FINITE ELEMENT METHOD OF ELECTROMAGNETIC-ENERGY HARVESTER: SIMPLE BEAM-MASS SYSTEM

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ABSTRACT

The objective of this study is to validate the experimental modal parameter of electromagnetic energy harvester using Finite Element Method (FEM). The performance of the vibration- electromagnetic energy harvester is investigated for different number of coils and length of beam. The relationship between the excitation frequencies and the mode shapes of the energy harvester produced has been analyzed. An electromagnetic energy harvester device was designed and implemented with modal testing is required to gain dynamic characteristic. The parameter used by varying three set of coils including 350 turns, 700 turns and 1050 turns and varying three different length of beam including 9 mm, 11 mm, and 13 mm. An analysis setup consists of FEM simulation with modal analysis and magnetostatic arrangement. The result showed that energy harvester design analysis using FEM indicates magnetic flux path, magnetic density and intensity. The magnetic flux from FEM validated with theoretical calculation and regardless of the parameter, the same set of natural frequencies will be obtained. These shows that the power can be generated and can be improve by varying the number of turn of the coil and length of beam. The increase number of turn coils and length of beam will increase the value of magnetic field intensity.

ABSTRAK

Objektif kajian ini adalah untuk mengesahkan parameter modal eksperimen elektromagnet tenaga penuai menggunakan Kaedah Unsur Terhingga (FEM). Prestasi getaran elektromagnet tenaga penuai disiasat untuk bilangan gegeulung yang berbeza dan panjang rasuk. Hubungan antara frekuensi pengujaan dan bentuk mod tenaga yang dihasilkan telah dianalisis. Tenaga elektromagnet peranti penuai telah direka dan dilaksanakan dengan ujian modal diperlukan untuk mendapatkan ciri-ciri dinamik. Parameter adalah diuji dengan mengubah tiga set gegelung termasuk 350 gelung, 700 gelung dan 1050 gelung bersama tiga yang berbeza-beza panjang yang berbeza rasuk termasuk 9 mm, 11 mm dan 13 mm. Persediaan analisis terdiri daripada simulasi FEM dengan analisis modal dan susunan magnetostatik. Hasilnya menunjukkan bahawa tenaga penuai analisis reka bentuk menggunakan Kaedah Unsur Terhingga (FEM) menunjukkan laluan fluks magnet, ketumpatan magnet dan intensiti. Fluks magnet dari FEM disahkan dengan pengiraan teori dan tanpa mengira parameter, set yang sama frekuensi semula jadi akan diperolehi. Ini menunjukkan bahawa kuasa boleh dihasilkan dan boleh memperbaiki dengan mengubah bilangan gegelung dan panjang rasuk. Jumlah peningkatan bilangan gegelung dan panjang rasuk akan meningkatkan nilai keamatan medan magnet.

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LIST OF SYMBOLS

ω	Natural Frequency
emf	Electromagnetic Force
Q	Energy Charge
V	Potential Difference
B_0	Magnetic Field
k	Beam Stiffness
I	Moment of Inertia
f	Frequency
m	Mass
Φ	Flux Linkage

LIST OF ABBREVIATIONS

RF	Radio Frequency
MEM	Microelectromechanical
FEM	Finite Element Method
FEA	Finite Element Analysis
NdFeB	Neodymium Iron Boron
FRF	Frequency Response Functions
CAD	Computer Aided Design
SDOF	Single Degree of Freedom

CHAPTER 1

INTRODUCTION

1.1 PROJECT BACKGROUND

This chapter will discuss about the project background, problem statement, project objective and the scope of the project. The project is about the simulation study of electromagnetic-energy harvester based on simple beam-mass system. Energy harvesting is the process of capturing minute amounts of energy from one or more of these naturally-occurring energy sources, accumulating them and storing them for later use. Vibration energy harvesting is the technique that can be used to harvest the energy from vibrations and vibrating structures, a general requirement independent of the energy transfer mechanism is that the vibration energy harvesting device operates in resonance at the excitation frequency. Transduction mechanism such as electromagnetic is requires in order generating electrical energy from motion. Vibration energy is suited to inertial generators with the mechanical component attached to an inertial frame with acts as fixed reference.

