DESIGN AND MODELLING OF MICRO LINEAR GENERATOR FOR VIBRATION ENERGY HARVESTING

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Certification of Approval

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Approved :

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Certification of Originality

This is to certify that I am responsible for the work submitted in this project, that the work is my own except as specified in the references and that the original work contained in the report have not been done without unspecified sources or references.

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Nur ‘Izzah binti Mohamad Nor

Abstract

In the present world, the search for renewable energy is on-going. The need to power up wireless sensor network is on high demand. Some of the sensors are located in hard to reach areas, thus the need to power it up wirelessly. The usage of batteries in these sensors is unconventional since the replacement of the batteries is tedious. By powering these sensors wirelessly, there will be no need to change the batteries.

There are many different types of sources for renewable energy, such as solar energy, thermal energy and vibration energy. By harvesting these energies, the usage of non-renewable energies such as batteries can be reduced. Other than saving the environment, the usage of renewable energy produces continuous power to the wireless sensors and thus, reduces the incidence of no power.

Vibration occurs in almost all appliances used by users nowadays. Different appliances produce different levels of energy. By harvesting this energy, it is possible to power up any wireless sensor network. Vigorous vibration will produces a higher power needed for the wireless sensor networks with higher power demand. To use this energy, a harvester must be designed. The harvester will be attached to the vibrating appliance to harvest the vibration energy. The use of micro linear generator compromising of magnets, slotted and moving rotor and static stators will enable users to harvest the vibration energy. The generator will be able to convert the vibration energy to electrical energy. In this research, the optimum design of the linear generator will be discussed. The magnetic flux and magnetic field of the generator will be analysed to ensure that a better design can be produced. With the software, the output voltage of the design can be measured. This will ensure that the design is suitable to power up wireless sensor networks. The benefit and the future of this project will be analysed further.

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In the present world, the search for renewable energy is on-going. The need to power up wireless sensor network is on high demand. Some of the sensors are located in hard to reach areas, thus the need to power it up wirelessly. The usage of batteries in these sensors is unconventional since the replacement of the batteries is tedious. By powering these sensors wirelessly, there will be no need to change the batteries.

Table of Contents

Abstract i

Acknowledgement ii

Chapter 1 1

Introduction 1

- Project Background 1
- Problem Statement 1
- Objectives 2
- Scope of studies 2
- Tools and software 2

Chapter 2 3

Literature Review 3

- Wireless Sensor Network 3
- Power of Wireless Sensor Network 4
- Electric machine 6
- Energy Harvesting 8
- Principles of Vibration 10
  - Vibration characteristics 10
- Methods of Vibration Energy Conversion 12
  - Electromagnetic Generator 12
  - Electrostatic Generators 13
  - Piezoelectric 15
- Comparison of Sources of Vibration Energy 16
- Micro Linear Generator 17
  - Properties of a Linear Generator 19
  - Working principle of a linear generator. 21
  - Types of Linear Generator Proposed 22
- Designing and modelling 23

Chapter 3 24

Methodology 24

- Gantt Chart 24
- Flow Chart 25
- Current Research of Vibration Energy Harvesting 27
- Analysis of Problem and Finding the Solution 27

Deliverables ... 27
Chapter 4 ... 28
Results ... 28
Design ... 30
Flux Lines and Magnetic Density of the 4 Designs ... 36
Air Gap Flux Distribution ... 42
Flux Line VS Distance ... 42
Flux Distribution VS Distance ... 44
Open Circuit Test ... 46
Flux Linkage VS Time ... 47
Induced Voltage VS Time ... 49
Discussion ... 51
Conclusion ... 52
References ... 53

List of Figures

Figure 1 - Global WSN Revenues in Buildings [3] 4
Figure 2 - Power in WSN [4] 5
Figure 3 - Energy Harvester System 8
Figure 4 - Prototype A 12
Figure 5 - Prototype B 12
Figure 6 – In-Plane Gap Closing [9] 14
Figure 7 - Out-of-Plane Gap Closing [9] 14
Figure 8 – In-Plane Overlap [9] 14
Figure 9 - D33 Mode 15
Figure 10 - D31 Mode 15
Figure 11 - Design of Simple Linear Generator 18
Figure 12 - Linear Generator [24] 21
Figure 13 - Tubular Linear Generator 22
Figure 14 - Planar Linear Generator 22
Figure 15 - Components of Generator 30
Figure 16 - Measurement of Planar Slotted Micro Linear Generator 31
Figure 17 - Planar Slotless Micro Linear Generator 32
Figure 18 - Tubular Slotted Micro Linear Generator 33
Figure 19 - Tubular Slotless Micro Linear Generator 34
Figure 20 - Flux Line Distribution 36
Figure 21 - Magnetic Flux Density 37
Figure 22 - Flux Line Distribution 37
Figure 23 - Magnetic Flux Density 38
Figure 24 - Flux Line Distribution 39
Figure 25 - Magnetic Flux Density 39
Figure 26 - Flux Line Distribution 40
Figure 27 - Magnetic Flux Density 40
Figure 28 - Graph of Flux Line VS Distance (Planar) 42
Figure 29 - Graph of Flux Line VS Distance (Tubular) 42
Figure 30 - Graph of Magnetic Density VS Distance (Planar) 44
Figure 31 - Graph of Magnetic Density VS Distance (Tubular) 44
Figure 32 - Graph of 10 cycles per second 46
Figure 33 - Graph of Flux Linkage VS Time (Planar) 47
Figure 34 - Graph of Flux Linkage VS Time (Tubular) 47
Figure 35 - Graph of Induced Voltage VS Time (Planar) 49
Figure 36 - Graph of Induced Voltage VS Time (Tubular) 49

List of Tables

Table 1 - Levels of frequency and amplitude of applications 11
Table 2 - System Comparison 16
Table 3 - Components of Generator 30
Table 4 - Design Parameters 36
Table 5 - Open Circuit Test Parameter 46

Abbreviations and Nomenclatures

AC - Alternating Current

DC - Direct Current

EMF – Electromotive Force

NdFeb – Neodymium Iron Boron Magnets

PM - Permanent Magnet

s - Second

V - Voltage

W - Watt

Wb - WeberWSN – Wireless Sensor Networks

Chapter 1

Introduction

This chapter discussed on the background of the project. The problem faced by the manufacturers of the increasing usage of Wireless Sensor Network (WSN) in the industry and the solution that can be implemented to overcome the problems will be discussed. The author has focused on the problem of changing the power sources of these WSN that are placed at inaccessible places. The solution that has been discussed will involve the use of converting vibration energy from a vibrating system into electricity to efficiently power up the wireless sensor devices.

Project Background

Technologies are evolving every single day. Other sources of energy are on high demand to supply power to the systems. This study will be focusing on the harvesting of energy from a vibrating source. Even though the power harvested from the system will be small, the power can be used to power up WSN or any low power electronics devices. The sources of vibration can be from piezoelectric, electromagnetic and electrostatic. For this project, the vibration energy will be harvested by using magnetic levitation and linear generator concepts. Energy will be from the vibrating source. Vibration is chosen since vibrating source is available almost everywhere. Almost all the appliances and machines used in the world vibrate and this energy can be harvested, converted and stored as electrical energy for the use of the WSN.

Problem Statement

Sensors are located everywhere. Some might even be located at an inaccessible place. Most of the sensors available are powered up using battery. The use of batteries makes the sensors bulky and bigger than it should be. The replacement of the batteries could be a tedious process. Therefore, the use of the micro linear generator powered by vibration energy could be the future power source of the sensors. The sensors will be able to generate their own power to transmit data to the outside receiver. This will reduce the need for batteries and also be a new source of renewable energy for any electrical systems.

Objectives

1. To design a micro linear generator for vibration energy harvesting.
2. To compare between planar and tubular design.
3. To compare between slotless and slotted design.

Scope of studies

The research will be based on the harvesting of vibration energy. The different methods of vibration energy harvesting will be discussed and analysed in the research. The results and advantages of each system will be analysed and an optimum design of the energy harvester and the linear generator will be designed using the ANSYS Software. The designs of the planar, tubular slotted and slotless designs will be simulated and analysed.

Tools and software

ANSYS Software will be used to simulate the prototypes from previous researches. From the software, the prototypes will be analysed and the results will be documented. An optimized design of the generator will be designed and validated using the software.

Chapter 2

Literature Review

Power consumption for low powered electronic devices is small and low. Thus, use of ambient energy will reduce the need to use non-renewable energy. Ambient energy can be scavenged from usable energy from natural and human-made sources. The sources can be from vibrating objects, solar, thermal, wind and others. The energy harvested can be converted to electrical energy with the use of an energy harvester or micro generator.

Wireless Sensor Network

WSN technology is a technology that is important is this 21st century. WSN is a new information acquirement system. Thus, the energy needed to power up the technology need to be able to supply energy throughout the operation of the equipment.

WSN networks consist of devices such as sensors that can be used to monitor various conditions and environment such as the temperature, sound, vibration, pressure, seismic activities and others [1]. Nowadays, WSN is used in wide areas from health monitoring, habitat observation, military smart home applications and etc. WSN plays the role of localizing, tracking, sensor deployment like battlefield awareness, infrastructure protection, industrial sensing diagnostics and others [2]. Thus, it is vital to ensure that power is supplied to the applications without any problem. The application of the sensor varies according to the requirements of the applications :

1) Modes of deployment
2) Sensing modality
3) Power supply

Energy supply is an important key factor that restricts the performance and the lifetime of the WSN. Some sensors are placed in areas that are bad, unattended and areas with difficulty for any maintenance. This will cause problems in changing the batteries in the case of battery drainage. The aim to improve and extend the lifetime of the WSN applications is the key to ensure that the application work and are able to function better.

According to Ding et al, there are two main aspects to improve the network which are the energy supply and energy consumption. Since non-renewable energy such as batteries and oil are getting expensive and depleting, the need to find other sources of energy is high. To ensure that the applications work all the time, the issue of continuation of energy must be researched on. A useful type of energy will be the ambient energy harvesting technique which can recharge energy efficiently.

"A transformation is underway in the building automation market due to low-cost Internet based services enabled by wireless sensor networks," says Mareca Hatler ON World’s research director. "From building-wide wireless mesh networks to room-level controls, there are dozens of new entrants that are challenging the incumbents especially for small and medium sized buildings" [3].

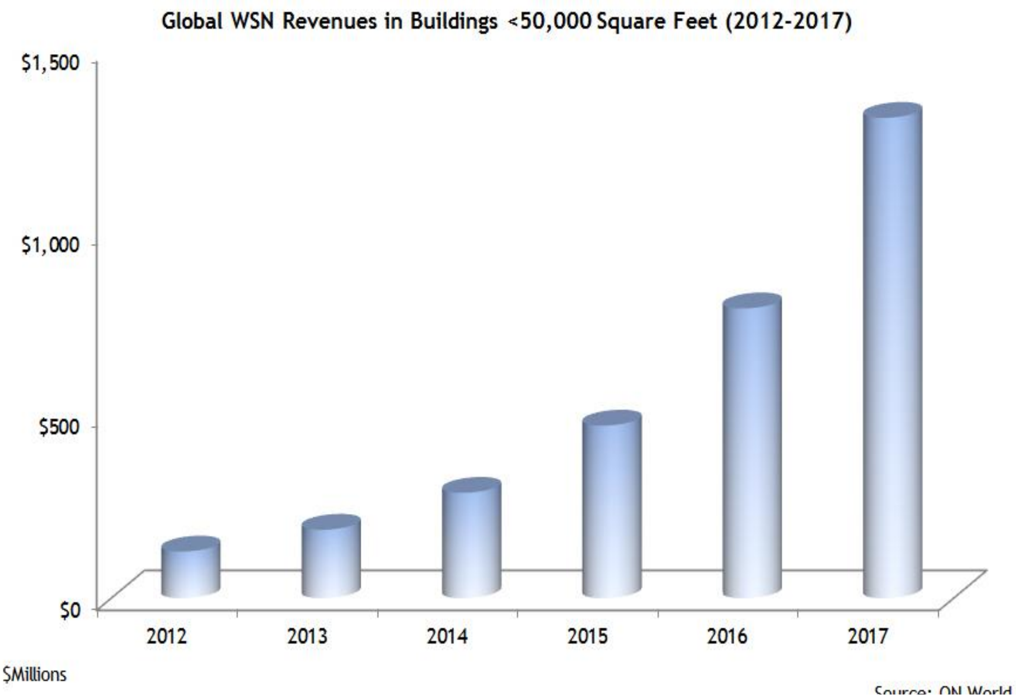


Figure 1 - Global WSN Revenues in Buildings [3]

Power of Wireless Sensor Network

Based on the graph below, it is shown that the total power for a transmitter decreases with the increase in the number of transmitters. This is different for receivers which increase in the power consumption with the increase in receivers. The total power however increases with the increase of the receivers and transmitters. Even though the power increases with the increase in number of the transmitter and receiver, the total power required is still in the range of milli-watts which is very low. The highest power needed, according to the graph is 120mW. The power depends on the sampling range, transmission range and transmission speed of the sensor node. The power can be less or more depending on the situation. Since WSN is small, battery replacement is tedious, time consuming and uneconomical. Another disadvantage of using battery is the size of the device gets bulkier, occupying more space [4].

