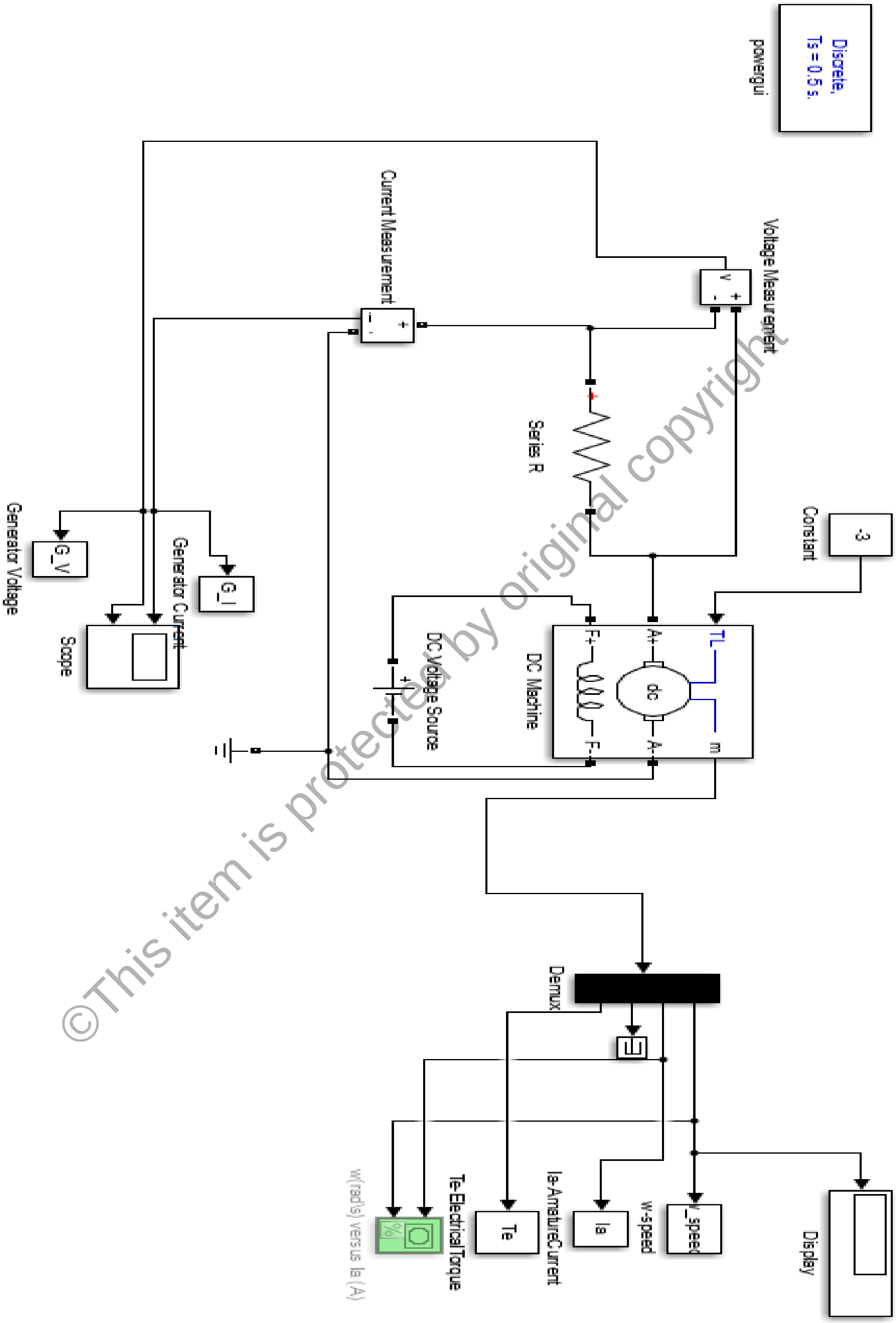

Figure 3.8: DC machine power generator MATLAB/Simulink model.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Introduction

The project result generated can be categorized into three main different sections, first section is the DC generator which use to illustrate how to generate power from the turbine generating machine, second section is the waste vibration generated from the DC machine while the third model convert this waste vibration energy into useable electrical energy using PZT material.

4.2 DC Generator for Turbine

The model considers for the DC generator machine is a simple model which produces voltage by varying the speed as shown in Figure 4.1, the results show the proportionality between voltage and speed, that is when the speed of generator increase, there is an increase in output voltage.

