THESIS REPORT

TOPIC: DEVELOPMENT OF AN ELECTROMAGNETIC VIBRATIONAL ENERGY HARVESTING SYSTEM

THESIS SUPERVISOR:DR. MOHAMMED BELALHOSSAINBHUIAN

GROUP MEMBERS:

RAFQUATNIZAM – 09221139

MD. LABIBEHSAN – 09221052

AURIN KHAN - 09221164

RAIYAN KHAN – 09221231

DATE OF SUBMISSION:30/04/14

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DECLARATION

We hereby declare that the thesis titled "DEVELOPMENT OF AN ELECTROMAGNETIC VIBRATIONAL ENERGY HARVESTING SYSTEM" is submitted to the Department of Electrical and Electronics Engineering of BRAC University in partial fulfillment of the Bachelor of Science in Electrical and Electronics Engineering. This is our original work and was not submitted elsewhere for the award of any other degree or any other publication.

Date: 30th April, 2014

Supervisor: Dr. Mohammed BelalHossainBhuian

RafquatNizam – 09221139

Md. LabibEhsan – 09221052

Aurin Khan – 09221164

Raiyan Khan – 09221231

ACKNOWLEDGEMENTS

We would like to start by acknowledginga few people whose hard work and constant support made this thesiswork possible. Firstly, we would like to express our deepest gratitude and sincere thanks to our thesis supervisor, Dr. Mohammed BelalHossainBhuian who constantly encouraged us to use and work with the software COMSOL Multiphysics. He enabled us to develop the core concepts and basics for understanding this topic. Without his supervision, effective support and positive feedback we would not have been able to complete the thesis successfully.

We also express thankfulness toMd. MonirHasan, who helped us in the developing stages of this thesis with the hardware work.

We would also like to thank Allah, for helping us in this work, and giving us the ability to do the hard-work and determination that was required for this thesis.

ABSTRACT

The project proposes to develop a power generation system that can harness the mechanical vibration from ambient electromagnetic energy. The system employs an electromagnetic transducer which is able to convert the vibration energy into electrical energy. The system consists of copper coils, four magnets, two fixed and two movable. Fixed magnets are placed at two open ends of a cylinder and movable magnets are arranged in a way such that they remain floated inside the cylinder due to the interaction of the fixed magnets.

CHAPTER 1

INTRODUCTION

1.1 MOTIVATION

The history of energy harvesting dates back to the windmill and the waterwheel, like operating mills, which were used to grind flour etc. People have searched for ways to store the energy from heat and vibrations for many decades. One driving force behind the search for new energy harvesting devices is to give power to devices without batteries, to give power to wireless devices and sensor networks. Harvesting energy via wind, heat or vibrations is the only ‘green’ form of energy available to humankind at the moment. This will also address the issues of climatic change through Global Warming.

Countries like Sweden, Germany, Belgium, Austria and Spain have all opted for Nuclear power phase out [1]. It is the discontinuation of usage of nuclear power to produce energy. The three catastrophic nuclear accidents have influenced the discontinuation of nuclear power:

In 1979, the three mile island partial nuclear meltdownin the United States, the 1986 Chernobyl disaster in the USSR, and the 2011 Fukushima nuclear disaster in Japan.Following the latest disaster in 2011, Germany have unanimously voted to shut down 8 of its 17 nuclear power plants and have pledged to shut down the rest by the year 2022.

In a country like Bangladesh, electricity is the main source of power for most of the country’s economic activities. The government struggle to provide enough amount of energy for daily use throughout the country. Harvesting energy from vibrations will provide renewable energy, in small amounts of electricity, which can be used for charging electronic devices instead of batteries. Helping mankind, contributing to the society and improving the standard of living – these were our main motivation for this project.

1.2 WHAT IS ENERGY

In physics, Energy is defined as a property of objects, transferrable among them via someform of interaction and can be converted and can never be created or destroyed. The SI unit of energy is called the Joule. 1 joule of energy is required to do mechanical work of 1 meter against a force of 1 Newton [2].

There are many different types of energy. Work and Heat are two types of categories of mechanisms that can transfer energy. Some energy is always lost as Heat energy while being transferred. The remaining energy that can go into work is known as Available Energy. Systems such as machines and humans beings require available energy to do work. Mechanical energy or any other form of energy can be transferred in the other direction as Heat Energy without any limitations.

Other common energy forms that obey the conservation of energy, while being converted are Kinetic Energy of a moving object, Electromagnetic radiation, and Potential Energy stored in objects in a magnetic field, Radiant Energy carried by light and Elastic Energy stored by stretching or deformation of objects.

Type of Energy	**Description**
Kinetic	that of the motion of a body
Potential	A category comprising many forms in this list
Mechanical	the sum of (usually macroscopic) kinetic and potential energies
Mechanical wave	a form of mechanical energy propagated by a material's oscillations
Chemical	that contained in molecules
Electric	that from electric fields
Magnetic	that from magnetic fields

Radiant	that of electromagnetic radiation including light
Ionization	that of bindingnucleons to form the atomic nucleus
Elastic	that of deformation of a material (or its container) exhibiting a restorative force
Gravitational	that from gravitational fields

TABLE1: FORMS OF ENERGY

Natural Energy:

Wind, water flow, ocean waves, and solar energy can provide limitless energy availability from the environment.

Mechanical Energy:

Vibrations from machines, mechanical stress, strain from high-pressure motors, manufacturing machines, and waste rotations can be captured and used as ambient mechanical energy sources.

Thermal Energy:

Waste heat energy variations from furnaces, heaters, and friction sources.

Light Energy:

This source can be divided into two categories of energy: indoor room light and outdoor sunlight energy.Light energy can be captured via photo-sensors, photo diodes, and solar photovoltaic (PV) panels.

Electromagnetic Energy:

Inductors, coils, and transformers can be considered as ambient energy sources, depending on how much energy is needed for the application.