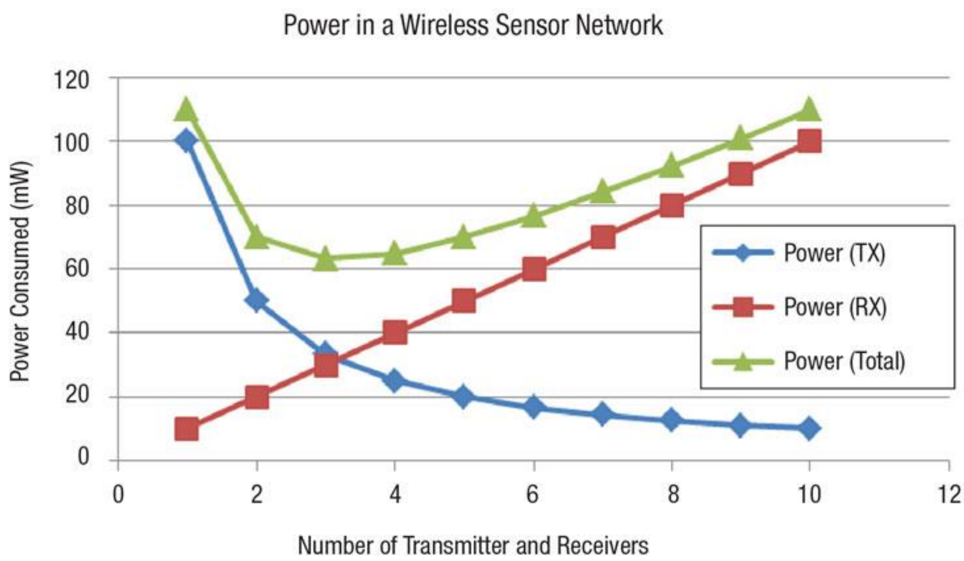


Figure 2 - Power in WSN [4]

Electric machine

Electric machines are systems where mechanical energy is converted to electrical energy or vice versa. When the power produced is converted from mechanical to electrical energy, it is called a generator. On the other hand, motor is when the power produced is converted from electrical to mechanical energy [5].

Electric machine consists of two important parts, a moving system called rotor and a stationary system called stator. Both stator and rotor are made of magnetic material. Flux is conducted across the air gap between the stator and rotor. When rotor rotates or moves, voltage is induced in the armature windings which then exchanges current with the external circuit.

Flux density produced between the air gaps depends on a few factors. The factors are the length of the metal core, the area and the core permeability. Calculation of flux involves :

$$\emptyset = \frac{lc}{\mu c A c}$$

Where

l_c = mean core length (m)

A_c = core cross-sectional area (m^2)

μ_c = core permeability = $\mu_0\mu_{rc}$

μ_0 = absolute permeability = $4\pi \times 10^{-7}$ H/m

μ_{rc} = relative permeability of core

Lenz Law is a law for electromagnetic. The law explains the working principles behind electromagnetic and how electromagnetic obey the third Newton's law and the conservation of energy. Lenz law states that an induced electromotive force (EMF) always gives rise to current whose magnetic field opposes the original change in magnetic flux.

Lenz law stated that

$$e = N\frac{d\emptyset}{dt} = \frac{d\lambda}{dt}$$

Where

e = electromagnetic force

N = number of turns in the coil windings

$\frac{d\emptyset}{dt}$ = change of flux

And the formula for induced electromotive force (EMF) is

$$e = Blvsin\theta$$

Where

B = flux density (Wb/m^2 or T)

v = conductor speed m/s relative to flux

l = conductor length (m)

θ = angle between direction of flux and conductor velocity

When a magnet moves in relation with an electromagnetic coil, magnetic flux passing though the coil changes and this induces a flow of electric current in the system. The electric current can be stored and used as a power source for electrical systems. Linear generator converts linear motion into electrical energy.

Energy Harvesting

Energy harvesting can be defined as the process by which energy is derived from external sources, captured and stored for small, autonomous wireless devices. The external sources range from solar energy, thermal, wind, water vibration and others.

Energy harvesters provide small output power to power up low energy devices. Using non-renewable energy such as oil and coil, the price for the power is high. By harvesting energy from the external sources, the costs can be minimized and sometimes free [6].

Approaches of energy harvesting that converts light, thermal, heat and kinetic energy that are available nowadays increases the potential of renewable energy sources which will one day replace the use battery in the WSN. These renewable energy sources will reduce the environmental impact on the world due to battery disposal and increases the lifetime and capability of the WSN [7]. By using energy harvesting, battery-less and near-perpetual operations off sensors is possible [8]. These low-powered devices are used to sense signals, digitize, process and transmit low data rate information to the receiver which is the base station.

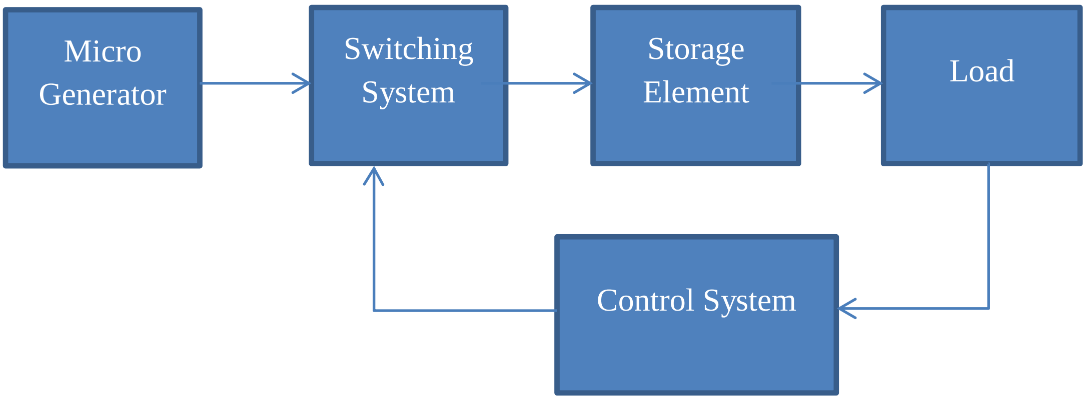


Figure 3 - Energy Harvester System

Components of an energy harvester :

1) An energy conversion device such as a piezoelectric element that can translate the energy into electrical form.
2) An energy harvesting module that captures, stores and manages power for the device.
3) An end application such as wireless sensor network or control and monitoring devices.
4) An electronic interface device or module, such as a low voltage step up booster module, to condition the energy captured from a low voltage source (less than 500mV) and power the energy harvesting module
5) A supplementary energy storage device, such as thin-film batteries, ultra capacitors, and super capacitors
6) An energy or power management module that will further regulate and condition the power output from the supplementary energy storage devices

Principles of Vibration

Vibration is usually classified as noise to a system. Vibration can be categorized into three basic categories.

1) Seismic vibration – ground vibrations. Examples of sources are foot traffic, vibration due to wind and ventilation fans.
2) Acoustic vibration – measure of the effects of air pressure variations.
3) Forced vibration – vibration sources that are directly coupled mechanically to experiment setup. An example is vibrations system transmitted to the working surface via vacuum system tubing.

Vibration characteristics

Vibration can either be random or periodic. Examples of periodic vibrations are the vibrations caused by continuous running of vacuum system and the ones caused by fans of air handling systems. A random vibration is vibrations from unpredictable sources like the vibration of a building due to wind or from the movement of a jack hammer. To know the vibration system better, the frequency and amplitude of the vibrations have to be recorded. Frequency will usually range from 4-100Hz.

Vibration sources can also be the combination of various sources of vibration. For example, a working vacuum will produce both seismic and acoustic vibration. However, the contribution of the sources also depends on the coupling efficiency of the sources. Mechanical coupling efficiency is higher than the coupling efficiency of the acoustic source [9].

Table 1 - Levels of frequency and amplitude of applications

Type	**Frequency(Hz)**	**Amplitude**
Air Compressors	4 – 20	10^{-2} in
Handling Equipment	5 – 40	10^{-3} in
Pumps (Vacuum, comp or non-comp fluids)	5 – 25	10^{-3} in
Building Services	7 – 40	10^{-4} in
Foot Traffic	0.5 – 6	10^{-5} in
Acoustics (B)	100 – 10000	10^{-2} to 10^{-4} in
Air currents	Labs can vary depending on class	Not applicable
Punch Presses	Up to 20	10^{-2} to 10^{-5} in
Transformers	50 – 400	10^{-4} to 10^{-5} in
Elevators	Up to 40	10^{-3} to 10^{-5} in
Building Motion	46/Height in meters, Horizontal	0.1 in
Building Pressure Waves	1 – 5	10^{-5} in
Railroad*	5 - 20	±0.15g
Highway Traffic*	5 - 100	±0.001g

Based on the table, the levels of frequency and amplitude of vibration for some basic things in a room is shown. These are some of the sources of vibration that can be harvested and the energy stored to power up any wireless sensor networks.

Methods of Vibration Energy Conversion

Vibration energy is gathering a lot of interest from the world. It is a new way of powering wireless sensor nodes. Vibration energy can be harvested from various sources. Examples of sources for vibration energy are piezoelectric, electromagnetic transduction and others. The vibration energy harvester is a kinetic energy generator that converts mechanical energy in the form of vibrations present in the application into electrical energy. The vibration in the appliances is typically converted into electrical energy using electromagnetic, piezoelectric or electrostatic transduction mechanisms.

Electromagnetic Generator

Based on a paper written by Glynne-Jones et al, their research are based on two types of electromagnetic generator. Prototype A is based on two magnets coupled to a coil and the experimental results were for resonant frequency while prototype B was based on four magnets and the research was on the Q factor in air and vacuum. Prototype A produced low output voltage while prototype B is capable of generating useful power and voltage levels [10].

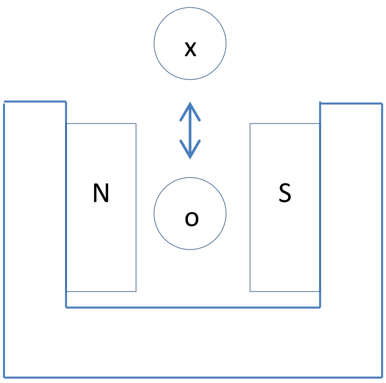


Figure 4 - Prototype A

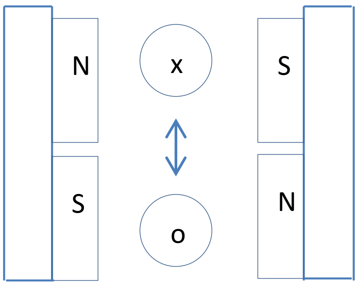
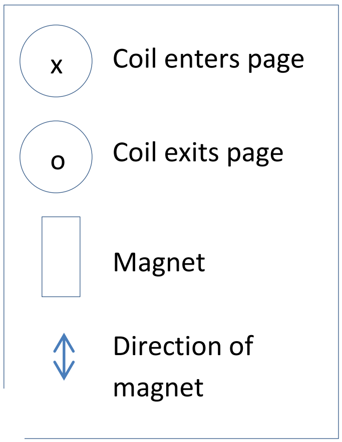


Figure 5 - Prototype B



The prototype uses Neodymium Iron Boron (NdFeB) as their magnet in the design. This magnet is known for its powerful magnetic property. From the design, the magnets provide a magnetic field across the air gap. When the system moves, the magnetic flux is cut and this produces electromagnetic flux.

When the coil passes through the magnet bars, the charged particles in the elements are attracted to the opposite charges in the elements. This attraction will produce the electric energy within the conductor through the magnetic field.

Continuous flow of electricity will be produced with the continuous movement of the system.

In the design proposed for the project, the NdFeB magnets will be used. The magnet will be able to produce the needed magnetic flux distribution and magnetic field lines required for the project.

Electrostatic Generators

Electrostatic is another type of source for vibration energy. Electrostatic generators produce static electricity or electricity at high voltage with low current. The generators use the principle of conversion from mechanical energy to electrical energy. There are two basic types of the generators, the friction effect and the electrostatic induction.