Since DC machine vibration frequency is changed with increasing speed as shown in Figure 4.2, the results provide a linearity between motor speed and vibration frequency in order to extract the data for determining the amount of vibration generate by the machine load.

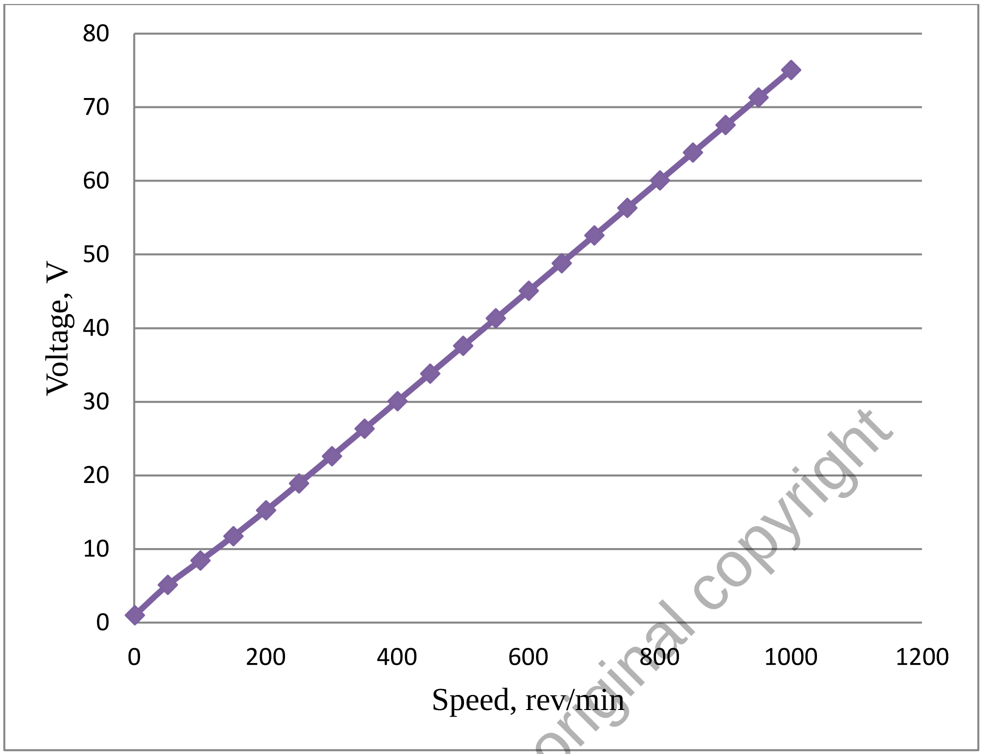

Figure 4.1: DC generator voltage produced.