1.3 ENERGY HARVESTING

Energy harvesting (also known as power harvesting) is the process by which energy is derived from external sources (e.g. solar power, thermal energy, wind energy, salinity gradients, and kinetic energy), captured, and stored for small, wireless autonomous devices, like those used in wearable electronics and wireless sensor networks [3].

Energy harvesters provide a very small amount of power for low-energy electronics. While the input fuel to some large-scale generation costs money (oil, coal, etc.), the energy source for energy harvesters is present as ambient background and is free. For example, temperature gradients exist from the operation of a combustion engine and in urban areas; there is a large amount of electromagnetic energy in the environment because of radio and television broadcasting.

It is called ambient energy harvesting, ambient here means natural or something which is in unlimited number. So obtaining usable energy from natural or human-made sources is known as energy harvesting.

The concept of ambient energy scavenging has existed for decades. In recent years, mounting interest in alternative energy has accelerated the pace of research. Here are a few examples of current research[4]:

- The U.S. Defense Advanced Research Projects Agency (DARPA) is developing an integrated energy scavenging and storage system for use with portable electronics, weaponry and vehicles, among other things. The integration of renewable energy with storage could enable batteries that would constantly remain charged.
- Technology from a company called Voltree harvests the metabolic energy of trees and converts it to electricity that power wireless sensor networks used to detect and control forest fires.
- Piezoelectric (PE) generators, created with crystals that give off a charge under pressure, are being used or tested under roadways, walkways and in sports stadiums to obtain usable energy from traffic and activity above them. For example, an Israeli company called Innowattech placed PE generators beneath 33 feet of highway. The company estimates that such devices under a half-mile of a busy highway could generate enough electricity to power 250 homes.

1.4 DIFFERENT FORMS OF ENERGY HARVESTING

Energy harvesting can be obtained from different energy sources, such as mechanical vibrations, electromagnetic sources, light, acoustic, air flow, heat, and temperature variations. Energy harvesting, in general, is the conversion of ambient energy into usable electrical energy. When compared with energy stored in common storage elements, such as batteries, capacitors, and the like, the environment represents a relatively infinite source of available energy.

Systems continue to become smaller, yetless energy is available on board, leading to ashort run-time for a device or battery life.Researchers continue to build high-energy density batteries, but the amount of energy availablein the batteries is not only finite but also low,which limits the life time of the systems.Extended life of the electronic devices is veryimportant; it also has more advantages in systems with limited accessibility, such as thoseused in monitoring a machine or an instrumentin a manufacturing plant used to organize achemical process in a hazardous environment.The critical long-term solution should thereforebe independent of the limited energy availableduring the functioning or operating of such devices. **Table 2** compares the estimated powerand challenges of various ambient energysources [5].

Energy Source	**Power Density and Performance**
Acoustic Noise	0.003 µW/cm3 @ 75Db 0.96 µW/cm3 @ 100Db
Temperature Variation	10 µW/cm3
Ambient Radio Frequency	1 µW/cm2
Ambient Light	100 mW/cm2 (direct sun) 100 _W/cm2 (illuminated office)
Thermoelectric	60 _W/cm2
Vibration (micro generator)	4 _W/cm3 (human motion—Hz) 800 _W/cm3 (machines—kHz)

Vibration (piezoelectric)	200 µW/cm3
Airflow	1 µW/cm2
Push buttons	50 _J/N
Shoe Inserts	330 µW/cm2
Hand generators	30 W/kg
Heel strike	7 W/cm2

TABLE 2: COMPARISON OF POWER DENSITY OF ENERGY HARVESTING METHODS

1.4.1 AMBIENT ENERGY SOURCES

Ambient energy harvesting, also known as energy scavenging or power harvesting, is the process where energy is obtained and converted from the environment and stored for use in electronic applications. Usually this term is applied to energy harvesting for low power and small autonomous devices, such as wireless sensor networks, and portable electronic equipments. A variety of sources are available for energy scavenging, including solar power, ocean waves, piezoelectricity, thermoelectricity, and physical motions (active/passive human power). For example, some systems convert random motions, including ocean waves, into useful electrical energy that can be used by oceanographic monitoring wireless sensor nodes for autonomous surveillance. This just shows that no single power source is sufficient for all applications, selection of power sources must be considered according to the application.

Additionally, chemical and biologicalsources and radiation can be considered ambientenergy sources. **Figure 1** shows a block diagramof general ambient energy-harvesting systems.The first row shows the energy-harvestingsources. Actual implementation and tools are employed to harvest the energy from the source are illustrated in the second row. The third row shows the energy-harvesting techniques from each source.