Particularly, we consider a simple harvesting system in which the electromagnetic transduction is limited to a finite element interval over the displacement of the inertial mass. Thus, when the harvesting masses move outside this region no energy conversion occurs. A simple design of an electromechanical energy harvesting device is proposed and modeled by a single degree-of-freedom system. Finite-element method is used widely in industry and it can be used to simulate the response of a physical system to structural loading, and thermal and also the electromagnetic effects. Based on this method we can solve the underlying governing equations and the associated problem-specific boundary conditions.

As our everyday life is getting more and more complexes and energy sources more important, some alternative ways to generated energy is become the main idea of energy harvesting. Nowadays, vibration-based energy harvesting concept has received much attention in recent years. There are many intentions in micro-electromechanical (MEMS) where its applications are wide range in areas. One of the examples that had always been used is the medical implants and embedded sensors in building and similar structures. In kinetic energy generator, mechanical energy in the form of vibrations present in the application environment is converted into electrical energy. Kinetic energy is typically converted into electrical energy using electromagnetic, piezoelectric or electrostatic transduction mechanisms.

The amount of energy generated by this approach from electromagnetic is depends fundamentally upon the quantity and form of the kinetic energy. It is available in the application environment and the efficiency of the generator and the power conversion electronics. The design of the mechanical system should maximize the coupling between the kinetic energy source and the transduction mechanism and will depend entirely upon the characteristics of the environmental motion. In the case of electromagnetic energy harvesters, increasing the generated power density is accomplished by using multiple degrees of freedom, optimizing coil geometry and dimensions, or simply designing the generator to operate at high frequencies.

A few researches finds that the amount of money spent on energy harvesters will be USD0.7Bn, with several hundred developers involved (Happich, 2011). The majority of the value this year is in consumer electronic applications, where energy harvesters have been used for some time. In 2011, 1.6 million energy harvesters will be used in wireless sensors, resulting in $13.75 million being spent on those harvesters. The analysis is shown the Figure 1.1 which represents millions of US dollars. Furthermore, the vibration energy harvesting technique is becoming a higher market value. Energy harvesting devices produced by MEMS technologies will be mainly thermal thin-film technology whose production will start industrially in 2012 as shown in Figure 1.2. Other mechanical vibration MEMS harvesters will take longer time to be adopted due to cost challenge.