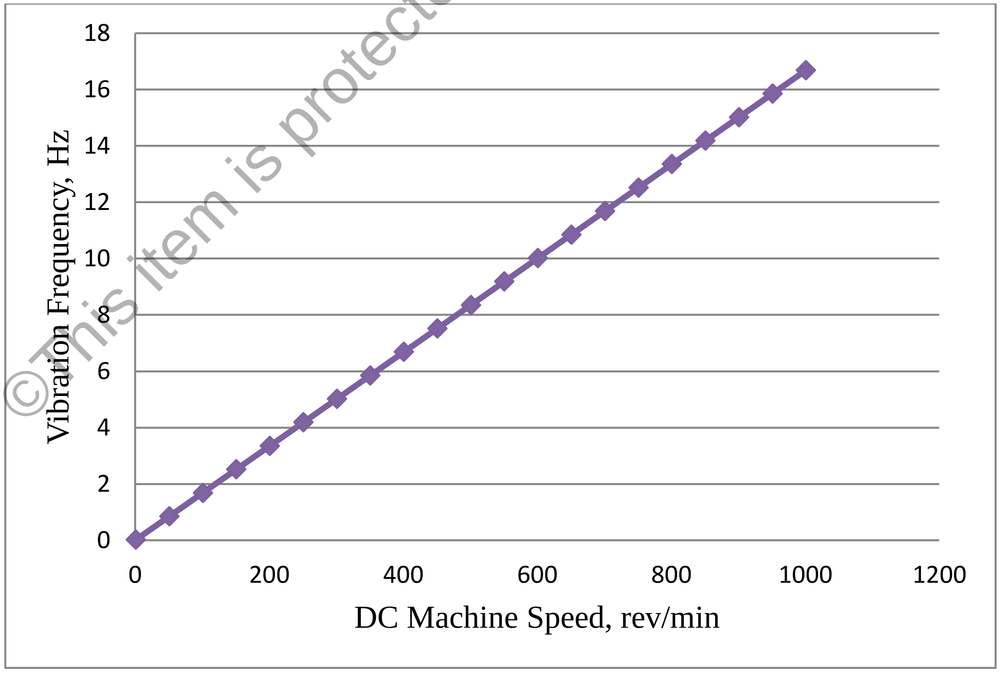

Figure 4.2: Sample result for generator speed and motor vibration frequency.

4.3 Free Generated Vibration with Damping

Results in Figure 4.3 indicated that, when PZT vibration energy harvest device is subjected to a damping force having a damping coefficient range from 0 – 3 zeta or more, the oscillation will be subjected to exponential decay over time, this provided that, damping force is inversely proportion to the mass of the oscillator, this will have a vast effect on vibration energy harvester devices.

The resulting experience is the decrease in amplitude and transmitting forces as vibration frequency increase, this effect is due to the presence of damping ratio, which tend to drain the system energy in order to overcome any resistance force that is generated. However, as a low frequency and lower damping value, vibration amplitude and transmitting forces produce a desired output.

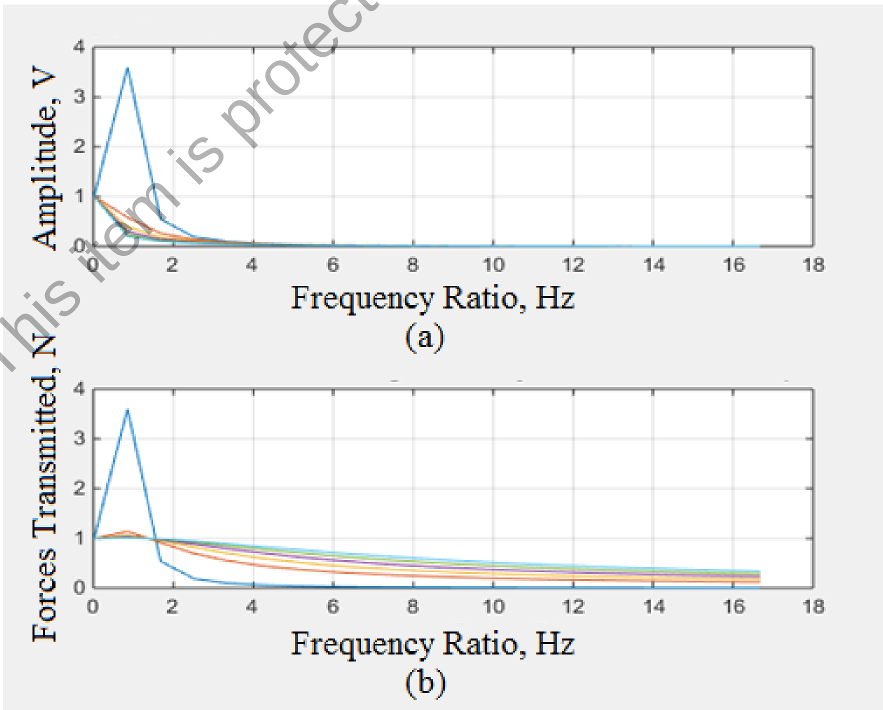

Figure 4.3: (a) Force response of single mass system for vibration damping, (b) Forces transmitted for single mass system for various damping.

4.4 Conversion of Waste Vibration Energy into Useable Electrical Energy Using Piezoelectric Material

These results demonstrate vibration energy was harvested and the output power generated, these include the internal voltage generated by a PZT device as shown in Figure 4.4, compressive force apply to the voltage generated as shown in Figure 4.5, the comparative curve of different voltage generate based on different damping value as shown in Figure 4.6 and PZT energy dissipated due to the presence of damping as shown in Figure 4.7.

The result expectation was to achieve a linearity between PZT internal voltage and vibration frequency, however, this is not the case due to the presence of damping in the system, and the damping exponentially decays the vibration frequency which causes a decay in transmitted force applied to PZT material and dissipated the energy stored in PZT.

However, a comparative curve graph is plotted in order to understand the effect of damping ration to PZT voltage output or power output, this result indicated that, at lower damping ration, PZT do store more energy in comparison with higher damping ratio, but low damping ration system are more subjected to faster energy losses if compare with the system having high damping ration.