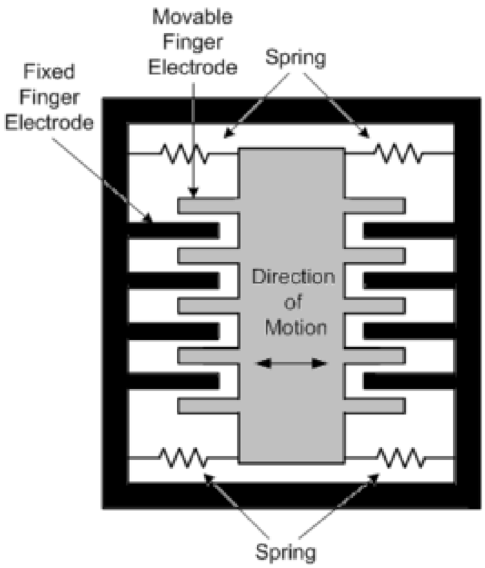
The friction effect is caused by friction in the generation process. The imbalance charges in a surface enable an object to exhibit attractive or repulsive forces. These forces will produce static electricity and electricity is generated by touching the two different surfaces with each another and separating the surfaces. The different charges will react and produce the required electric energy.

The electrostatic induction on the other hand works by converting mechanical work into electrostatic energy. The movement of magnets or the planes inside the system produces the required energy to be converted to electricity. The different charges in the system react from the movement.

The basic component for electrostatic generator is capacitor. When the capacitance charge is limited, the charge produced will move from the capacitor to the storage device or to the load. The movement of charge produces mechanical energy and this is converted to electrical energy.

According to Zhu D, electrostatic generator can be classified into 3 types, In-Plane Overlap, In-Plane Gap Closing and Out-of-Plan Gap Closing [11].

The differences between the three generators is the gap between the electrode plates for the first type, the overlap area varies between the electrode fingers while for the second generator, the gap between the electrode fingers varies. The third generator has varying gaps between two large electrode plates.



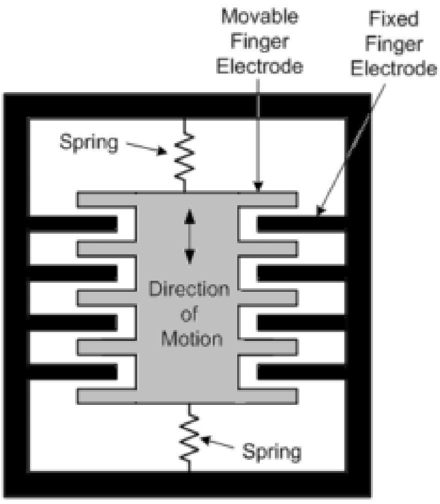


Figure 6 – In-Plane Gap Closing [9]

Figure 8 – In-Plane Overlap [9]

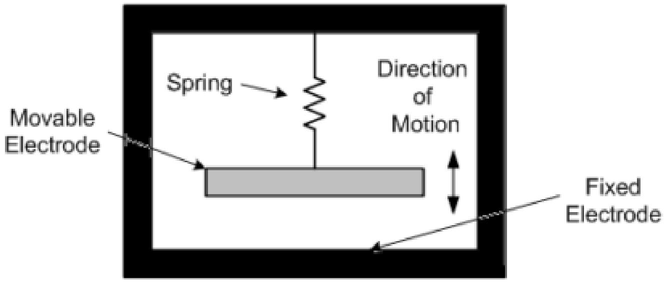


Figure 7 - Out-of-Plane Gap Closing [9]

Piezoelectric

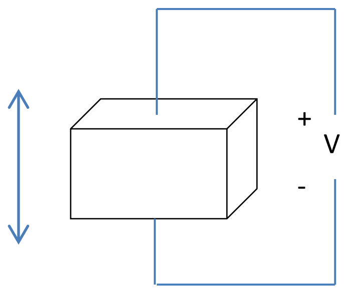


Figure 9 - D33 Mode

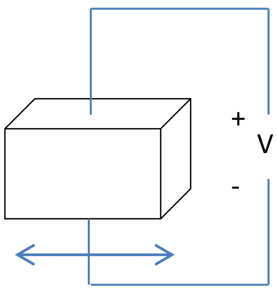


Figure 10 - D31 Mode

Piezoelectricity is produced from pressure. Electricity is produced when mechanical energy is applied to the piezoelectric material. The piezoelectric material will be deformed slightly with the mechanical force and this produces the output electric power.

Piezoelectric effect happens when the charge is separated within the material due to applied strain. The separation creates an electric field and this is known as the piezoelectric effect. There are two main models of the piezoelectric generator discussed by Townley. The first is the D33 mode where the electric field produced is the same direction as the applied strain. Meanwhile, for D31 mode, the electric field produced is directly proportional to the applied strain. According to Townley, piezoelectric coefficient for D33 mode is higher but with the higher coefficient, the design is more complex with lower capacitance and higher output impedance [12].

Comparison of Sources of Vibration Energy

There are various types of generators that harvest vibration energy. Based on the presentation paper by Cottone [13], the comparison of the different systems is as shown in Table 2. Based on the comparison done between the different sources of vibration energy, the linear generator designed will implement the basic elements of the different types of the vibration energy harvesters.

Table 2 - System Comparison

Type	Advantages	Disadvantages	Average Output Power
Electromagnetic	- Usage of everyday items - No external voltage source	- Bulky – magnets and coils - Hard to be incorporated with MEMS. - Max voltage = 0.1V	-Prototype A = 37uW – 180uW -Prototype B = 157uW
Electrostatic	- Usage of everyday items - Can be integrated with MEMS. - Voltages = 2-10v	- External voltage source - Mechanical constraints - Capacitive	-1-1052uW
Piezoelectric	- No external voltage source - Voltage = 2-10v - Compact setup - Can be integrated with MEMS. - High coupling in individual crystals	- Depolarization - Brittle - Poor coupling in piezo-film - Leakage of charge - High output impedance	-1-1600uW

Micro Linear Generator

Generators can be classified into few types. Some of the classifications are linear, rotary, synchronous and asynchronous generators. Linear generator is a mechanism where linear motion is converted into electricity. The term micro applies to systems that are small in size and produces small output power, from the range of mili-watt (mW) to micro-watt (µW). The smallest generator ever designed is by Steve Beeby, an engineer at the University of Southampton, UK. The size of the generator is 7.0 millimetres by 7.0 mm by 8.5 mm [14].

Micro generator is a miniaturized form of the larger scale generators. The generator uses miniature discrete components that enable the generator to exploit the advantages of the bulk magnetic material properties and large coil winding density. This proves that even a compact generator is able to produce usable levels of power without the need of gears and screws. This enables the system to overcome the problem of stiffness, mass friction and backlash [15].

The main differences between linear and rotary generators are the way the generator moves. Linear generator is classified as linear motion electromagnetic systems. Linear generator utilizes translational forces. The force is from back and forth, up and down movements. The other conventional approach is the rotational generator. The rotary generator uses a semi-circle disk to obtain continuous rotation of the rotor. For the linear generator, it uses permanent magnets as the translator. The source harvested is from a linear motion. It is either a horizontal or vertical movements. The generators can be classified under AC generators since they produce AC current.

Figure 11 shows an example of a simple micro linear generator [16]. The armature is movable and this is the source of the production of electricity. The magnets and the laminated poles in the stator produce a radial air-gap field. The stator winding flux is controlled by the movement of the armature. When the armature moves along the gap, it cuts the magnetic field produced by the magnets. This generates induced EMF. The movement of the armature produces vibration linearly and this is the source harvested to be converted to electrical energy.

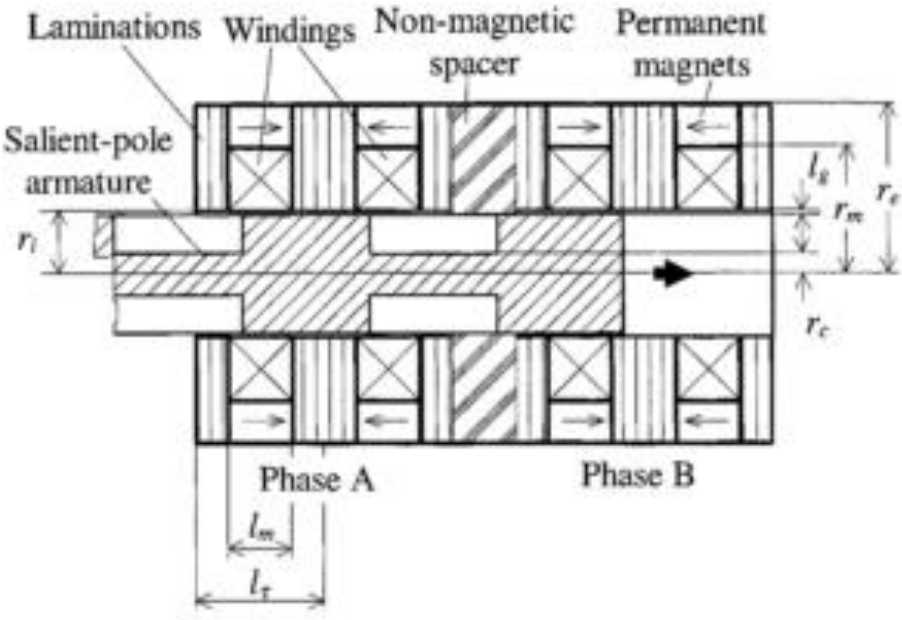


Figure 11 - Design of Simple Linear Generator

Examples of linear generators are the electromagnetic generators, electrostatic generators and piezoelectric generators. The generators work best with NdFeB magnets as their rotor. According to Chye et al, [17] the magnet is the common magnet used in any magnetic based generators due to their special properties of strong magnetic flux and magnetic energy density. It is known for its powerful magnetic properties per cubic centimetre and able to operate at temperatures up to 140^0C. With the use of NdFeB, the aim to obtain a smaller size of micro generator will be able to be achieved.

The working principle of a linear generator is in the systems translational speed. It is important to couple low speed and high trust of the source to convert the energy into useful electrical energy.

Faraday's law is one of the laws that involve the change in the magnetic environment. The concept of Faraday's Law is that any change in the magnetic flux of a wire coil will produce induced voltage in the coil. As long as there is change in the magnetic flux, voltage will be generated. The voltage generated is known as induced voltage. There are a few ways to produce the change in magnetic flux. The change could be produced by changing the magnetic field strength, moving the magnet toward or away from the coil, moving coil into or out of the magnetic field, rotating the coil relative to the magnet and others.

Faradays law states that

$$E = N\frac{d\emptyset}{dt}$$

N = number of turns in coil

$\frac{d\emptyset}{dt}$ = rate of change of magnetic flux

In order to increase the induced voltage, it is necessary to increase the speed of the changing of magnetic field or increase the magnetic flux.

Properties of a Linear Generator

There are a few components that are necessary in a linear generator such as stator, translator, air gap, magnet, iron core and others. Each component has its own uses and benefits.

Stator	Stationary armature of an electrical machine. Stator is usually connected to the load. Provides magnetic field to the system.
Translator	Moving part of the electrical machine. Provides the magnetic flux. Provides the cutting of the magnetic flux when the translator moves.
Air gap	Provides a gap for the translator to move freely without affecting the stator of the system. Air gap is selected as small as mechanical possible. A system with a larger air gap will need a bigger volume of permanent magnet and this causes reduction in the motor thrust force. A very small air gap will cause mechanical fault and manufacturing difficulties [18].
Magnet	Provides the magnetic field and magnetic attraction for the system. Different height, design and width affect the system.
Iron Core	Confine and guide magnetic field in the system.
Copper Coil	Provides the winding for the system and creates magnetic field through the conductor. The more turns of wire, the stronger the field.
Pole Shoes	Provide better possibilities to shape the magnetic flux curve in the air gap. Produce less leakage. Pole shoes also protect magnets from transient magnetic fields generated by short circuit.

A linear generator requires a working stator, coil windings, working translator and a configuration of magnet. The configurations of the elements can affect the performance of the micro generator.

For the stator and translator, it can either be of the same length or different length based on the requirements. The length will affect the performance of the micro generator.

For the magnet configuration, it can either be axial, radial, different shapes, slotless or slotted. All the configurations need to be decided to ensure that the design is optimized and produces the required voltage and power. Each design will produce different results, different affects.

In the research paper written by Hamim et al [19], they compared three different configurations of magnets for the linear generator design. The designs are the rectangular layout, T-Halbach layout and the trapezoid-halbach layout. The advantage of the rectangular layout is that it is easier to construct. For the T-halbach, the design is called such due to the shape of the magnet resembling the letter T. The advantage of this design is also the cost and the construction of the design is easy. For the design of trapezoid-halbach layout, the magnets are hard to construct but the trapezoid magnets will create magnetic flux that is more focused on the halbach layout.

Cogging torque is another issue in generators. Based on the research done by Alshibani et al, cogging torque of the generator can actually be reduced by using the halbach configuration of magnet. The cogging torque causes vibration and acoustic noise in the machine [20].

The height, volume, number of segments of the magnets and designs of magnet can affect the performance and this can be simulated in ANSYS to construct the magnetic field lines and magnetic flux density and the results of the designs are analysed. By comparing the parameters, the most effective design can be designed and optimized for future advantage.

Different arrangements of the stator and translator also affect the performance. By mounting the coils on the stator, no flexible connection to the coils is required and number of magnets is reduced. If stator is significantly longer than the translator, stator can be split up into several parts. This design will allow switching of the generator and reduce the losses.