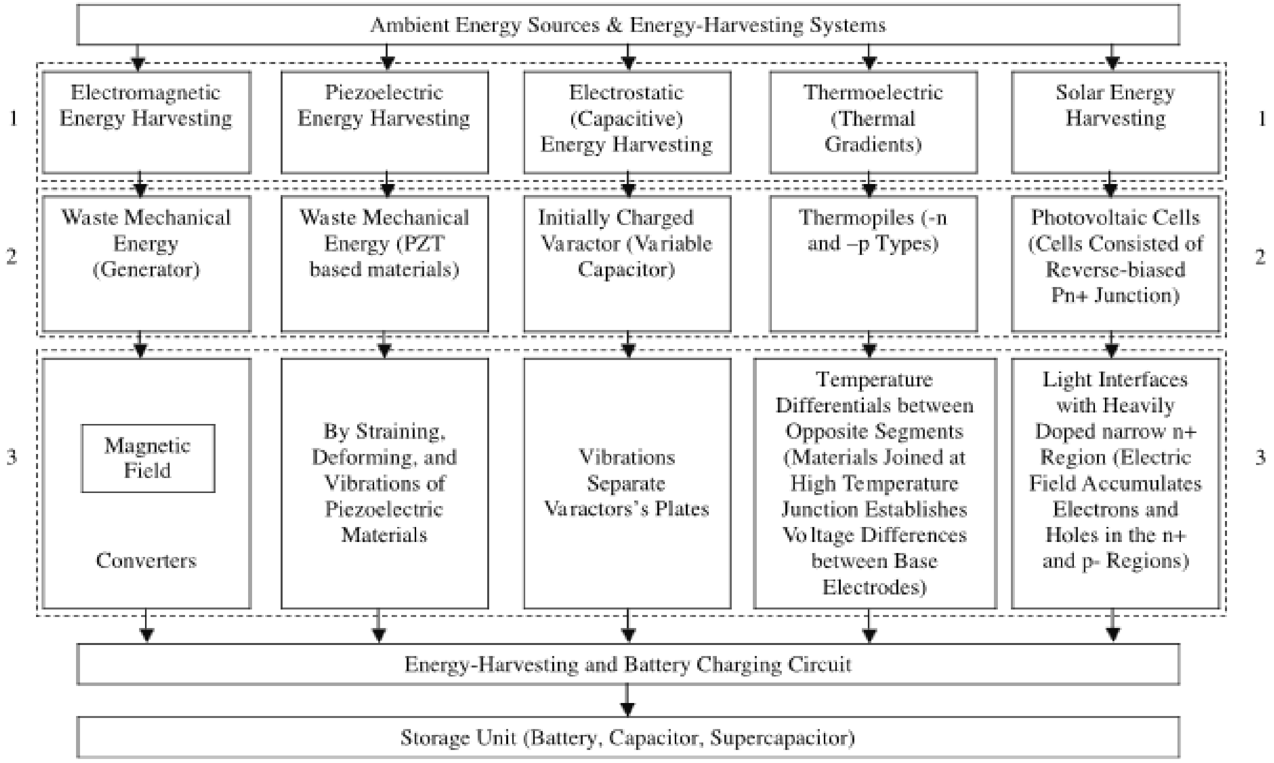


Figure 1. Ambient Energy Systems

1.4.2 MECHANICAL ENERGY HARVESTING

An example of electric power generation using rotational movement is the self-powered, battery-less, cordless wheel computer mouse. The system was designeduniquely to capture rotational movements by thehelp of the mouse ball to generate and harvestelectric power. The electric generator is poweredthrough exploiting rolling energy by draggingthe mouse. The energy-harvesting system was intended to power the electronic system of a mouse device, such as the ultra low power RFtransmitter and microcontroller. The experimental results of the study showed that the mouseonly needed 2.2mW energy to operate. The totalenergy captured using an energy-harvesting system was bigger than 3mW, which was enoughfor the wireless mouse operations in a transmitrange of one meter [6].

Another example of mechanical energy harvesting is an electrets-based electrostatic micro generator. In this system, a micro machined electrostatic converterconsisted of a vibration sensitive variable capacitor polarized by an electret. A general multidomain model was built and analyzed in the same study, and it showed that power generationcapabilities up to 50μW for a $0.1cm^2$surface areawere attainable [7].

1.4.3 MECHANICAL VIBRATIONS

Indoor operating environments may have reliable and constant mechanical vibration sources for ambient energy scavenging. For example, indoor machinery sensors may have plentiful mechanical vibration energy that can be monitored and used reliably. Vibration energy harvesting devices can be either electromechanical or piezoelectric. Electromechanical harvesting devices, however, are more commonly researched and used. Energy withdrawal from vibrations could be based on the movementof a spring-mounted mass relative to its supportframe. Mechanical acceleration is produced byvibrations that, in turn, cause the mass component to move and oscillate. This relative dislocation causes opposing frictional and dampingforces to be applied against the mass, therebyreducing and eventually extinguishing the oscillations. The damping force energy can be converted into electrical energy via an electric field(electrostatic), magnetic field (electromagnetic),or strain on a piezoelectric material. These energy conversion schemes can be extended andexplained under the three listed subjects becausethe nature of the conversion types differs even ifthe energy source is vibration. In the sectionbelow, the main differences of the three sourcesare discussed [8].

Electromagnetic

This technique uses a magnetic field to convert mechanical energy to electrical energy [9]. A coilattached to the oscillating mass is made to passthrough a magnetic field, which is establishedby a stationary magnet, to produce electric energy. The coil travels through a varying amount ofmagnetic flux, inducing a voltage according toFaraday's law. The induced voltage is inherentlysmall and therefore must be increased to becomea viable source of energy [10]. Techniques to increase the induced voltage include using a transformer, increasing thenumber of turns of the coil, or increasing thepermanent magnetic field [11]. However, each of these parametersis limited by the size constraints of themicrochip as well as its material properties.

Piezoelectric

This method alters mechanical energy intoelectrical energy by straining a piezoelectricmaterial [12]. Strainor deformation of a piezoelectric material causescharge separation across the device, producingan electric field and consequently a voltage dropproportional to the stress applied. The oscillatingsystem is typically a cantilever beam structurewith a mass at the unattached end of the lever,which provides higher strain for a given inputforce [8]. The voltageproduced varies with time and strain, effectivelyproducing an irregular AC signal on the average.Piezoelectric energy conversion produces relatively higher voltage and power density levels than the electromagnetic system. Moreover,piezoelectricity has the ability of some elements,such as crystals and some types of ceramics, togenerate an electric potential from a mechanicalstress [13]. Thisprocess takes the form of separation of electriccharge within a crystal lattice. If the piezoelectricmaterial is not short circuited, the appliedmechanical stress induces a voltage across thematerial. There are many applications based onpiezoelectric materials, one of which is the electric cigarette lighter. In this system, pushing thebutton causes a spring-loaded hammer to hit apiezoelectric crystal, and the voltage that is produced injects the gas slowly as the current jumpsacross a small spark gap. Following the sameidea, portable sparkers used to light gas grills,gas stoves, and a variety of gas burners havebuilt-in piezoelectric based ignition systems.