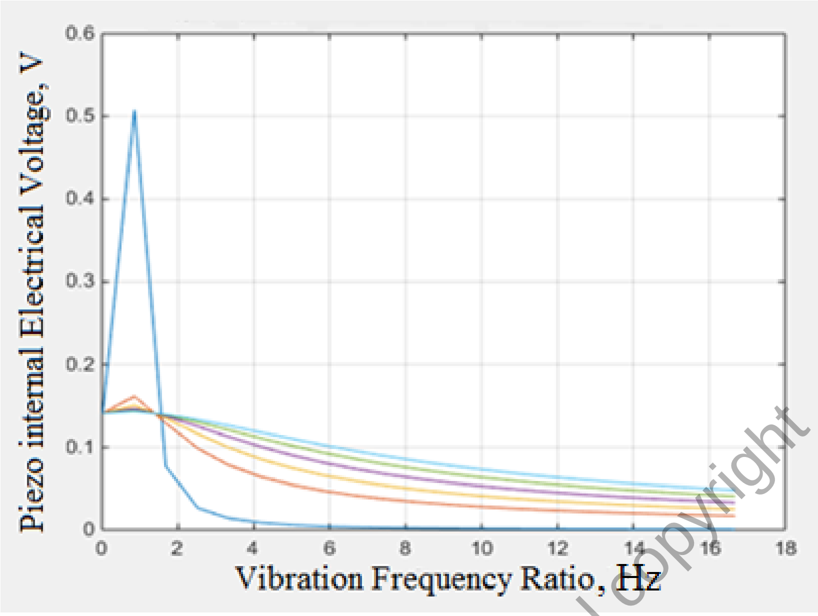

Figure 4.4: Internal voltage generated by piezoelectric material with low frequency range from 0 - 17 Hz.

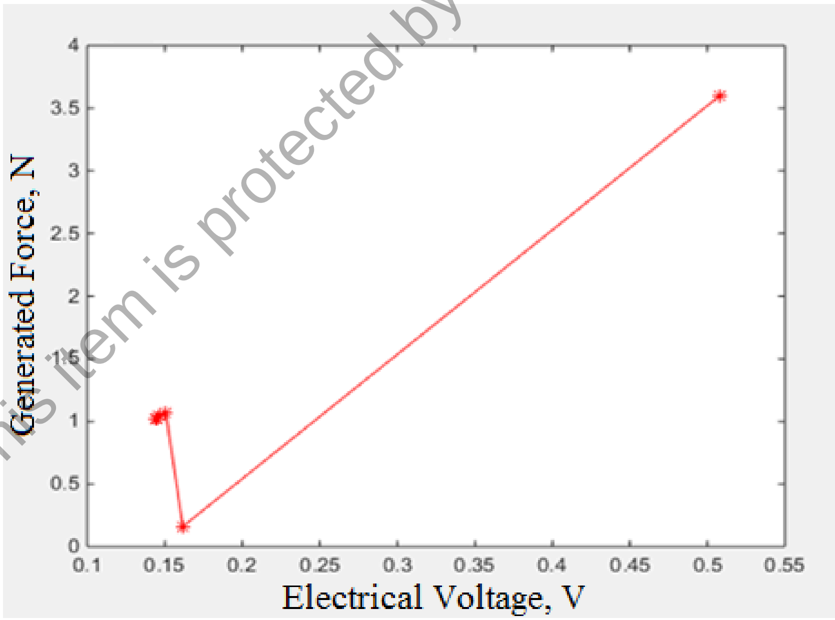

Figure 4.5: Compressive force applied to piezoelectric generating voltage.