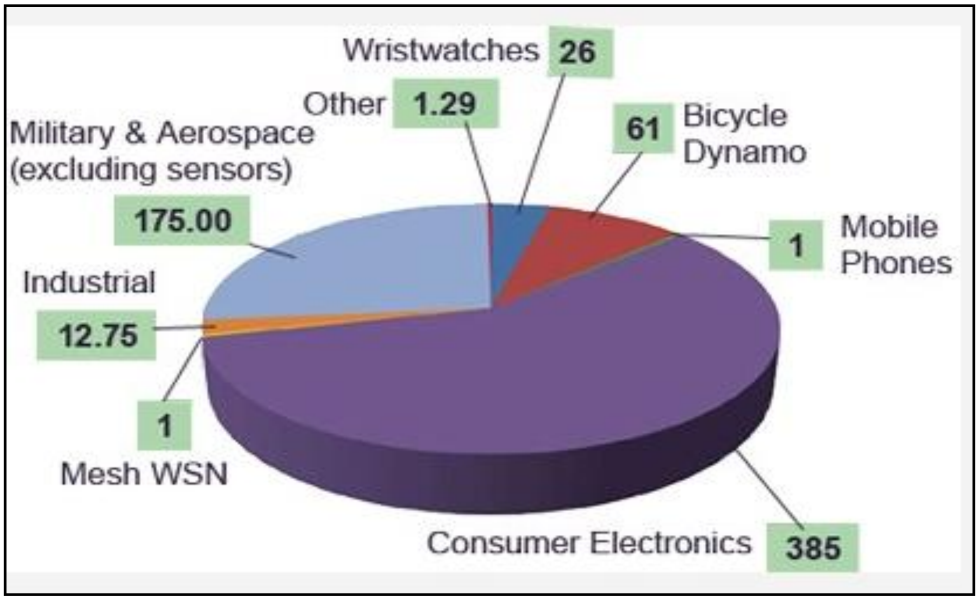

Figure 1.1: The Energy Harvesting Market in 2011 $0.7Bn

Source: Julien Happich of IDTechEx 2011

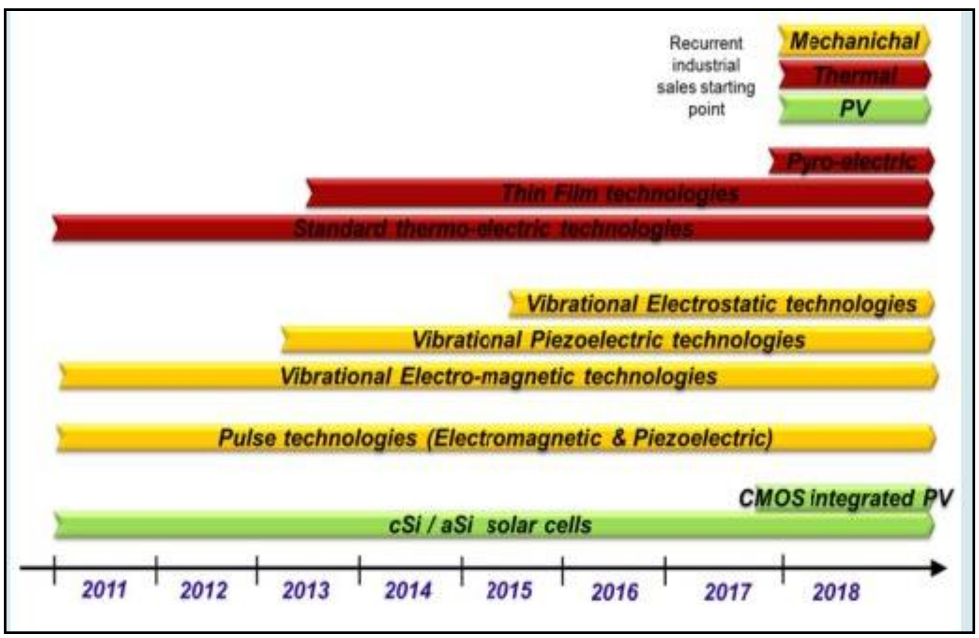

Figure 1.2: The Energy Harvesting Technologies Time to Market

Source: http://www.i-micronews.com/reports/Emerging-Energy-Harvesting-Devices/1/330/

1.2 PROBLEM STATEMENT

Energy harvesting devices scavenge energy from the environment such as ambient forced excitation, flow induced vibration, wind power and mechanical itself and electromagnetic harvesting, and is one of the oldest techniques for energy harvesting. The size of magnets and number of coils will also affect the performance and energy of the system. The conductor where are located within the magnetic field typically takes the form of a coil and the electricity is generated relative to the movement of the magnet and coil, and it is because of changes in the magnetic field. According to El-Hami et al. (2001) in order to maximize power, this must be done with the coil parameters in mind. The Finite Element Method is a numerical technique for solving models in differential form. For a given design, this method requires the entire geometry, including the surrounding region, to be modeled with finite elements. A system of linear equations is generated to calculate the potential at the nodes of each element. Therefore, this study will conducted an investigation to validate the modal parameter of electromagnetic-energy harvester using finite element method. This will consist of a modal analysis simulation to obtain the natural frequency and mode shape.