Below is the diagram of the internal section of a linear generator. Based on the diagram, the generator consists of windings, stator, translator and magnets. The translator consists of the windings of the system while the stator houses the magnets.

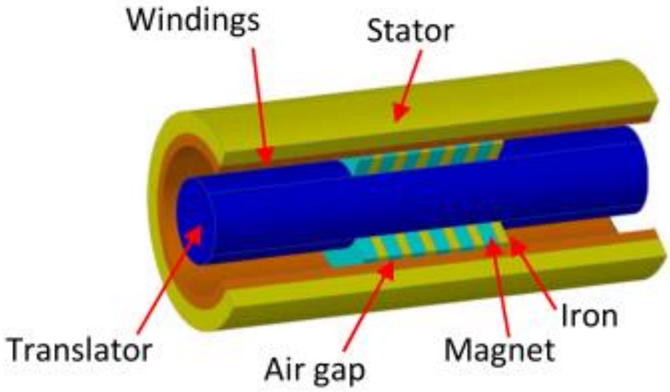


Figure 12 - Linear Generator [24]

Working principle of a linear generator.

Translator is the moving part of an electrical machine. The stator is the non-moving static part. In between the stator and translator, air gap is present. The air gap will ensure that the translator moves freely along the stator.

In some designs, the permanent magnets are mounted in between pole shoes. The pole shoes are made of steel and the steels serve as conductors of the magnetic flux. The flux from the pole shoes passes the air gap and flow to the stator where it goes to the neighbouring pole shoes. This is the complete flow of the magnetic flux. By using low permeable material for the coil, the magnetic circuit design will be better and the magnetic flux will be maximised.

A time varying magnetic field is produced in the stator coils when the translator moves. The magnetic field will be cut when the translator moves [21].

Since a generator uses many different materials with different properties, these will produce some power losses to the system. Some examples of the losses are

1) Losses due to the changing magnetic field.
2) Resistive losses in the coil windings.
3) Hysteresis losses which is the energy to reverse magnetization of the material.

Types of Linear Generator Proposed

There are two types of generator, planar and tubular. Most of the generators are iron-cored. For this project, the linear generator proposed is iron-cored. Mass of the generator is reduced if the shape of the generator is tubular. For a tubular linear generator, the advantage of the design is that the stator is closed looped around the permanent magnets which are mounted on the translator. This will produce a denser magnetic flux for the system. Denser magnetic flux will give the generator a higher efficiency than the planar linear generator [22].

Slotless and slotted stator core affects the analysis of the linear generator too. Slotless generator is when the copper windings are located outside the stator core while the slotted generator is when the windings are located inside the stator core. Removal of slots reduces the cogging forces between the stator and the translator but it also reduces the induced voltage produced [22].

For air-cored generator, the attraction forces are significantly reduced but the electromagnetic layout is compromised [23].

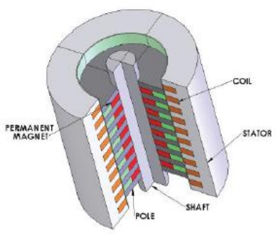


Figure 13 - Tubular Linear Generator

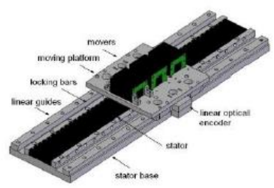


Figure 14 - Planar Linear Generator

Designing and modelling

The designing and modelling of the generator will be done by using the finite element analysis software, ANSYS. The geometry, frequency, material characteristics and temperature and other physical aspects directly affecting a component's design performance can be calculated using ANSYS simulation software. Other than that, the software will be able to provide visualization and solves the field parameters that are important for the simulation such as force, torque, capacitance, inductance, resistance and impedance.

By modelling the micro linear generator, an optimized generator can be designed. The optimized generator will be able to produce better results.

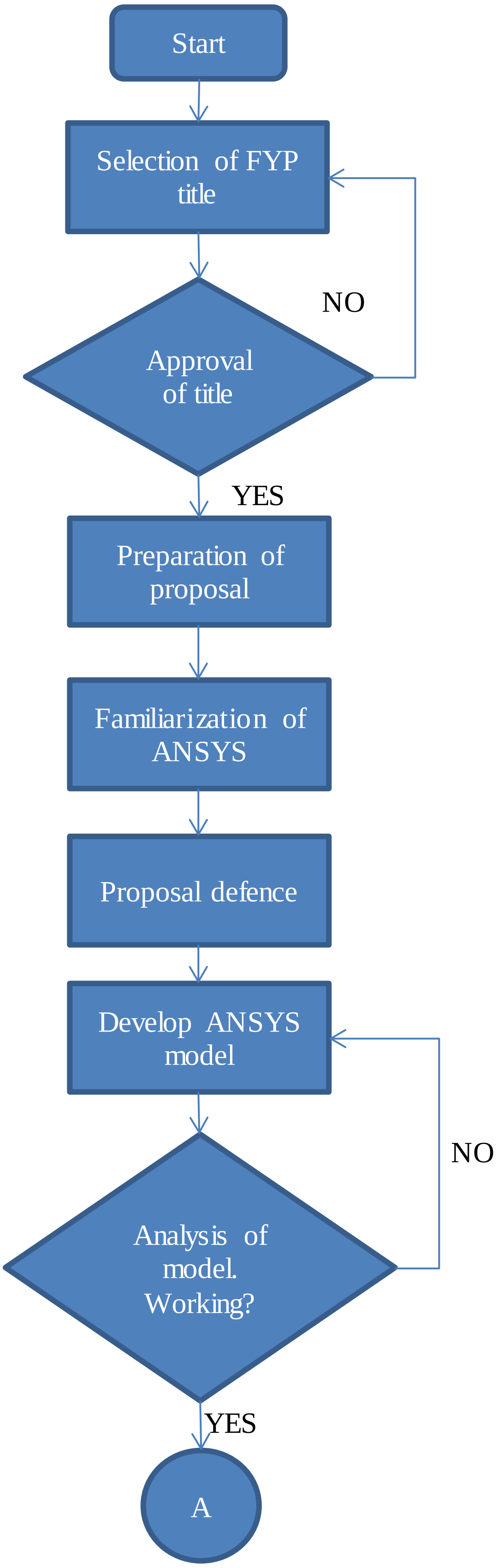
Chapter 3

Methodology

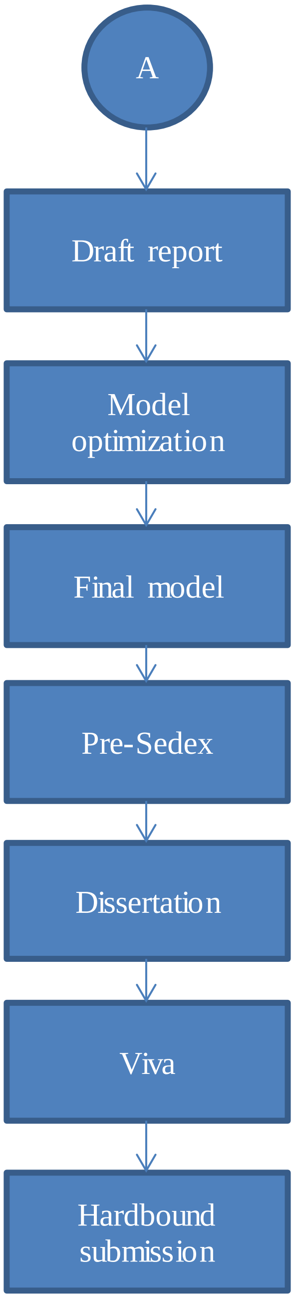
Gantt Chart

Project Flow	2	3	4	5	6	7	8	9	10	11	12	13	14	
FYP 1														
Study on methods to read research articles. (Mendeley)	■													
Prepare project plan & Gantt chart		■												
Preparation of literature review 1) study on energy harvesting methods 2) linear generator design for vibration energy harvesting			■	■	■									
Extended Proposal					●									
Install and familiarize with ANSYS Software						■	■	■						
Proposal Defence								●						
Develop a model on ANSYS									■	■	■	■		
Test and simulate design										■	■	■		
Analyze the result											■	■		
Draft Report												●		
FYP2														
Design model optimiziation	■	■	■	■	■	■								
Progress Report						●								
Test and simulate optimized model				■	■	■	■							
Analyze results					■	■	■							
Draft report						■	■	■						
Final simulation								■	■	■				
Pre sedex									●					
Final presentation										■	■			
Dissertation											●			
Final report												■		
Viva												●		
Hard bound submission														●

Flow Chart



Start
Selection of FYP title
NO
Approval of title
YES
Preparation of proposal
Familiarization of ANSYS
Proposal defence
Develop ANSYS model
NO
Analysis of model. Working?
YES
A


A
Draft report
Model optimization
Final model
Pre-Sedex
Dissertation
Viva
Hardbound submission

Current Research of Vibration Energy Harvesting

The research done on the vibration energy harvesting was based on various research papers, journals, reports and experiments that are related to this topic. For the first semester, the project were more focused on gathering the required information about the potential sources of vibration energy, methods of converting the vibration energy into electricity, the design done by previous researchers and others. As for the second semester, the project was continued with the simulations of the design and the analysis of the designs. A few designs are done to compare the results and the analysis.

Analysis of Problem and Finding the Solution

A specific problem has been identified for the project. The goal of the project is to find a solution to power up wireless sensor networks using vibration energy. Presently, the sensors are using batteries as the main power source. Usage of batteries is not practical and causes a lot of problem when a large number of the systems are in used. Replacing the batteries is too tedious and this reduces the efficiency of the system.

The objective of the project is to come out with a solution to the problem. Vibrating energy is a very vast area of energy and is available anywhere. Harvesting this energy will reduce the dependency on batteries for any wireless network sensors. Designing a micro generator that is able to convert vibration energy into electricity is the solution that will be discuss in the project. The generated energy will be used to power up the WSN.

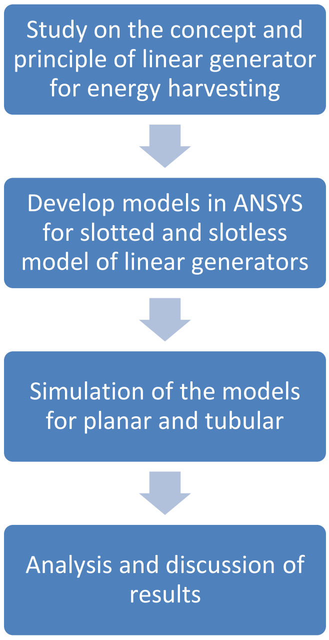
Deliverables

The aim of the project is to :

- Produce an optimum design of a micro linear generator for vibration energy harvesting
- Analysis of the design

Chapter 4

Results



The aim of this project is to design an optimum energy harvester for vibration energy and a micro linear generator. The expected result from this project is to improve the design of the energy harvester and the linear generator that are currently available in the market. The improved design will be able to produce better output and power up more electronic devices. With a better system, more WSN devices can be powered up and this will benefit all the users.

A few designs of a linear generator were done using ANSYS. Simulations to view the distributions of the magnetic flux in the designs were analysed. From the simulations, the effectiveness of the design can be analysed and the design can be compared and analysed to make the effect of the magnets better.

The design method begins by selecting magnet sizes and the number of magnets based on intuition or experience, determine steel requirements, calculate the number of turns required in the coil as well as the wire diameter, estimate the cost for the design, and repeat with different magnet selections. Lower cost designs will be recorded and higher cost designs discarded. Hopefully, a good design will be found with just a few iterations.

Design of the micro linear generator is modelled using the software Ansoft's Maxwell 14.0. The previous chapter explained about the essential elements in designing the generator. This chapter is dedicated for the discussion of the results of the simulation.

Design

Below are the designs simulated is ANSYS. There are four designs that will be discussed.