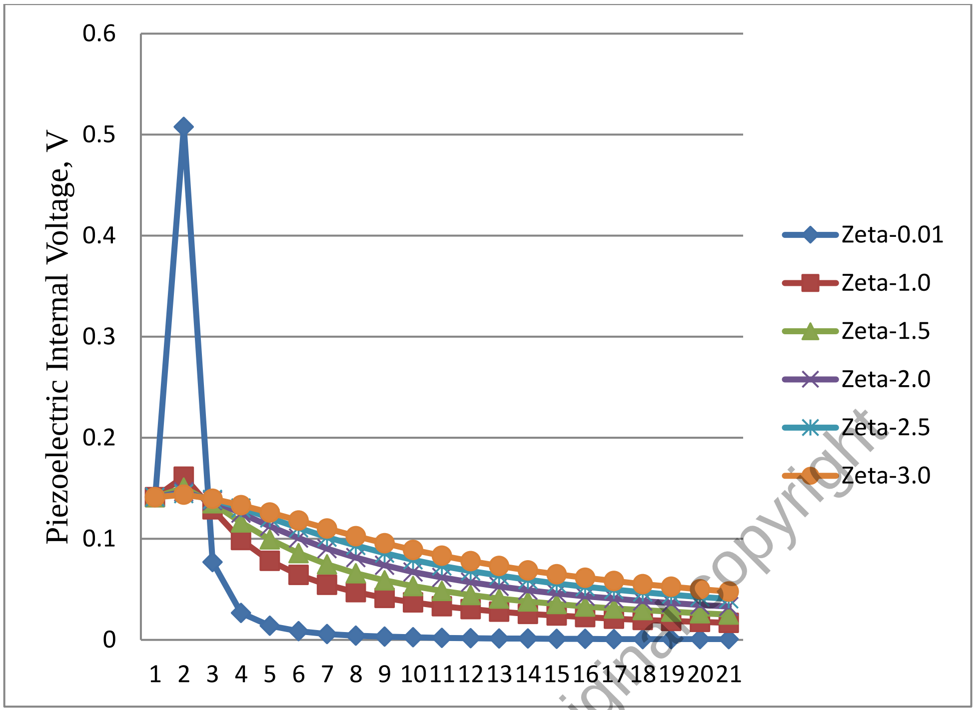

Figure 4.6: Comparative curve of piezoelectric internal voltage at different damping, zeta.

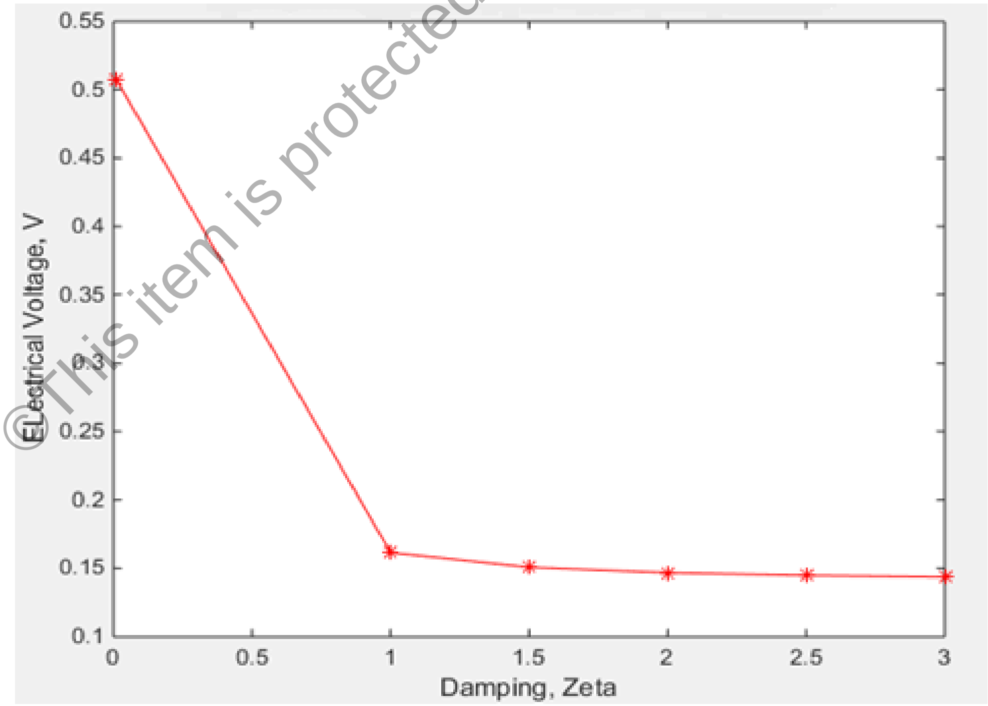

Figure 4.7: Dissipated piezoelectric store energy over time due to increase in damping value.

4.5 Data Collection

The system model using MATLAB was developed based on mathematical equations and different theories from other researchers, Table 4.1 described the speed and vibration and DC motor output voltage data collected during the simulation phase.