1.3 PROJECT OBJECTIVES

To solve above problem statement, the project objectives are:

- To validate the experimental modal parameter of electromagnetic energy harvester using finite element method.
- To analyze the modal of energy harvesting system due to various number of turn coils and length of beam.
- To validate magnetic flux intensity of energy harvesting system for various number of turns coils and length of beam.

1.4 SCOPE OF THE PROJECT

To obtain the maximum voltage of the energy harvester, it must be excited at its natural frequency. Modal parameter such as natural frequency and mode can be obtained using experimental modal analysis, analytical solution and numerical analysis. Analytical solution is suitable for simple structures such as beam, plate etc. while for complex structure, numerical analysis are preferred. The experimental data has been collected by the previous student and should be taken as reference to validate the simulation study. This parameter has been investigated whether it would affect the performance of the energy harvester by varying the number of turns of the coil and the length of the beams. Summarize of the experimental result is shown in the Appendices A3. Analysis of finite element method of energy harvesting to obtained the natural frequencies and mode shape in determining the performances of the electromagnetic energy harvester. Later on, comparative study for value of magnetic intensity from calculation and FEA based on equation to discovered the percentage of error.

1.5 CHAPTER OUTLINE

This writing report is organized into five (5) chapters. The first chapter introduced the introduction of the project, brief of the project, project objectives and scopes of the project. This chapter introduced the general overview about the project. Chapter 2 reviews the historical background of the project. This chapter reviews the concept, theory used in order to fabricate the system. Algorithms used in developing the system are also explained in this chapter. The parameters used are described in this chapter to get the path of the project flow. Chapter 3 presents the research methodology, system design procedures and application tool that have been used in this project. The project further planning and the method used are described whether in experimental, analytical or computer simulation. The experimental method is shown in arrangement step and same with the analytical method. The flow of the project was presented by the flow chart to get general overview project progress. Chapter 4 presents the result for the system and discussion of the overall result. The output or the results of the parameters that are used to investigate are shown in this chapter. In the final chapter, the research work or the project result is summarized and the potential future works are given.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

This chapter is presented about theory of energy which is how energy is generated and how to capture the energy, theory of the energy harvesting, the generator of energy, design and modeling of energy harvester and state of art of the energy harvester for historical research. The relationship between vibration and energy and the application of energy harvested using is included.

2.2 THEORY OF ENERGY

2.2.1 Source of Energy

An energy source is a system which makes energy in a certain way, for instance a hydro-electric station. A hydro-electric station uses the current of the river for the making of electricity. Nowadays, all the apparatus need energy. Instead of human itself, the other things such as vehicles, building also needs energy. There are many sources of energy. Energy comes from different forms which are heat (thermal), light (radiant), motion (kinetic) and more else. Fossil energy is generated throughout the burning of fossil remains. The big advantage of fossil energy is to generate the energy from the raw materials is easy and cheap. But the disadvantage is that during the process of combustion a lot of toxic materials come into the air which causes extra pollution of the atmosphere and these materials also increase the effect of global warming.

Alternative energy can be defines as a form of an energy without waste matters. It is also a form where the source had delivers the energy, is endless. Some alternative energy-sources are sun, water and wind energy. The advantage of alternative energy is where the energy source is endless and doesn't give any pollution. In addition, there are not many alternative energy forms, because for instance the techniques which transform sun-beams into electric energy are very expensive.

Energy source, for instance, radiofrequency (RF) may be used to indicate the presence of electromagnetic field. Electromagnetic radiation consists of waves of electric and magnetic energy moving together (that is, radiating) through space at the speed of light. Taken together, all forms of electromagnetic energy are referred to as the electromagnetic spectrum. Radio waves and microwaves emitted by transmitting antennas are one form of electromagnetic energy. RF enjoys many advantages over other energy sources. It does not depend on the time of day, does not require exposure to heat or wind, and can be moved freely within the range of the transmission source. It can be completely controlled, meaning that the energy can be transmitted continuously, on a scheduled basis or on demand.