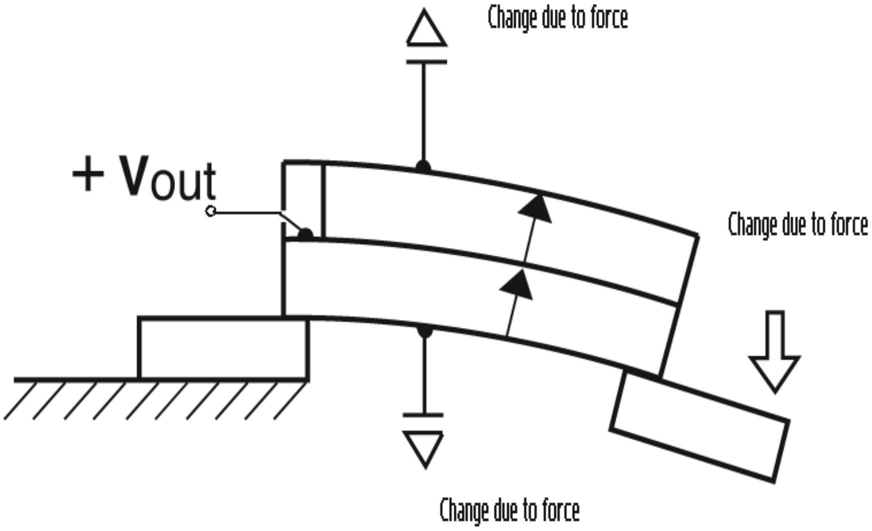


FIGURE2: PIEZOELECTRIC EFFECT

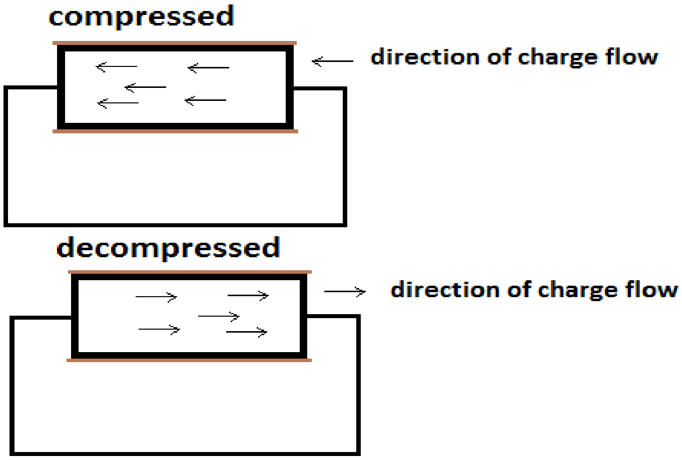
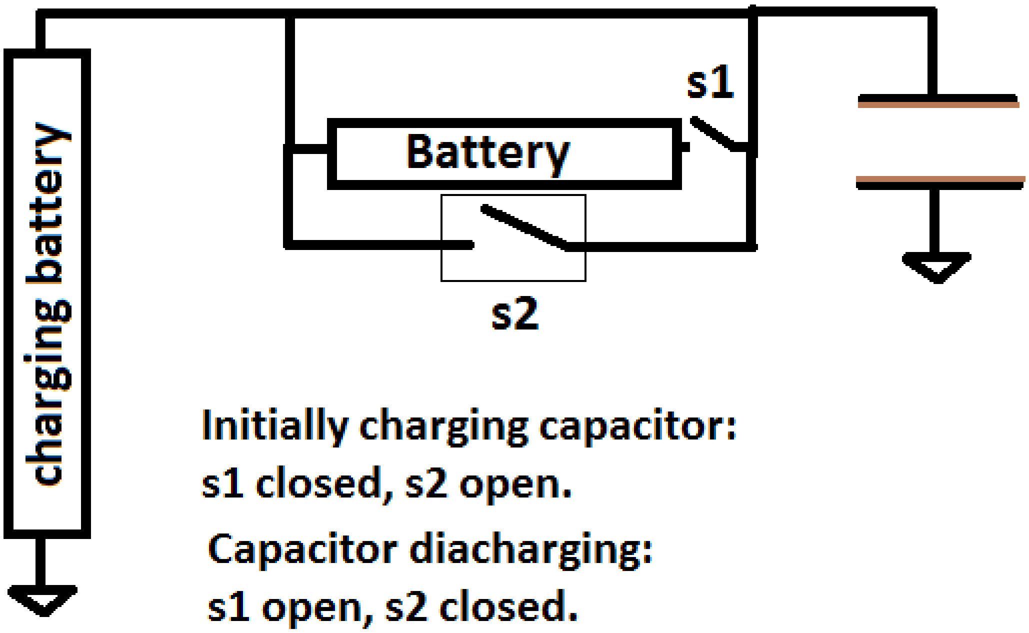


FIGURE 3: THE SCHEMATIC DIAGRAM OF A PIEZOELECTRIC ENERGY HARVESTER

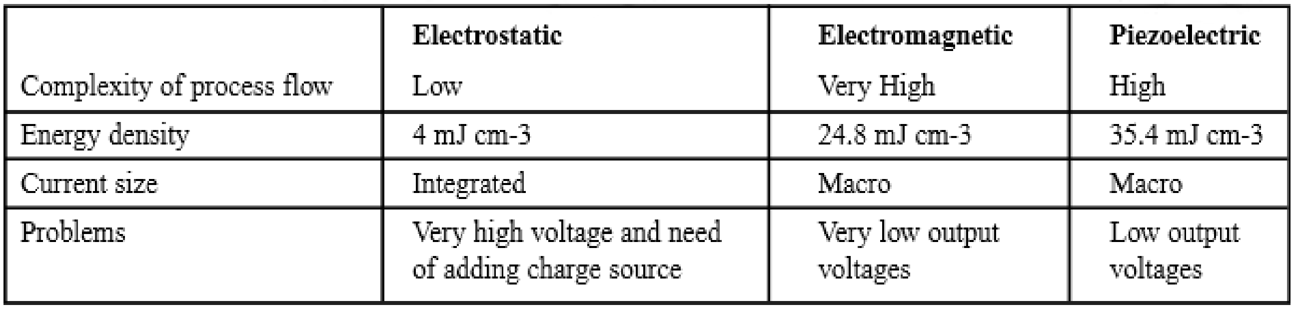
Electrostatic (Capacitive)