In these projects, data are first recorded using MATLAB work space and graph are plotted with the MATLAB command such as plots, data like generating force, vibration frequency, DC machine voltage, PZT internal voltage, damping value and motor speed as described in Table 4.1, Table 4.2 and Table 4.3 were recorded using Microsoft excel, this allowed us to plot a clear curve and to do the comparative curve between PZT internal voltage outputs.

The result for five different damping-zeta value range from 0.01 to 3 is 0.01, 1, 1.5, 2, 2.5 and 3.

Tested generator speed (rotor) range from 1 - 1001 rev/min producing a vibration frequency and voltage range from 0.0167 - 16.6 Hz and 1 - 75 V respectively was tabulated, the compressive force applies to PZT at 5 different damping value range from 0.01-3 and the voltage produced by PZT were all tabulated.

Table 4.1: Tabulated result for rotor speed, frequency and DC machine output voltage.

DC Generator Speed, rev/min	Vibration Frequency, Hz	DC Machine Voltage, V
1	0.02	0.99
51	0.85	5.10
101	1.68	8.42
151	2.52	11.74
201	3.35	15.26
251	4.18	18.90
301	5.02	22.61
351	5.85	26.34
401	6.68	30.08
451	7.52	33.83
501	8.35	37.58
551	9.18	41.33
601	10.02	45.08
651	10.85	48.83
701	11.68	52.57
751	12.52	56.32
801	13.35	60.07
851	14.18	63.82
901	15.02	67.57
951	15.85	71.32
1001	16.68	75.07

Table 4.2: Tabulated result for free generated compressive force apply to PZT.

Generated Force, N					
1.00	1.00	1.00	1.00	1.00	1.00
3.60	1.15	1.07	1.04	1.03	1.02
0.55	0.92	0.96	0.98	0.98	0.99
0.19	0.70	0.82	0.89	0.92	0.94
0.10	0.55	0.70	0.80	0.86	0.89
0.06	0.46	0.61	0.71	0.79	0.84
0.04	0.39	0.53	0.64	0.72	0.78
0.03	0.33	0.47	0.58	0.66	0.73
0.02	0.29	0.42	0.52	0.61	0.68
0.018	0.26	0.38	0.48	0.56	0.63
0.014	0.24	0.34	0.43	0.52	0.59
0.012	0.22	0.31	0.40	0.48	0.55
0.010	0.20	0.29	0.37	0.45	0.52
0.008	0.18	0.27	0.35	0.42	0.49
0.007	0.17	0.25	0.33	0.40	0.46
0.006	0.16	0.23	0.31	0.37	0.43
0.005	0.15	0.22	0.29	0.35	0.41
0.0051	0.14	0.21	0.27	0.33	0.39
0.004	0.13	0.20	0.26	0.32	0.37
0.0041	0.13	0.19	0.25	0.30	0.36
0.0038	0.12	0.18	0.23	0.29	0.34

Table 4.3: Tabulated result for electrical energy harvest from low vibration.

Piezoelectric Internal Voltage, V					
0.14	0.14	0.14	0.14	0.14	0.14
0.51	0.16	0.15	0.15	0.14	0.14
0.08	0.13	0.14	0.14	0.14	0.14
0.03	0.10	0.12	0.13	0.13	0.13
0.01	0.08	0.10	0.11	0.12	0.13
0.008	0.06	0.09	0.10	0.11	0.12
0.005	0.05	0.07	0.09	0.10	0.11
0.004	0.05	0.07	0.08	0.09	0.10
0.003	0.04	0.06	0.07	0.09	0.10
0.0025	0.04	0.05	0.07	0.08	0.09
0.002	0.03	0.05	0.06	0.07	0.08
0.0017	0.03	0.04	0.06	0.07	0.08
0.0014	0.03	0.04	0.05	0.06	0.07
0.0012	0.03	0.04	0.05	0.06	0.07
0.0010	0.02	0.04	0.05	0.06	0.06
0.0009	0.02	0.03	0.04	0.05	0.06
0.0008	0.02	0.03	0.04	0.05	0.06
0.0007	0.02	0.03	0.04	0.05	0.06
0.0006	0.02	0.03	0.04	0.04	0.05
0.0005	0.02	0.03	0.03	0.04	0.05

4.6 Summary of Results

This chapter provides the system model results and categorized them into three main different sections such as power generation from turbine generating machine, waste vibration generated from DC machine and conversion of waste vibration energy into useable electrical energy using PZT material.