Geothermal energy was created by the heat of the earth. It generates the reliable power and emits almost no greenhouse gases. Resources of geothermal energy range from the shallow ground to hot water and hot rock found a few miles beneath the Earth's surface. In addition to providing clean, renewable power, geothermal energy has significant environmental advantages which contain few chemical pollutants and little waste. It is a reliable source of power that can reduce the need for imported fuels for power generation. Geothermal resources are categorized in several layers of accessibility and feasibility, from broadest criteria to criteria that includes technical and economic considerations (Beeby et al., 2006). The electricity produced by geothermal power operations is send to local power grids, providing clean energy to fuel the growth of some of the most rapidly expanding economies in the world.

A wide-spread use of renewable energy sources in distribution networks and a high penetration level will be seen in the near future many places. For example, Denmark has a high penetration (> 20%) of wind energy in major areas of the country and today 18% of the whole electrical energy consumption is covered by wind energy. The wind turbine technology is one of the most emerging renewable technologies (Sari et al., 2006). The technology used in wind turbines was in the beginning based on a squirrel-cage induction generator connected directly to the grid.

In contrast, some of the energy such as fuels causes pollution which can affect human health and human life. The renewable energy was created in order to supply the energy without giving any problems to the users. Renewable energy is an energy source that can be easily replenished and it can use as secondary energy sources. Renewable energy includes solar energy, wind energy, geothermal energy, biomass energy, and also from hydropower energy.

Figure 2.1 shows what energy sources that is using by United States in 2010. Nonrenewable energy sources such as coal, petroleum, natural gas and nuclear electric power was accounted for 92% of all energy used. Renewable energy includes solar, geothermal, wind and others offer 8% and biomass was accounted as the largest renewable source for over half of all renewable energy and 4% of total energy consumption. Table 2.1 shows some of the harvesting methods with their power generation capability (Arnold, 2007).

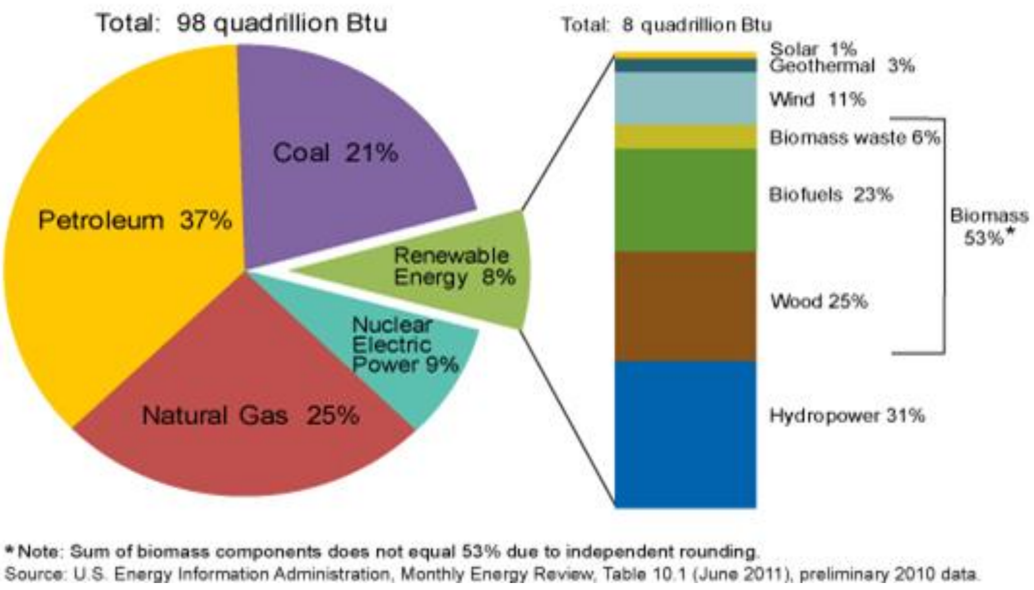

Figure 2.1: U.S Consumption by Energy in 2010.