This method depends on the variable capacitance of vibration-dependent varactors [14]. A varactor, orvariable capacitor, which is initially charged,will separate its plates by vibrations; in this way,mechanical energy is transformed into electricalenergy. Constant voltage or constant currentachieves the conversion through two differentmechanisms. For example, the voltage across avariable capacitor is kept steady as its capacitance alters after a primary charge. As a result,the plates split and the capacitance is reduced,until the charge is driven out of the device. Thedriven energy then can be stored in an energypool or used to charge a battery, generating theneeded voltage source. The most striking featureof this method is its IC-compatible nature, giventhat MEMS (Micro-electromechanical system)variable capacitors are fabricated through relatively well-known silicon micro-machining techniques. This scheme produces higher and morepractical output voltage levels than the electromagnetic method, with moderate power density. In a study conducted to test the feasibilityand reliability of the different ambient vibrationenergy sources by [15], three different vibration energy sources (electrostatic,electromagnetic, and piezoelectric) were investigated and compared according to their complexity, energy density, size, and encountered problems. The study is summarized in **Table 3.**



Initially charging capacitor:
s1 closed, s2 open.
Capacitor diacharging:
s1 open, s2 closed.

FIGURE 4: DIAGRAM OF AN ELECTROSTATIC ENERGY HARVESTER



	Electrostatic	**Electromagnetic**	**Piezoelectric**
Complexity of process flow	Low	Very High	High
Energy density	4 mJ cm-3	24.8 mJ cm-3	35.4 mJ cm-3
Current size	Integrated	Macro	Macro
Problems	Very high voltage and need of adding charge source	Very low output voltages	Low output voltages

TABLE 3A: COMPARISON OF VIBRATION- ENERGY HARVESTING TECHNIQUES

Types	**Advantages**	**Disadvantages**
Piezoelectric	1) no external voltage source 2) high voltages of 2~10V 3) compact configuration 4) compatible with MEMS 5) high coupling in single crystal	1) depolarization and aging problems 2) brittleness in PZT 3) poor coupling in piezo thin film 4) charge leakage 5) high output impedance
Electrostatic	1) No need of smart material 2) Compatible with MEMS 3) Voltage of 2~10V	1) External voltage or charge source 2) Mechanical constraints needed 3) Capacitive
Magnetostatic	1) ultra high coupling coefficient>0.9 2) no depolarization problem 3) high flexibility 4) suited to high frequency vibration	1) non-linear effect 2) pick-up coil 3) may need bias magnets 4) difficult to integrate with MEMS
Electromagnetic	1) No need of smart material 2) No external voltage source	1) Bulky size 2) Difficult to integrate with MEMS 3) Max voltage of 0.1V

TABLE 3B: THE ADVANTAGES AND DISADVANTAGES OF DIFFERENT TYPES OF ENERGY HARVESTING

CHAPTER 2

ELECTROMAGNETIC VIBRATIONAL ENERGY HARVESTING SYSTEM

2.1 MECHANICAL VIBRATIONS

The flux cutting phenomenon was first discovered by Michael Faraday. He discovered the law of electromagnetism predicting how a magnetic field will interact with an electric circuit to produce an electromotive force (EMF)—a phenomenon called electromagnetic induction. It is the fundamental operating principle of transformers, inductors, and many types of electricalmotors, generators and solenoids. If an electric conductor is moved through perpendicular to a magnetic field soas to cut the flux lines, a potential difference is induced between the ends of the conductor.

The principle of Faraday's law is applicable whenever time variation of voltage is created from the variation of flux linkage of a stationary coil or the magnetic flux is stationary and the coil moves through it or combinations of both the situations.

Suppose that the change in flux occurs in the small change in timeΔt, then the induced emf can be defined by:

$$V = \frac{\Delta\varphi}{\Delta t} = \frac{d\varphi}{dt}$$

Where V = the induced EMF (electro-motive force)

$\varphi =$ the flux linkage.

If we consider the case where a coil moves in the *x* direction through a magnetic field or flux density *B* where B field varies along the coil movement, then the voltage can be expressed as:

$$V = \frac{d\varphi}{dt}\frac{dx}{dt}$$

The flux linkage depends on the magnet and coil parameters and the air gap flux density between the magnet and coil. The shape of the air gap flux density could vary with the magnetic structure of the generator. The situation for vibrational generators can beapproximated by a coil moving in a single direction through a magnetic field which variesin the direction of movement, as depicted in **Figure 5**. The flux linkage through a single turnconductor which encircles a surface area (*dA=dx.dy*), and which is positioned in a *B* field which varies with *x* but not *y*, can be expressed as:

$$\varphi = \iint B.dA = \iint B.dxdy = \Delta y \int_{0}^{\Delta x} B(x)dx$$

and the flux linkage gradient is therefore:

$$d\varphi/dx = \Delta y[B(\Delta x) - B(0)\,]$$

where *B(0)* and *B(Δx)* are the flux density at the *x=0* position and the *x=Δx* position. The expression for the generated voltage as the product of the flux linkage gradient and the velocity is important for understanding the operation of the vibrational generator.