The model considers for the DC generator machine is a simple model which produces voltage. The result expectation was to achieve a linearity between PZT internal voltage and vibration frequency

CHAPTER 5

CONCLUSION

5.1 Introduction

The current efforts in providing an alternative energy sources include biomass energy, wind energy, solar energy and lots more while the vibration energy harvest is among the most promising source of free energy scavenging, major approach of scavenging this energy is the application of PZT devices, PZT device typically converts a mechanical energy into electrical energy such as converting a turning motion of a rotor which produce vibration into usable electricity.

This project work discussed the modelling of a system that generate power from a rotating power generating machine, since most power generator produced waste vibration energy, project development focused on modelling a system that could harvest the generator waste vibration energy and convert it into electricity.

However, vibration harvester would also require a full and better understanding of a produced mechanical oscillation, also depend on the main vibration frequency of vibration energy produced by rotating rotor.

This study considered the potentials of combining rotor with current properties of PZT as an efficient and practical method of harvesting energy from the wind energy.

The primary aim of the project is to convert this waste vibration energy into electricity and the project reports evaluated different journals and works done by other researchers, the review focused on researcher's primary objective, method and result related information while all this information was gathered towards the goal of the project.

According to the literature review, different model approach focus on efficiency and reliability while the source of vibration can either be a footstep, shaking and electrical power generation from PZT is challenging due to their low current, high voltage and high impedance output, paper proceed to describe the theoretical analysis for power generation using the PZT crystal material.

In this study, the researcher considered trapping the mechanical properties from obtainable source, then converting the mechanical energy into electrical energy with PZT and rotor and finally process the generated electrical energy and the principal simulation tool utilized was a MATLAB coding software along with MATLAB/Simulink package.

This software was utilized to mimic and simulate the mechanical side of the PZT material, including environment vibration produce by DC generator and the generator itself, alongside a resonator of PZT utilized as a part of one of the materials and the final model consist of the PZT resonator model, separately excited DC generator model, single mass system model.

Data collected were recorded using MATLAB work space and graph was plotted with the MATLAB command such as plots, data like generating force, vibration frequency, DC machine voltage, PZT internal voltage, damping value and motor speed are all later recorded using Microsoft excel.

5.2 Conclusion

The primary aim of the project is to model a system that generates power from a rotating power generating machine and modelling as a system that could harvest the generator waste vibration energy and convert it into electricity.

This project developed energy harvest from rotor vibration in order to generate electricity, development generates power using DC machine and PZT material, however power generated from PZT material is waste vibration from DC machine.

The project methodology process associated with converting mechanical low frequency into electrical energy using PZT and rotor transducer depends on transformation energy from mechanical to electrical energy which usually done using a rectifier and DC–DC converter circuit.

The project examines the PZT material and DC machine, validate the mathematical equation using a series of MATLAB code and MATLAB/Simulink, characterize them while using all this to develop a real time model for materials.

The project completed with DC machine, a single mass system for vibration and PZT material analysis and was extended into final research, demonstration and result analysis.

The project model provides the goals of determining a simple and affordable techniques to optimize power generation and also provide a way to understand material properties based on the project design and modelling techniques.

The model allows understanding and simulation of mechanical and electrical structure of the system. In addition, it provides a future development and enhancement of electrical energy conversion components in affordable and low cost simulation environment.

The final results were categorized into three main different sections, first section is the DC generator which was used to illustrate how to generate power from the turbine generating machine, second section is the waste vibration generated from the DC machine while the third model converted this waste vibration energy into useable electrical energy using PZT material.

5.3 Recommendation and Enhancement

Further work on this project will concentrate more on PZT output power optimization and amplification, other focus will be to streamline the modelling tools in order to achieve a better resonator modelling which will help to optimize the power output.

The current model tools were theoretically complicated to use due to the many steps that were involved from given to derived equations, however, streamlining this model tools and making the work more automated for practical purpose will improve the overall system performance.

Further enhancement will be to evaluate other PZT material and compare the performance with the selected materials, however, the focus will be based on better determination of the material properties, examples, dielectric constant and young's modulus in order to yield a more accurate result.

However, the current design possesses some advantages which include, design of a DC machine for power generation and collection of waste vibration for low power supply, therefore, the overall system model is easy to understand and correlate necessary mechanical input to provide an electrical output in real time.

These features can use its information to optimize PZT resonator and also to understand the percentage of compressive force required to generate an optimum output from piezoelectric material.