Table 2.1: Energy harvesting source

Harvesting method	**Power Density (μW/cm^3)**
Solar Cell	15000
Piezoelectric	330
Vibration	116
Thermoelectric	40

Source: Friswell et al., 2010

The general properties to be considered to characterize a portable energy supplier are described by Friswell et al. (2010). The list includes electrical properties such as power density, maximum voltage and current; physical properties such as the size, shape and weight; environmental properties such as water resistance and operating temperature range as well as operational and maintenance properties. Sufficient care should be taken while using the energy harvesters in the embedded systems to improve the performance and lifetime of the system.

2.2.2 Source of Vibrations

Vibration is the mechanical oscillations of an object about an equilibrium point. Most of the vibrations was measured from its sources, and also can classify as 'low level' vibrations. Low-level vibrations were targeted, rather than more energetic vibrations that might be found on large industrial equipment. Figure below shows the frequency spectrum for two vibration sources: a small microwave oven and large office windows next to a busy street.

Figure 2.2 shows the different in displacement vs. frequency and acceleration vs. magnitude between microwave casing and windows next to a busy street. Two important characteristics that are common to virtually all of the sources measured are: (a) there is a large peak in magnitude somewhere below 200 Hz, which can be referred to as the fundamental mode, and (b) the acceleration spectrum is relatively flat with frequency, which means that the displacement spectrum falls of as $1/v^2$ (Roundy et al., 2003).

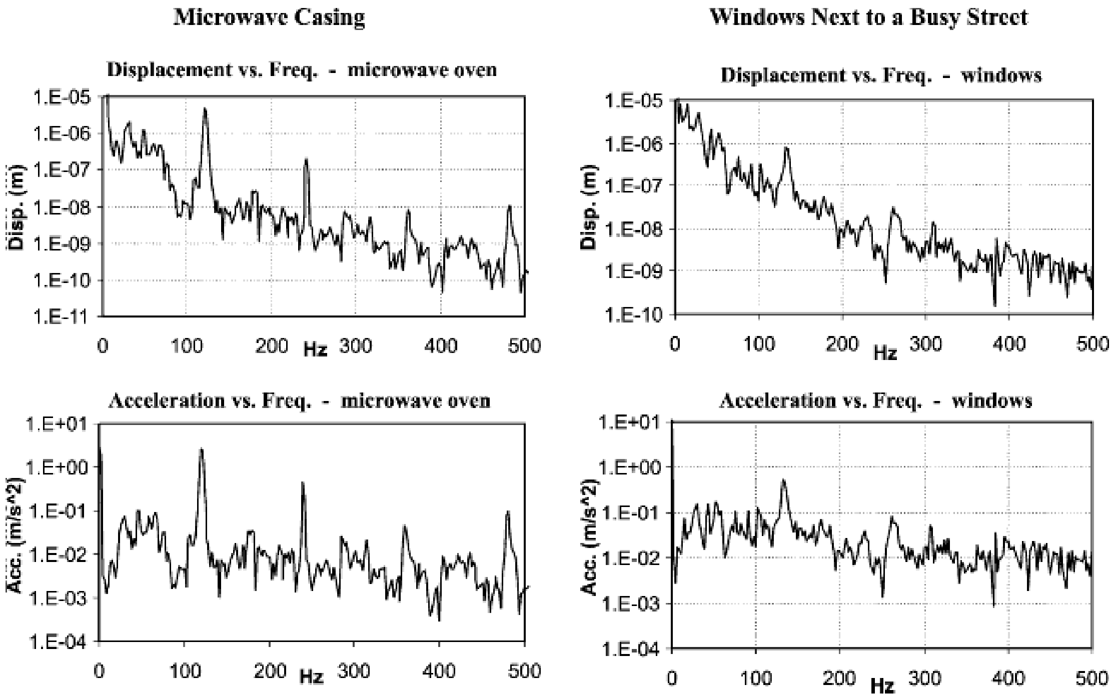

Figure 2.2: Vibration spectra for a microwave oven and office windows next to a busy street.