1) Planar Slotted
2) Planar Slotless
3) Tubular Slotted
4) Tubular Slotless

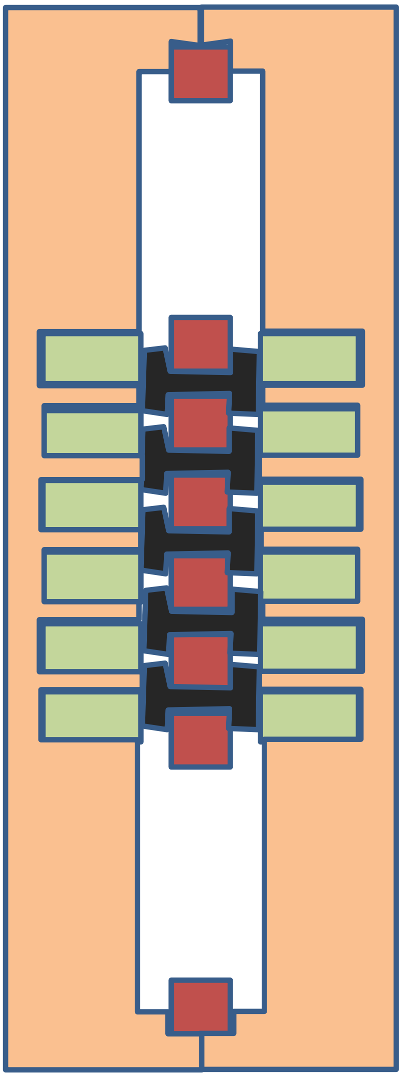


Table 3 - Components of Generator

Colour	Components
	Stator
	Magnets
	Coil Windings
	Pole Shoes

Figure 15 - Components of Generator

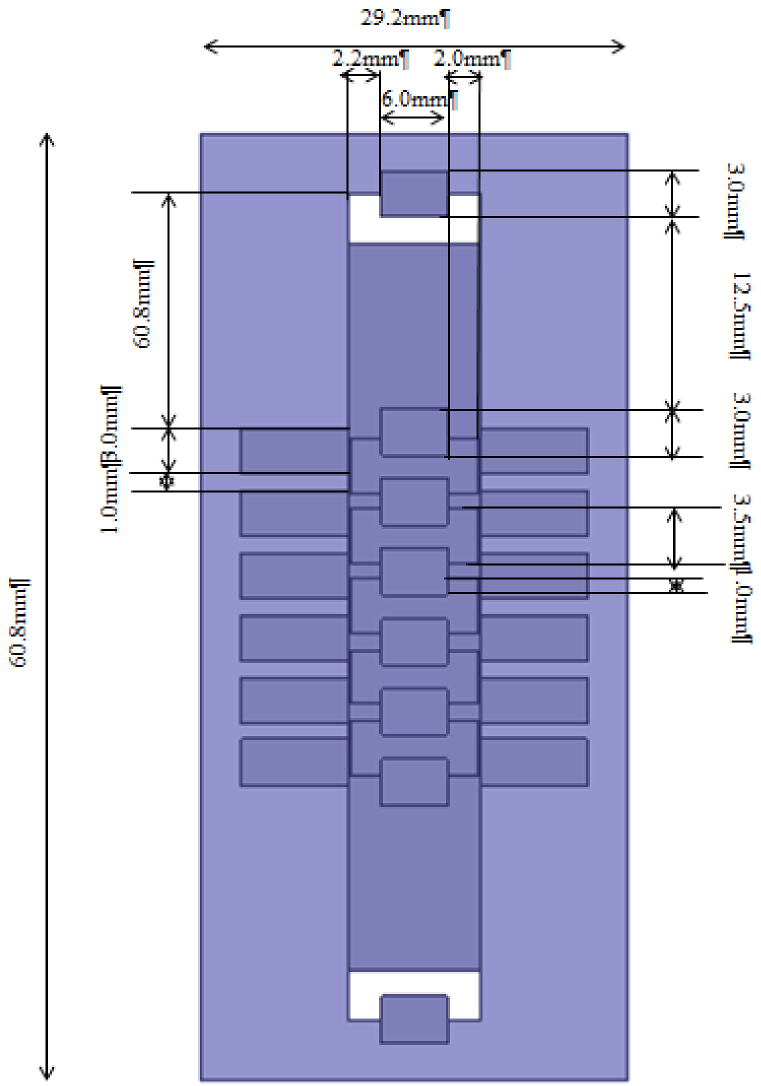


Figure 16 - Measurement of Planar Slotted Micro Linear Generator

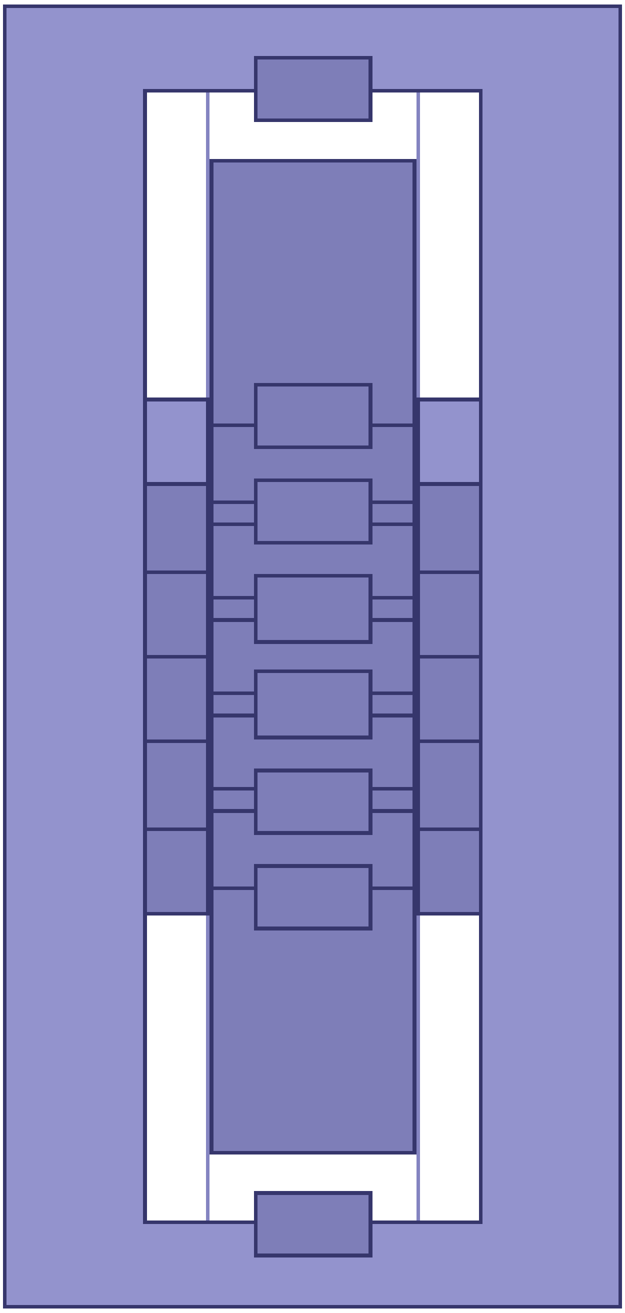


Figure 17 - Planar Slotless Micro Linear Generator

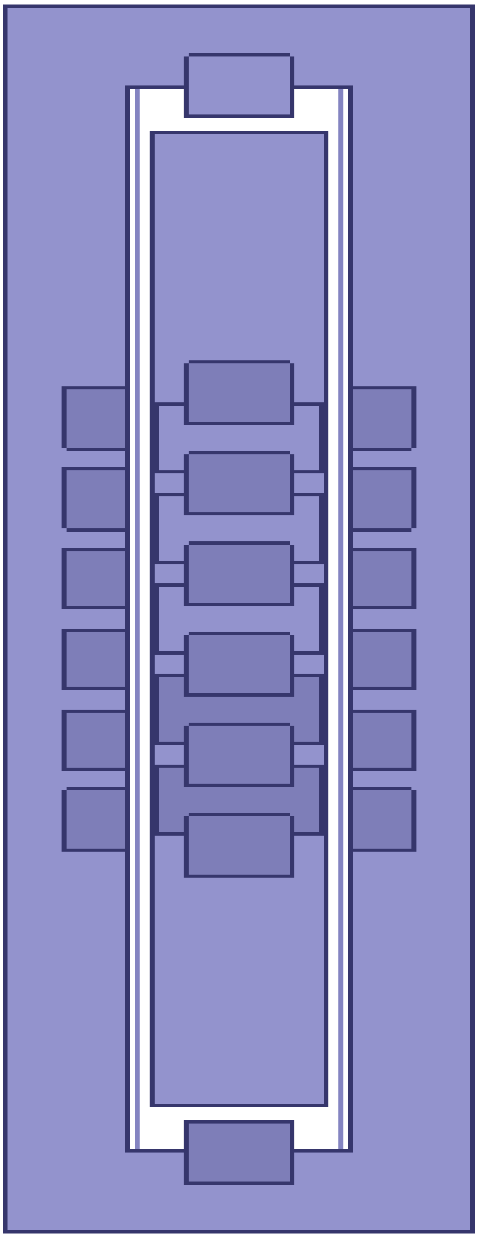


Figure 18 - Tubular Slotted Micro Linear Generator

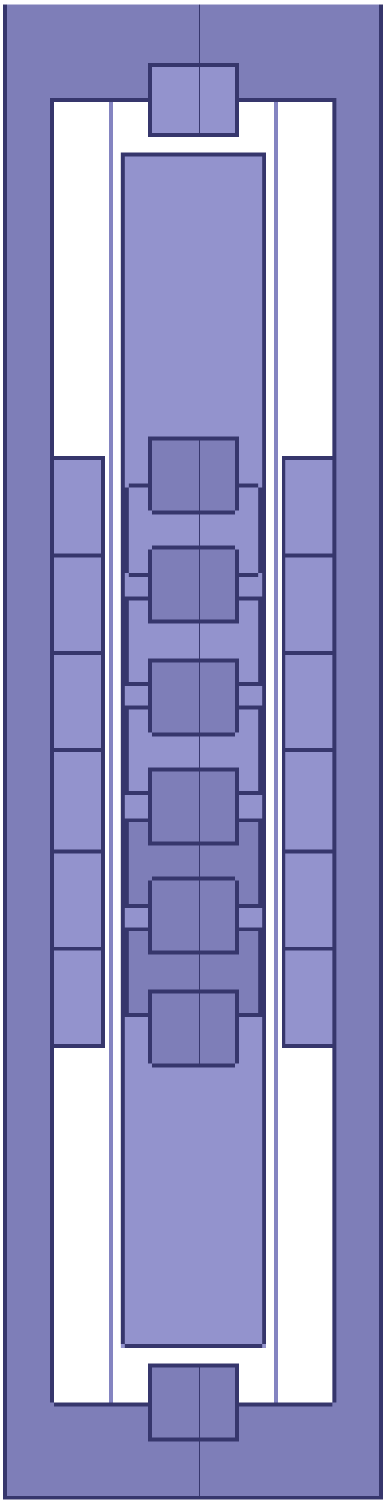


Figure 19 - Tubular Slotless Micro Linear Generator

Based on the designs, the results of the analysis are different for each one. The results analysed would be the magnetic flux lines, the magnetic density of the magnets, the flux linkage of the generator and the induced voltage.

Magnetic flux lines are the magnetic field of the magnets. It shows the direction of the magnetic field from the North Pole to the South Pole of the magnets. The length of air gap is 53mm and the width of the air gap is 0.2 mm. The direction of the flux lines depends on the polarity of the magnets.

Magnetic density is the density of the magnetic field. It is calculated in the unit of Tesla. It is the amount of magnetic flux in a unit area perpendicular to the direction of the magnetic flow. The magnetic density shows the strength of the flux.

Induced voltage is the voltage produced from the relative movement of a circuit and a magnetic field. Permanent magnet will move in relative to a conductor, which in this project is the copper coils, and this will produce the EMF. This will be the induced voltage of the system. If the wire is connected to an electrical load, current will flow and electricity is generated. Mechanical motion of the system is converted to electrical energy.

Flux linkage on the other hand is the product of the total flux and the number of coils in the wire. The flux linkage affects the total of induced voltage. If the coil is stationary, no EMF is produced. When the coil moves, flux linkage is produced between the magnet and the coil. The flux is cut by the movement of the translator and this produces the electrical energy. If the movement is towards the positive of the Y-axis, flux linkage will be in the positive axis of the graph. If the movement is along the negative of Y-axis, the flux linkage will be at the negative section of the graph. This is similar for the tubular design but involves the Z-axis of the design. For some designs, the flux linkage will not be a straight line. This might be because of the cogging forces that are present between the rotor and the translator. Cogging forces will also affect the movement of the translator.

Below are the parameters determined for the proposed designs. As the designs are done in 2D, for the planar generators, the full design is simulated and analysed. This is due to the design being simulated on a XY plane. For the tubular design, only half of the generator is simulated and designed since it is designed along the Z-axis. Thus, the design is assumed to rotate along the Z-axis.