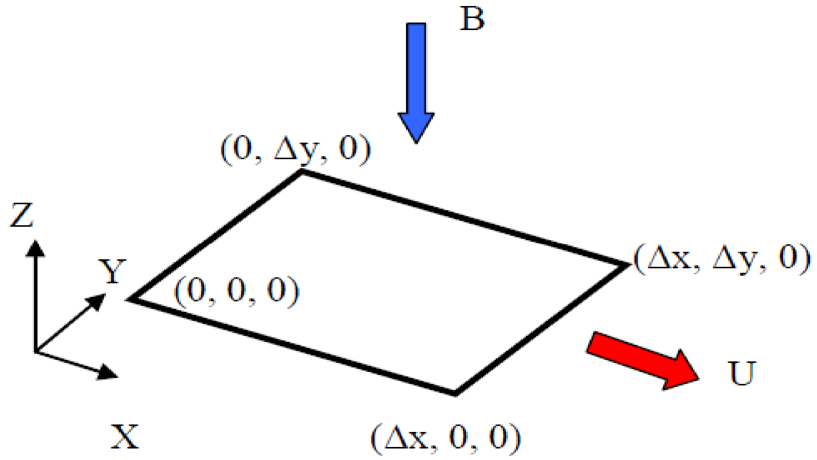


FIGURE 5: MOVEMENT OF A CONDUCTOR IN A POSITION VARYING MAGNETIC FIELD

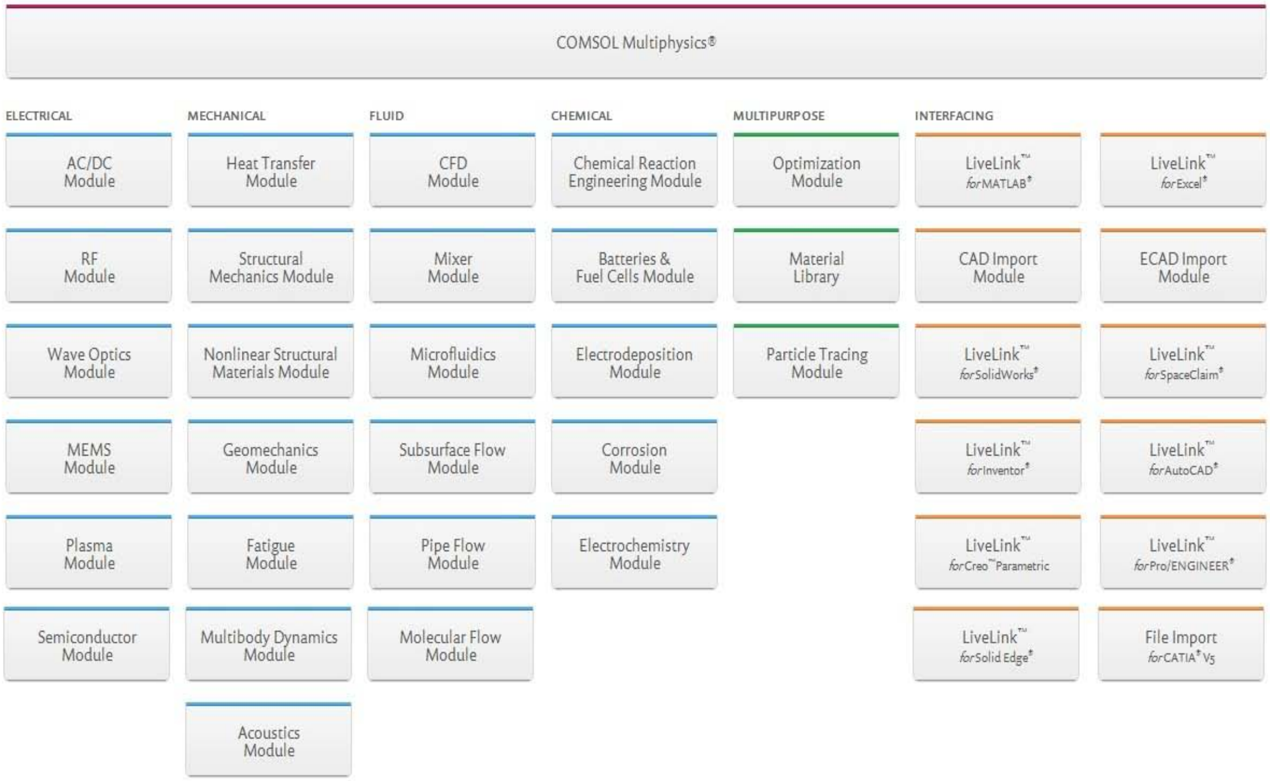
2.2 COMSOL

COMSOL MULTIPHYSICS is cross-platform Finite Element Method (FEM) software which uses numerical techniques to find approximate solutions to boundary value problems for differential equations. This software is popularly used for various physics and engineering applications. The main purpose of multiphysics is to make simulations that involve multiple physical models, basically each application mode contains multiphysics which have its own laws, equations, restrictions etc. Here in this case like in our project combining magnetostatics and finite elements. This software can also be used to solve partial differential equations.

The way it works is the user has to put various inputs. Starting with selecting the desire multiphysics, it can be both single and different multiple multiphysics. Then it involves setting desired parameters, drawing structures, then setting the subdomain and boundary conditions by giving appropriate values or selecting laws for the project. After every condition has been fulfilled by the users, now the person has to initialize the mesh according to the desire requirement and compute the results.

COMSOL Multiphysics can also be used for further programming, preprocessing and post-processing possibilities by linking with other software like MATLAB, Microsoft EXCEL, and PSpice for further works and analysis of data.