All recommendations are meant for future development of techniques suggested as a great area for overall system improvement.

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All recommendations are meant for future development of techniques suggested as a great area for overall system improvement.

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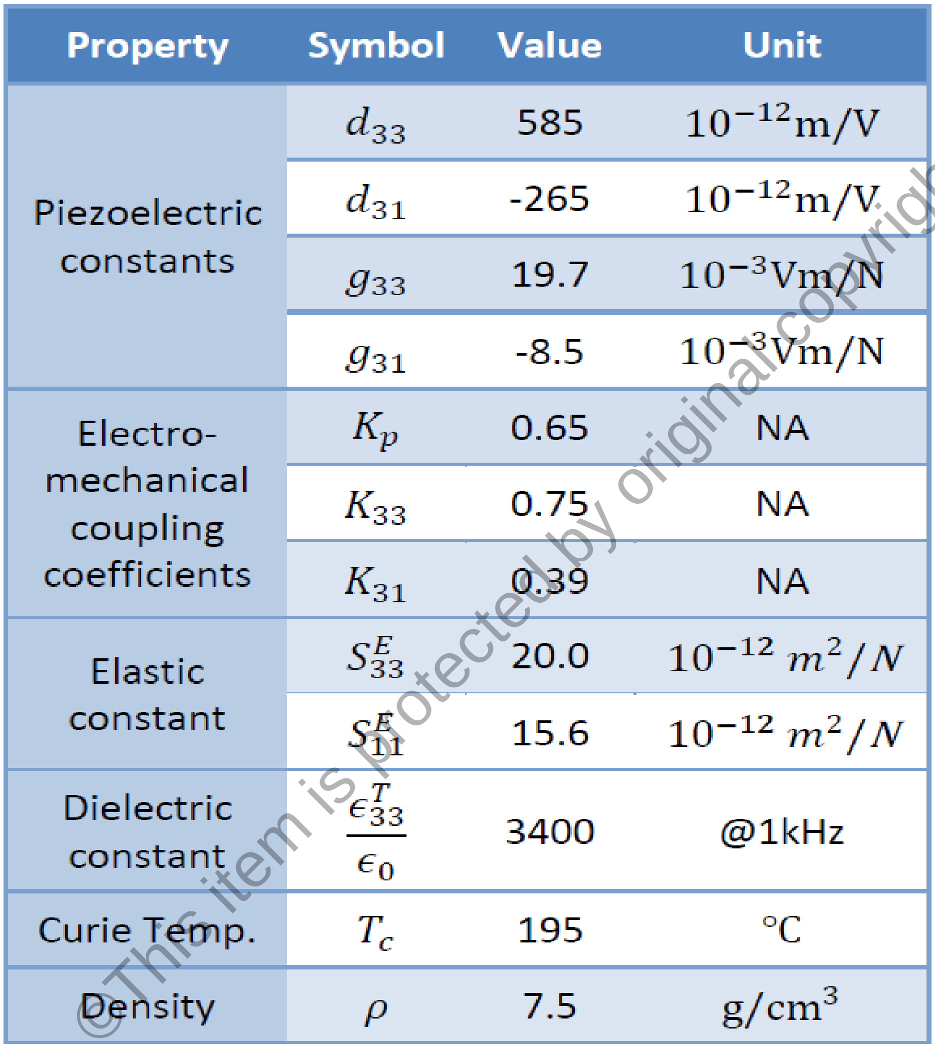
APPENDICES

Appendix A – Common Properties of PZT Material



Property	Symbol	Value	Unit
Piezoelectric constants	d_{33}	585	$10^{-12}\mathrm{m/V}$
	d_{31}	-265	$10^{-12}\mathrm{m/V}$
	g_{33}	19.7	$10^{-3}\mathrm{Vm/N}$
	g_{31}	-8.5	$10^{-3}\mathrm{Vm/N}$
Electro-mechanical coupling coefficients	K_p	0.65	NA
	K_{33}	0.75	NA
	K_{31}	0.39	NA
Elastic constant	S_{33}^E	20.0	$10^{-12}\ m^2/N$
	S_{11}^E	15.6	$10^{-12}\ m^2/N$
Dielectric constant	$\frac{\epsilon_{33}^T}{\epsilon_0}$	3400	@1kHz
Curie Temp.	T_c	195	°C
Density	ρ	7.5	$\mathrm{g/cm^3}$