Source: Roundy et al. (2003)

There are many vibrations that was discussed by the author and measured in terms of the frequency and acceleration magnitude of the fundamental vibration mode. Three reasons had discussed about the potential vibration sources to design the vibration converters. The first reason is the devices should be designed to resonate at the fundamental vibration frequency, which is quite low and may be difficult to obtain within 0.5 cm^3. Second, the higher frequency vibration modes are lower in acceleration magnitude than the low frequency fundamental mode. The potential output power is proportional to A^2/ω where ω is the frequency of the fundamental vibration mode (natural frequency of the converter). Third, in order to estimate the potential power generation, the magnitude and frequency of driving vibrations must be known.

2.3 THEORY OF ENERGY HARVESTING

Energy harvesting has been around for centuries in form of windmills and solar power system. It is the process by which energy is derived from external sources. Vibration energy harvesting is an attractive technique for low power devices application. Vibration energy harvesting is the technique that can be used to harvest the energy from vibrations and vibrating structures, a general requirement independent of the energy transfer mechanism is that the vibration energy harvesting device operates in resonance at the excitation frequency (Vinod et al., 2007).

Additionally, kinetic energy is typically present in the form of vibrations, random displacements or forces and is typically converted into electrical energy using electromagnetic, piezoelectric or electrostatic mechanisms. Suitable vibrations can be found in numerous applications including common household goods such as fridges, washing machines, microwave ovens, industrial plant equipment, automobiles and airplanes and structures such as buildings and bridges. Human-based applications are characterized by low frequency high amplitude displacements (Roundly et al., 2003).

The principle behind the vibration energy harvesting is a resonance operation of an oscillating mass and consequent an electro-mechanical conversion of kinetic energy into electrical energy (Priya et al., 2009).The general principle of the kinetic energy harvesting is to use the displacement of moving part or the mechanical deformation of some structure to produce an electric energy (Tudor, 2008). Kinetic energy is present in the form of vibrations, random displacements or forces and is typically converted into electrical energy using a transduction mechanism such as electromagnetic, piezoelectric or electrostatic (Vinod et al., 2007; Chala et al., 2008).

2.3.1 Faraday's Law

From Oersted's discovery, Micheal Faraday thought that if the current in a wire can produce a magnetic field, a magnetic field can produce a current in a wire. Together with Joseph Henry, they are observed that current was only induced in a circuit if the magnetic flux linking the circuit changed with time. The current induced in the loop establishes a potential difference across the terminal known as the electromotive force. This electromotive force, V_{emf}, is related to the rate of change of flux linking by circuit by Faraday's Law:

$$V_{emf} = -\frac{\delta\lambda}{\delta t} \tag{2.1}$$

The negative sign in the equation is a consequence of Lenz's Law. A negative V_{emf} is the induced current is going in the other direction. For a single loop, Faraday Law can be written as.

$$V_{emf} = -\frac{\delta\Phi}{\delta t} \tag{2.2}$$

where V is the generated voltage or induced emf and Φ is the flux linkage. In the most generator implementations, the circuit consists of a coil of wire of multiple turns and the magnetic field is created by permanent magnets. In this case, the voltage induced in an N turn coil is given by:

$$V = -N\frac{d\Phi}{dt} \tag{2.3}$$

Generating emf requires a time-varying magnetic flux linking the circuit. This occurs if the magnetic field changes with time or if the surface containing the flux changes with time. The emf is measured around the closed path enclosing the area through which the flux is passing, it can be written,

$$V_{emf} = \oint E.dL \tag{2.4}$$