Table 4 - Design Parameters

Parameters	Details
Velocity of Translator	40 mm/sec
Movement	+/- 2 mm (Y-axis / Z-axis)
No of Magnets	8
No of Coils	12
No of turns for each windings	1000
Air Gap Width	0.2mm
Air Gap Length	53mm

Flux Lines and Magnetic Density of the 4 Designs

1) Planar, Slotted Linear Generator

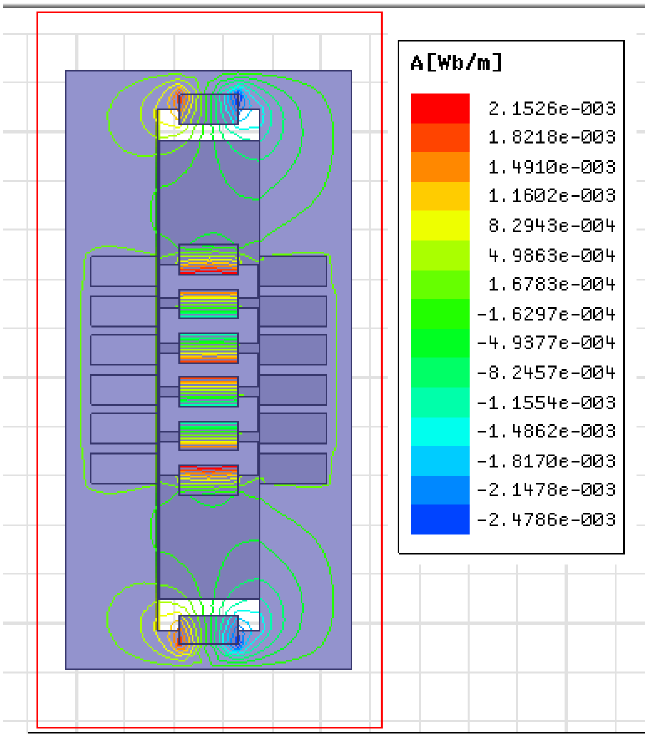


Figure 20 - Flux Line Distribution

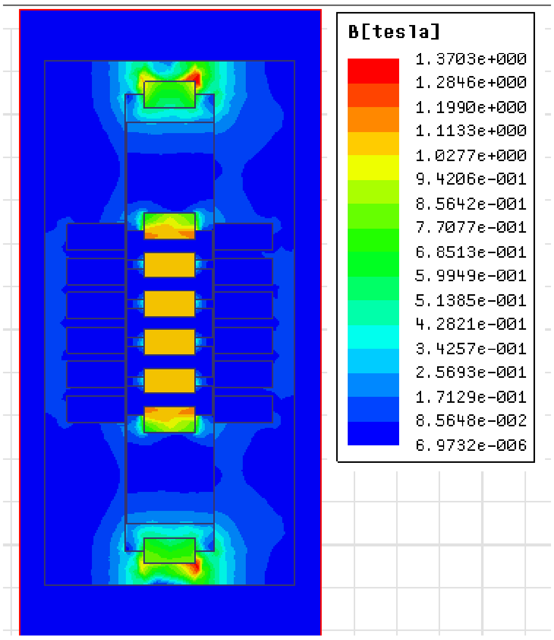


Figure 21 - Magnetic Flux Density

2) Planar, Slotless Linear Generator

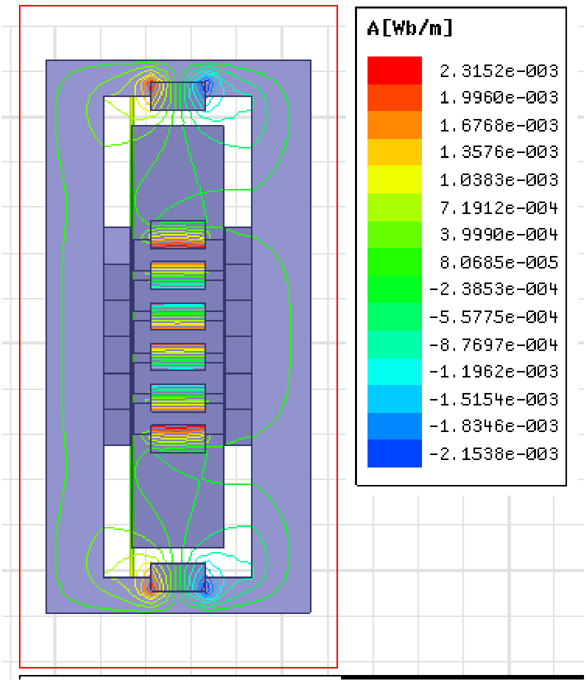


Figure 22 - Flux Line Distribution

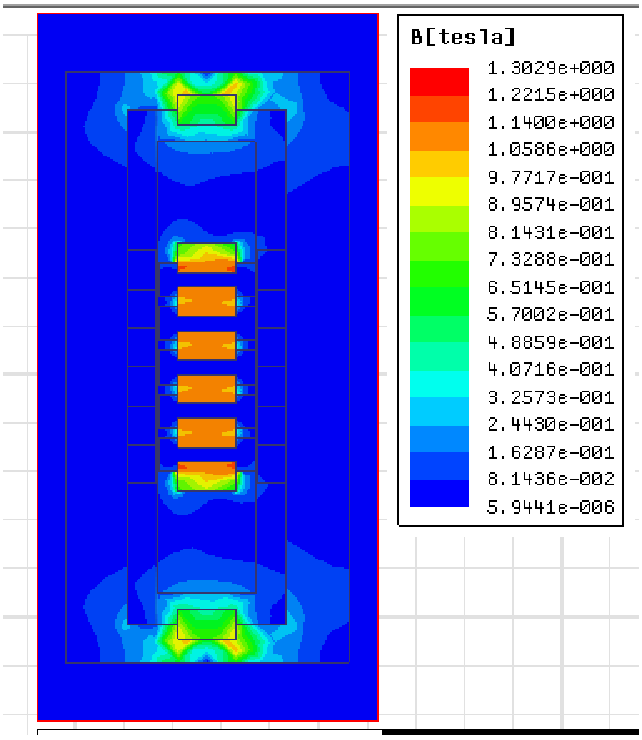


Figure 23 - Magnetic Flux Density

3) Tubular, Slotted Linear Generator

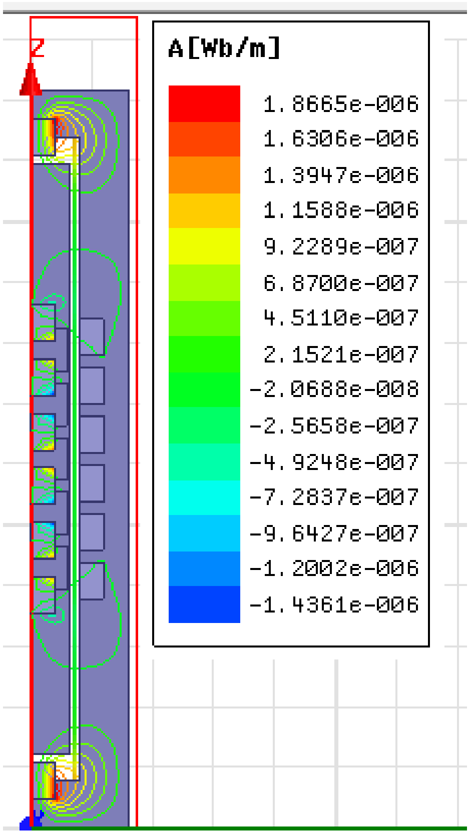


Figure 24 - Flux Line Distribution

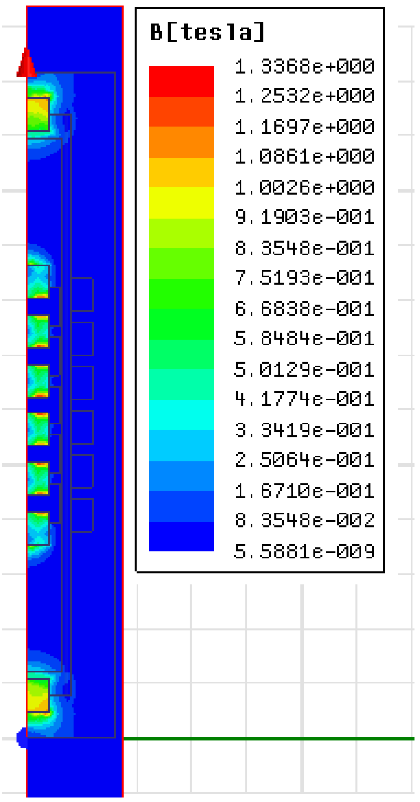


Figure 25 - Magnetic Flux Density

4) Tubular, Slotless Linear Generator

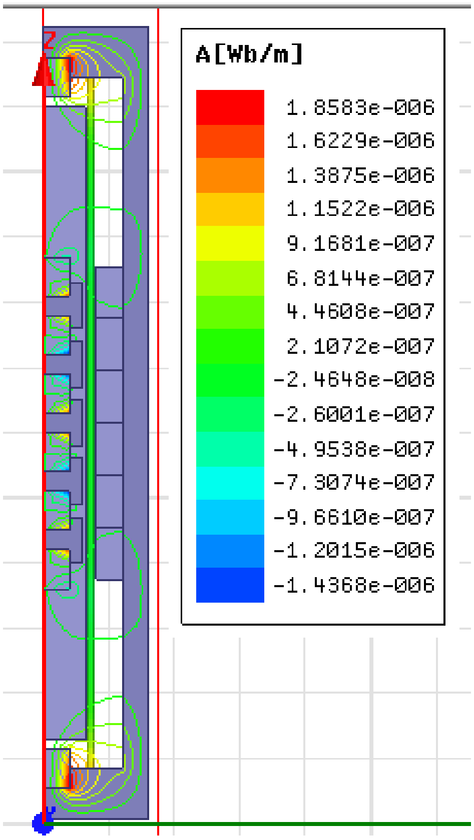


Figure 26 - Flux Line Distribution

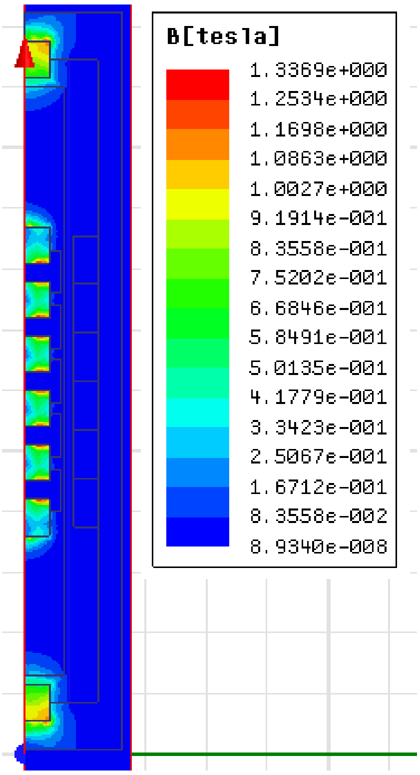


Figure 27 - Magnetic Flux Density

The diagrams show the distribution of flux lines and the magnetic density of the designs. With a few designs of a linear generator, the magnetic flux distribution and density can be compared and the design with the best results can be chosen.

By comparing the flux line distribution from the figures above, they showed that slotted generator will have a better distribution of flux lines. There are more flux lines for the slotted generators and the one with the better distribution of flux lines is the slotted tubular generator. Comparing the magnetic density of the generators, the magnetic density for the tubular slotted generator is the best. This is because the slots will distribute the flux density equally and evenly throughout the design.

As a conclusion for the comparison of the flux line distribution and the magnetic density for all four generators, the tubular generators will produce denser magnetic flux for the system.

Air Gap Flux Distribution

Flux Line VS Distance

1) Comparison for Planar Linear Generator, Slotted and Slotless

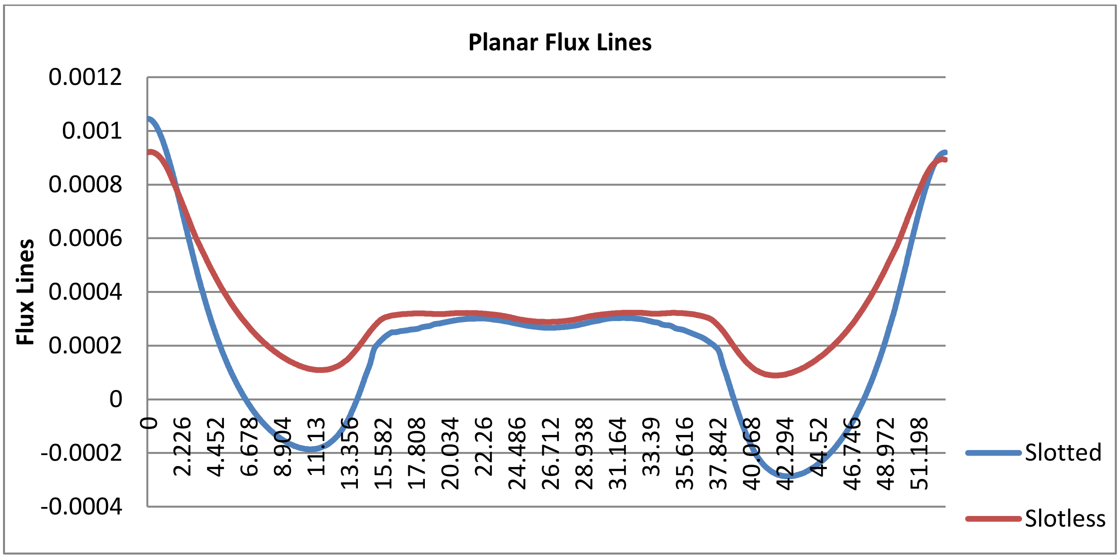


Figure 28 - Graph of Flux Line VS Distance (Planar)

2) Comparison for Tubular Linear Generator, Slotted and Slotless

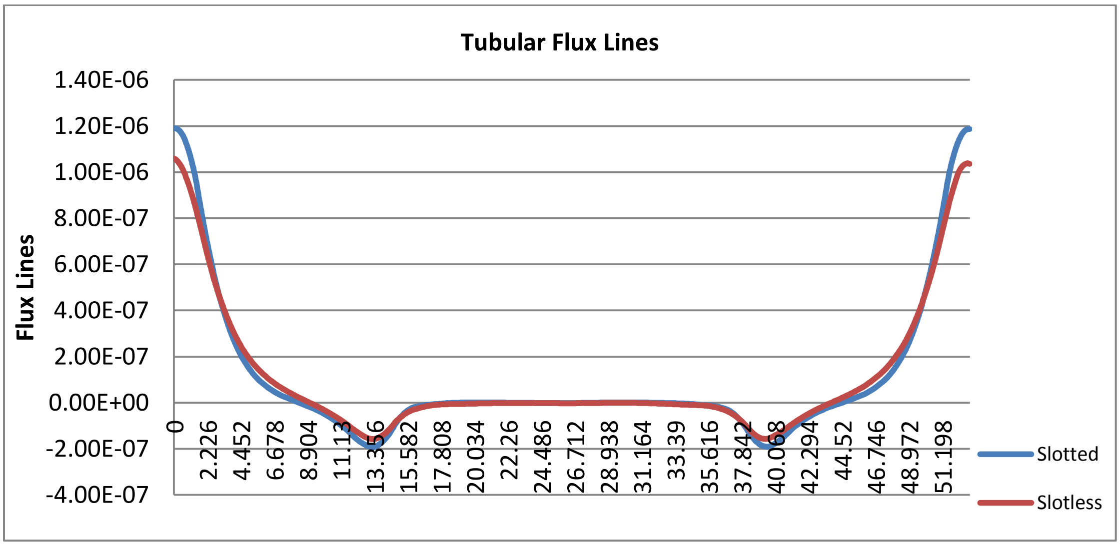


Figure 29 - Graph of Flux Line VS Distance (Tubular)

Figures 28 and 29 shows the result of flux line against distance for the 4 proposed designs. From the **Error! Reference source not found.**, it shows that the lotted design will produce the highest maximum flux line. The slotless generator produces a more linear and stable flux line density due to the size of the stator. This is applicable for both the planar and tubular designs. Even though the density of flux line is more linear, the slotted generators still produced higher flux line. For tubular generator, there are not many differences in the distribution of the flux lines. The distribution is similar due to the shape of the generator. The magnetic field will be distributed evenly throughout the tubular shape.

Flux Distribution VS Distance

1) Comparison for Planar Linear Generator, Slotted and Slotless

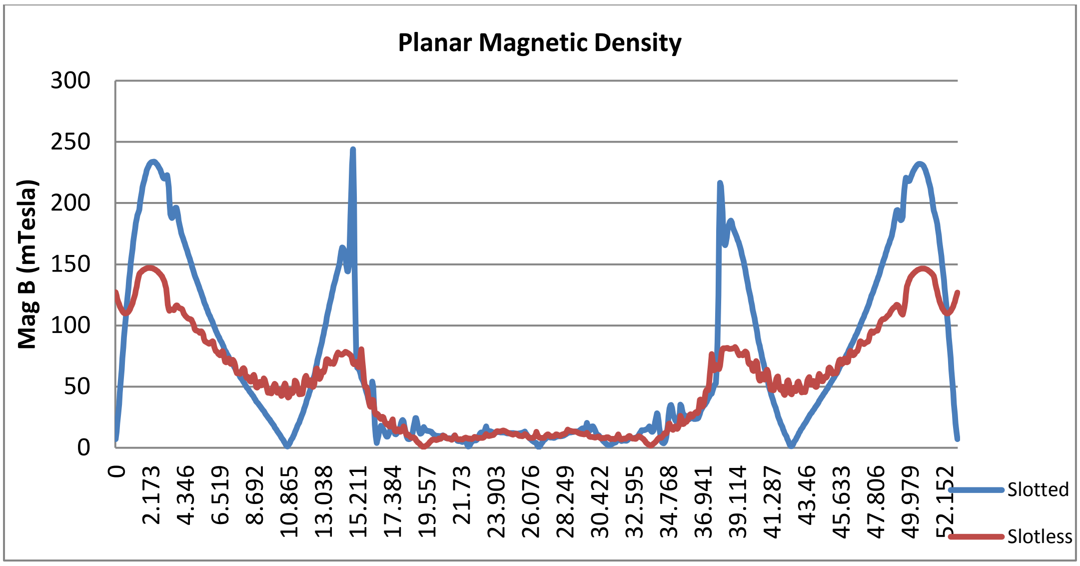


Figure 30 - Graph of Magnetic Density VS Distance (Planar)

2) Comparison for Tubular Linear Generator, Slotted and Slotless

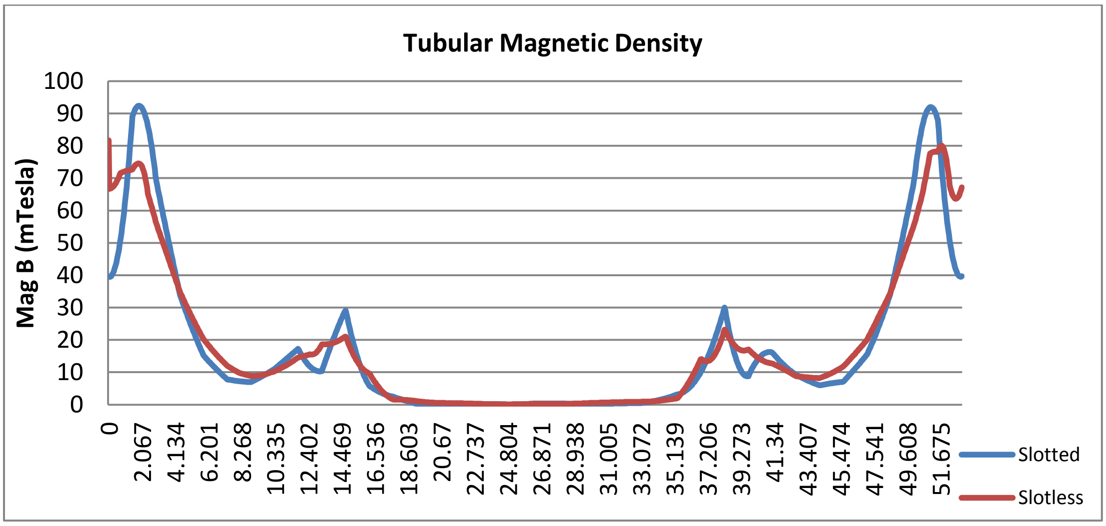


Figure 31 - Graph of Magnetic Density VS Distance (Tubular)

The figures 30 and 31 show the comparison on flux distribution along the air gap of the designs. Both the slotted generators for planar and tubular will have a higher magnetic density compared to the slotless generators. On the other hand, the slotted generators will produce a very unstable graph due to the thick stator and the slots present on the generator. The slots and the iron gaps in between the winding coils affect the graph. At the position where the iron gaps are located, the flux density will be at the lowest. For the tubular generator, the magnetic density is almost similar for both slotted and slotless due to the shape of the generator. Tubular shaped generators will produce a more equal distribution of magnetic flux.

Open Circuit Test

All the designs are analysed for the flux linkage and the induced voltage using the parameters as stated below.

Table 5 - Open Circuit Test Parameter

Parameters	Value
Stop Time	0.005s
Time Step	0.0005s
Velocity	40mm/sec

The velocity of the stator is chosen as 40 mm/sec since for a vibrating system, the frequency of vibration is quite high. The velocity s set to 40 mm/sec enables the translator to actually moves around 10 cycles in 1 second. The amplitude of the graph will be +/- 2mm since the translator is set to move 2mm on the positive axis.

The time steps are chosen to be 0.0005s and stop time as 0.005s to ensure that the graph will be clear and show the necessary values that are needed.

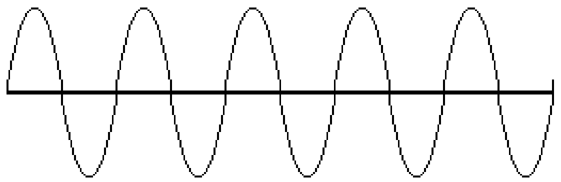


Figure 32 - Graph of 10 cycles per second

Flux Linkage VS Time

1) Comparison for Planar Linear Generator, Slotted and Slotless

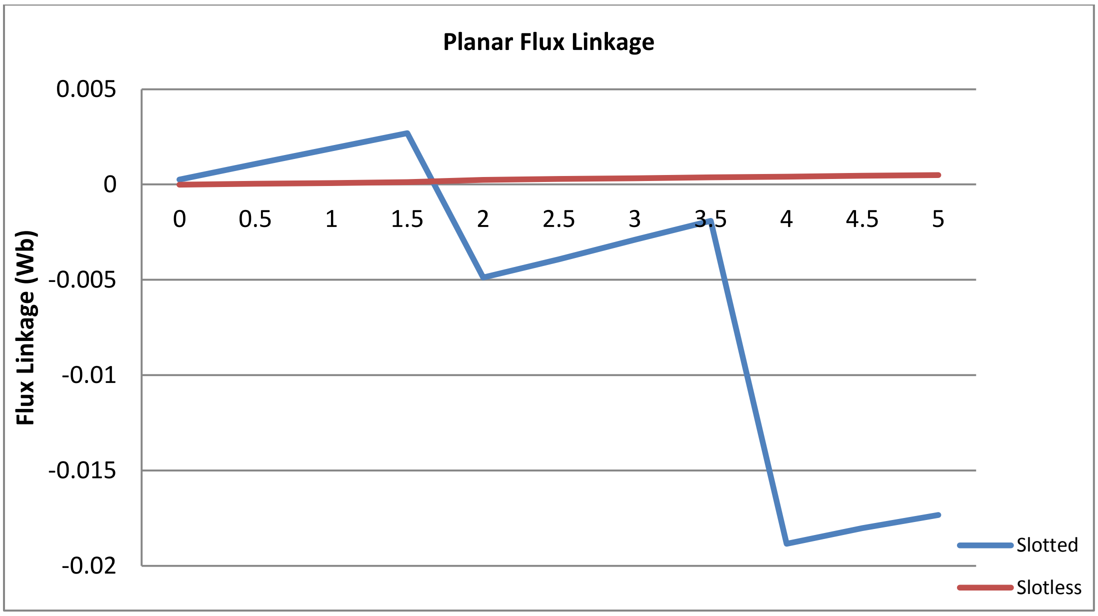


Figure 33 - Graph of Flux Linkage VS Time (Planar)

2) Comparison for Tubular Linear Generator, Slotted and Slotless

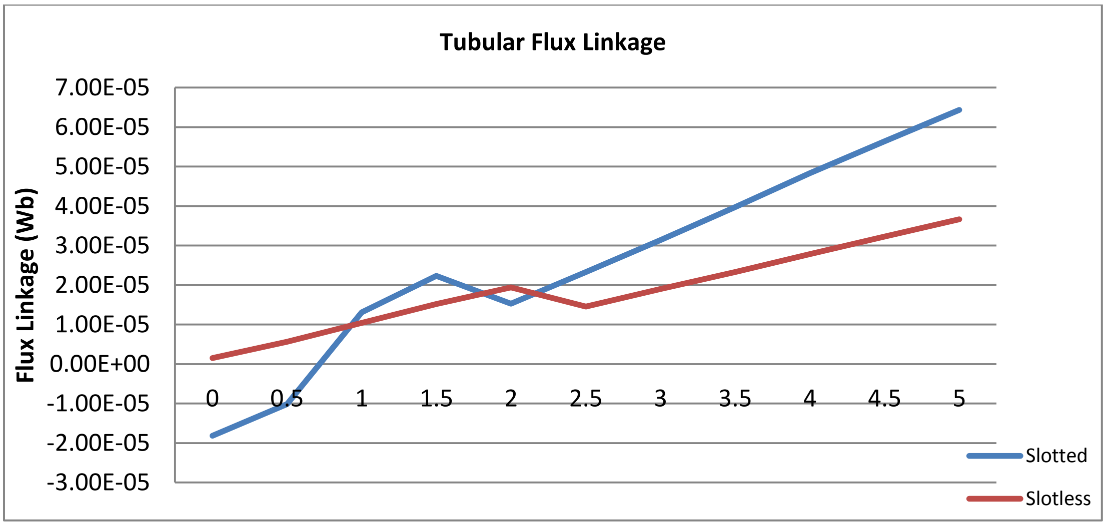


Figure 34 - Graph of Flux Linkage VS Time (Tubular)

Figures 32 and 33 show the comparison of the flux linkage for the designs. The flux linkage can be obtained depending on the amount of flux formed when the translator is moving. The result is approaching a linear graph since flux is proportional to the stroke of the translator. Since the air gap flux distribution for the slotless is almost linear, it shows here in the flux linkage also. The slotless generator gives a linear graph due to the absence of slots. Other than that, the cogging factor of the generator is less. For the slotted generator, the cogging factor is higher, thus the graph generated is not too linear.

The flux linkage graph will affect the graph of induced voltage. If the flux linkage graph is linear, the induced voltage produced will be stable. If the flux linkage graph is not linear, the induced voltage will not be stable. It will have overshoots and produces odd values.

Induced Voltage VS Time

1) Comparison for Planar Linear Generator, Slotted and Slotless

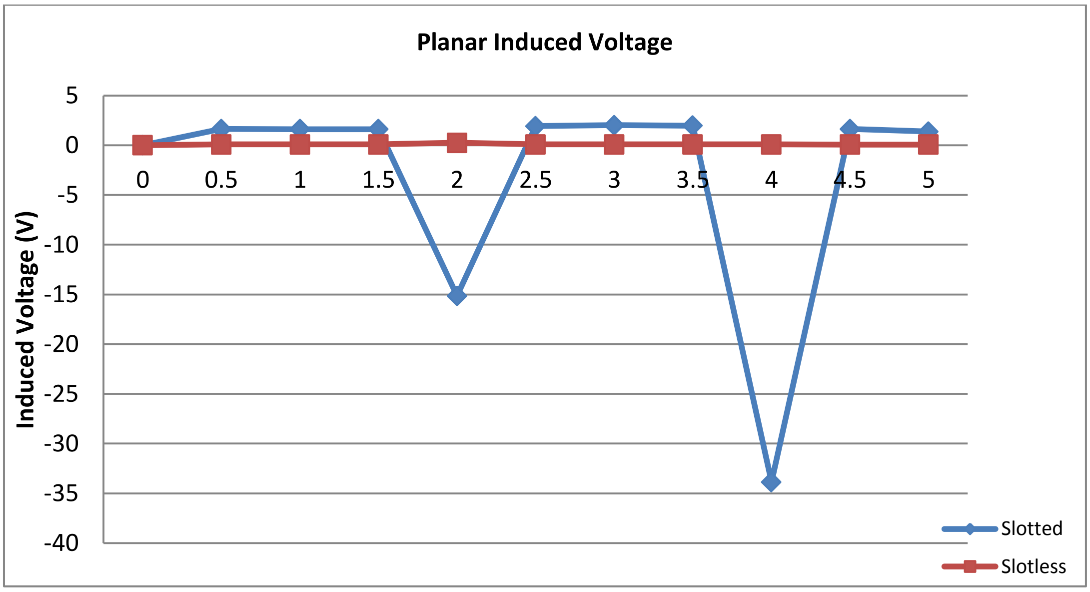


Figure 35 - Graph of Induced Voltage VS Time (Planar)

2) Comparison for Tubular Linear Generator, Slotted and Slotless

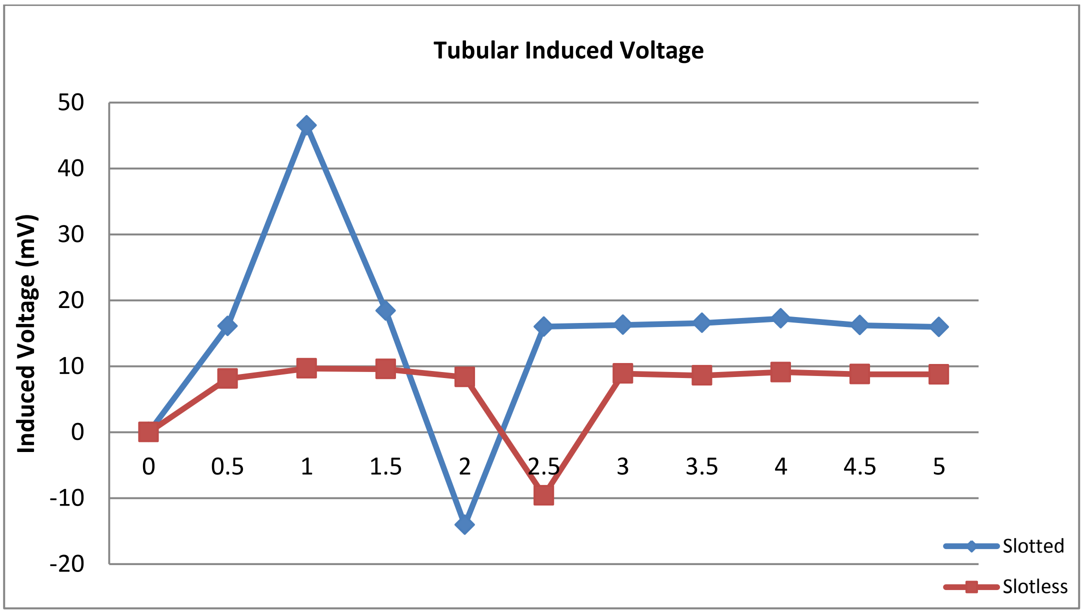


Figure 36 - Graph of Induced Voltage VS Time (Tubular)

Figures 34 and 35 show the comparison for the induced voltage. From the graph, it can be concluded that the induced voltage is at the maximum for the planar slotted generator. The generators have the highest maximum value and also the maximum average value. The connections for the generators are designed to be in series to obtain the maximum possible voltages. The value of voltage for all the generators that will be needed is the stable values.

Generator	Stable Voltage (V)	Maximum Voltage (V)
Planar Slotted	2	-33.86
Planar Slotless	0.09	0.24
Tubular Slotted	0.016	0.0465
Tubular Slotless	0.008	0.00965

Discussion

The graphs of the flux linkage and the voltage induced are not for the whole system. Instead, it is just for the positive movement of the translator. Using the software, the translator is animated only 2mm on the positive axis of the Y-axis for planar generators and Z-axis for tubular generators. Due to this, the graphs will only show part of the results.

The results for the tubular generator are less than the planar generators in the simulation results due to the design simulated in the software. The design is in 2D thus, the results are based on a part of the 2D design of the generator since it is on the plane that rotates along the Z axis. If the design is drawn in 3D, the results would have been more precise.

Throughout the chapter, the research managed to obtain the preliminary result to compare the performance of the proposed designs. Four micro linear generator designs were proposed and designed using ANSYS. Slotted generator is better than slotless. In theory, tubular is better than planar. Future research need to be conducted to prove this theory further.

Conclusion

Vibration energy can be the future source of energy for most appliances. Vibration energy will slowly be used to power up all the low powered electronic devices. Batteries can soon be the item of the past. Micro linear generators will be used to reduce the needs of batteries and be the new source of power.

Vibration energy can be harvested from various sources, from applications and mechanisms that vibrate. Each appliance vibrates with different levels of frequency. High frequency appliances will produce higher levels of vibration energy and this will produce higher level of power. With the use of vibration energy, the need for non-renewable energy decreases and this reduces the environmental impact to the world. Disposal of the batteries can be reduced. This will benefit everyone since the renewable energy will be available anytime and for everyone.

As a conclusion, the variation of the designs of the generators will cause the variation to the results obtained. The different characteristics such as slots and the shape of the generator therefore, from the research done, it showed that the slotted planar generator produced the best result and yield the highest efficiency that meet the objective of the research.

As the recommendation, designs of the micro linear generator can be optimized further in the future. Optimizing the design will enable a better generator to be produced. The design will produce a better output, higher power and will be able to power up different types of wireless sensor networks. The optimization of the design can be done by changing the types of the magnet, the type and design of stators and rotors and other elements of the micro linear generator.

References

[1] R. Kay, "The Design Space of Wireless Sensor Networks ∗ ," no. 5005, 2004.

[2] R. Deepika, B. Gomathi, and J. Karthik, "Study of Wireless Sensor Network and Its Current Trend in Application," vol. 3, no. 1, pp. 134–137, 2014.

[3] "ON World Wireless Sensor Networks in Small and Medium Sized Buildings to Increase 10X by 2017." [Online]. Available: http://www.prweb.com/releases/2013/9/prweb11154385.htm. [Accessed: 13-Dec-2014].

[4] "Wireless Sensor Networks Evolve to Meet Mainstream Needs RTC Magazine." [Online]. Available: http://rtcmagazine.com/articles/view/102871. [Accessed: 12-Dec-2014].

[5] D. P. Kothari and I. J. Nagrath, *Scilab Textbook Companion for Electric Machines Book Description*, 2nd Editio. 2001.

[6] B. P. D. Mitcheson, M. Ieee, E. M. Yeatman, S. M. Ieee, G. K. Rao, S. M. Ieee, A. S. Holmes, and T. C. Green, "Human and Machine Motion for Wireless Electronic Devices," vol. 96, no. 9, pp. 1457–1486, 2008.

[7] S. P. Beeby, R. N. Torah, M. J. Tudor, P. Glynne-Jones, T. O'Donnell, C. R. Saha, and S. Roy, "A micro electromagnetic generator for vibration energy harvesting," *J. Micromechanics Microengineering*, vol. 17, no. 7, pp. 1257–1265, Jul. 2007.

[8] S. Bandyopadhyay and A. P. Chandrakasan, "Platform architecture for solar, thermal, and vibration energy combining with MPPT and single inductor," *IEEE J. Solid-State Circuits*, vol. 47, no. 9, pp. 2199–2215, 2012.

[9] "Thorlabs - Your Source for Fiber Optics, Laser Diodes, Optical Instrumentation and Polarization Measurement & Control." [Online]. Available: https://www.thorlabs.de/tutorials/tables2.cfm. [Accessed: 08-Dec-2014].

[10] P. Glynne-Jones, M. J. Tudor, S. P. Beeby, and N. M. White, "An electromagnetic, vibration-powered generator for intelligent sensor systems," *Sensors Actuators A Phys.*, vol. 110, no. 1–3, pp. 344–349, Feb. 2004.

[11] D. Zhu, "Methods of Frequency Tuning Vibration Based Micro-Generator," University of Southamton, 2009.

[12] A. Townley and G. Piazza, "VIBRATIONAL ENERGY HARVESTING USING MEMS PIEZOELECTRIC GENERATORS."

[13] F. Cottone, "Introduction to Vibration Energy Harvesting," 2011.

[14] W. Knight, “Micro-generator feeds on good vibrations - tech - 04 July 2007 - New Scientist,” 2007. [Online]. Available: http://www.newscientist.com/article/dn12190-microgenerator-feeds-on-good-vibrations.html#.VFRW-fmUdnY.

[15] S. a. Zulkifli and M. Z. Ahmad, “Linear generator models in simulink block,” *2010 IEEE Int. Conf. Power Energy*, pp. 226–231, Nov. 2010.

[16] G. W. Jewell and D. Howe, “A low-power, linear, permanent-magnet generator/energy storage system,” *IEEE Trans. Ind. Electron.*, vol. 49, no. 3, pp. 640–648, Jun. 2002.

[17] W. C. Chye, Z. Dahari, O. Sidek, and M. A. Miskam, “Electromagnetic micro power generator — A comprehensive survey,” *2010 IEEE Symp. Ind. Electron. Appl.*, no. Isiea, pp. 376–382, Oct. 2010.

[18] I. I. Abdalla, T. Ibrahim, and N. Mohd Nor, “Analysis of a Tubular Linear Permanent Magnet Motor for Reciprocating Compressor Applications,” *Appl. Mech. Mater.*, vol. 448–453, pp. 2114–2119, Oct. 2013.

[19] M. A. F. M. Hamim, T. Ibrahim, and N. M. Nor, “Design o f a Portable Pieo Linear Permanent Magnet Generator f or Wave Energy Conversion,” pp. 0–5, 2013.

[20] S. Alshibani, R. Dutta, and V. G. Agelidis, “Flux Density Analysis of Using Halbach Array in MW Level Permanent Magnet Synchronous Generators for Wind Turbines : A Preliminary Linear Model,” pp. 274–280, 1980.

[21] O. Danielsson, “Design of a Linear Generator for Wave Energy Plant,” no. January, 2003.

[22] T. S. Parel, M. D. Rotaru, J. K. Sykulski, and G. E. Hearn, “Optimisation of a tubular linear machine with permanent magnets for wave energy extraction,” *COMPEL - Int. J. Comput. Math. Electr. Electron. Eng.*, vol. 30, no. 3, pp. 1056–1068, May 2011.

[23] J. Bard and P. Kracht, “Linear Generator Systems for Wave Energy Converters.”

[24] G. Bracco, E. Giorcelli, G. Mattiazzo, D. Meccanica, P. Torino, F. Marignetti, S. Carbone, C. Attaianese, D. Automazione, and U. Cassino, “Design and experiments of linear tubular generators for the Inertial Sea Wave Energy Converter,” pp. 3864–3871, 2011.