2.2.1 TYPES OF COMSOL MODULES



COMSOL Multiphysics®

ELECTRICAL	MECHANICAL	FLUID	CHEMICAL	MULTIPURPOSE	INTERFACING	
AC/DC Module	Heat Transfer Module	CFD Module	Chemical Reaction Engineering Module	Optimization Module	LiveLink™ for MATLAB®	LiveLink™ for Excel®
RF Module	Structural Mechanics Module	Mixer Module	Batteries & Fuel Cells Module	Material Library	CAD Import Module	ECAD Import Module
Wave Optics Module	Nonlinear Structural Materials Module	Microfluidics Module	Electrodeposition Module	Particle Tracing Module	LiveLink™ for SolidWorks®	LiveLink™ for SpaceClaim®
MEMS Module	Geomechanics Module	Subsurface Flow Module	Corrosion Module		LiveLink™ for Inventor®	LiveLink™ for AutoCAD®
Plasma Module	Fatigue Module	Pipe Flow Module	Electrochemistry Module		LiveLink™ for Creo™ Parametric	LiveLink™ for Pro/ENGINEER®
Semiconductor Module	Multibody Dynamics Module	Molecular Flow Module			LiveLink™ for Solid Edge®	File Import for CATIA® V5
	Acoustics Module					

<u>FIGURE 6</u>: TYPES OF COMSOL MODULES

2.2.2 COMSOL Reports

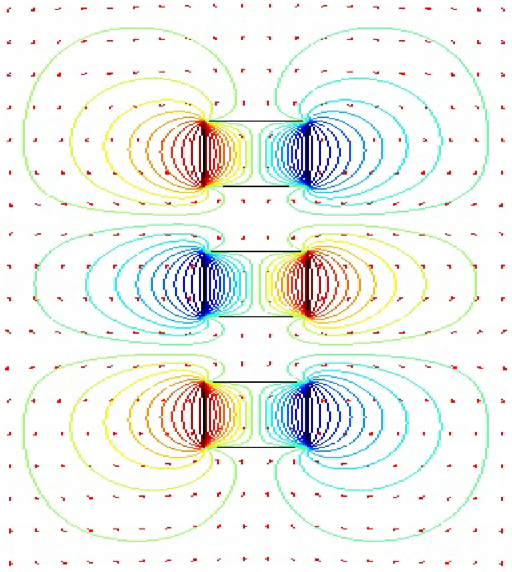


FIGURE 7A: DEFAULT POSITION

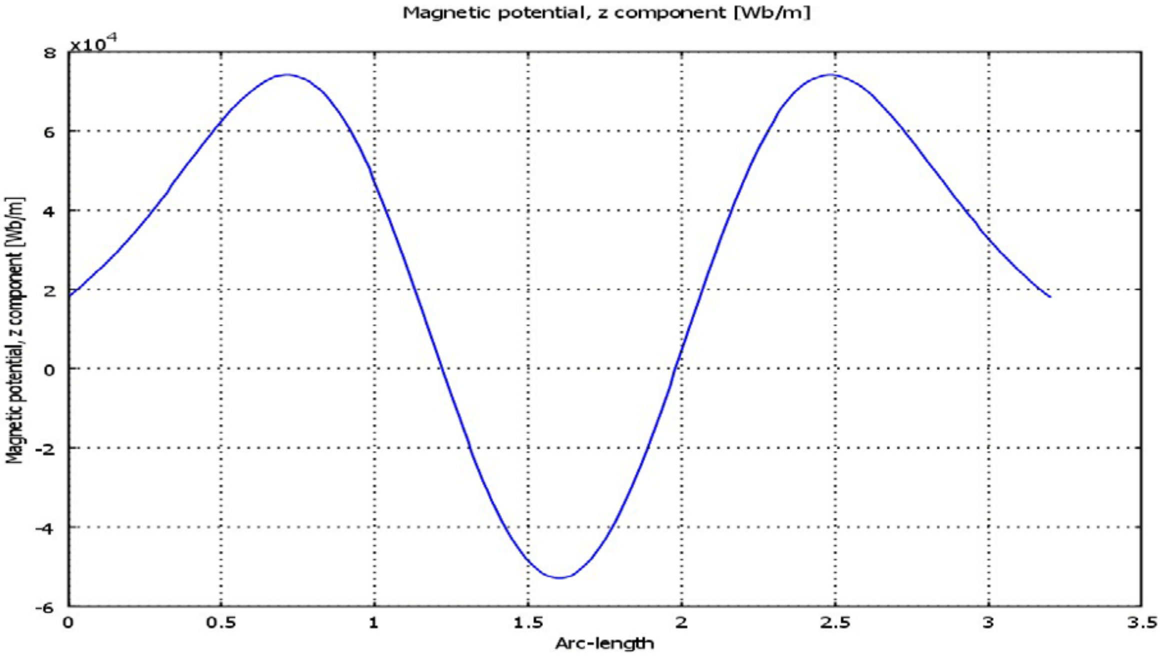


FIGURE 7B: GRAPH PLOT OF DEFAULT POSITION

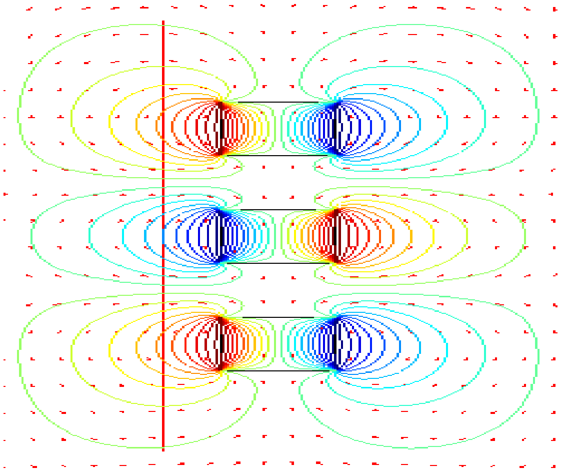


FIGURE 8A: LEFT CLOSE

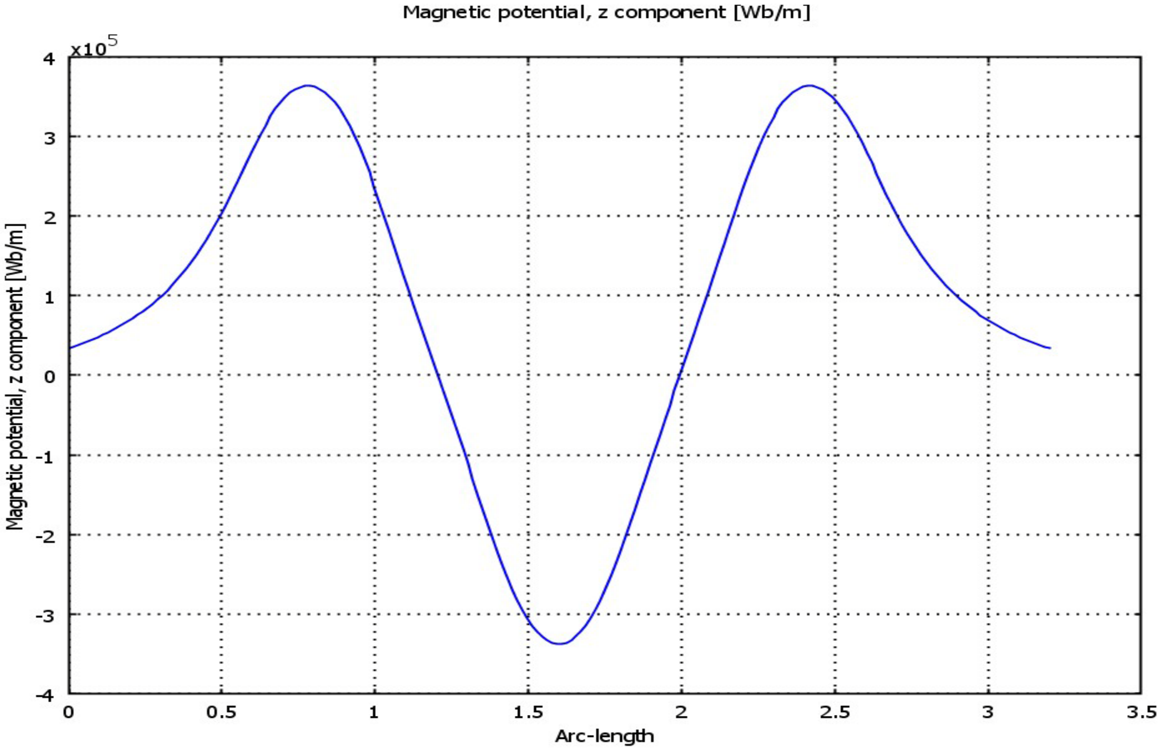


FIGURE 8B: LEFT CLOSE GRAPH

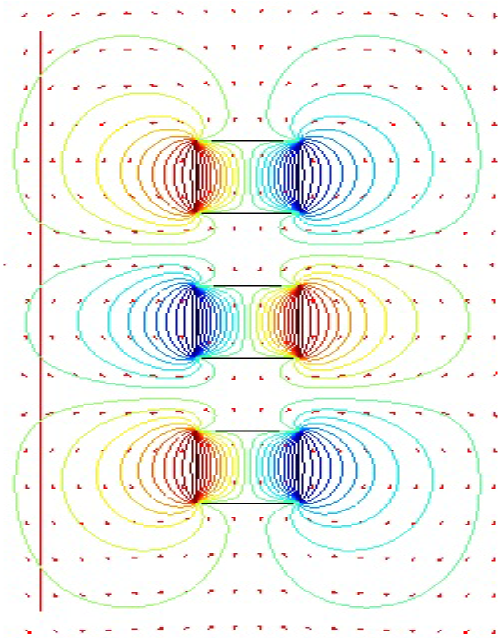


FIGURE 9A: LEFT FAR

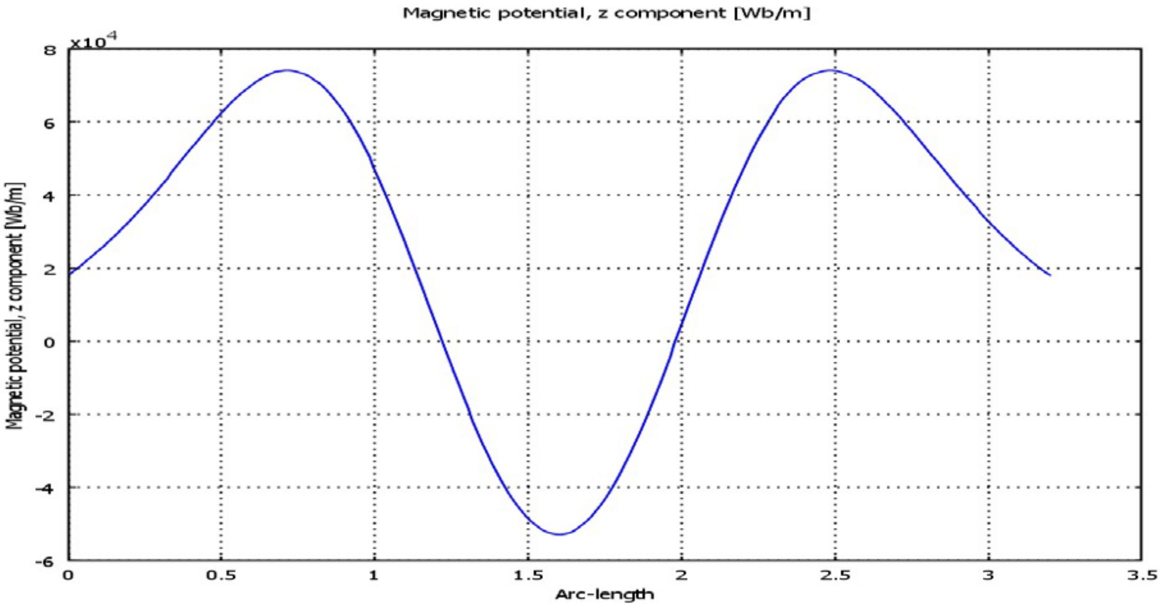
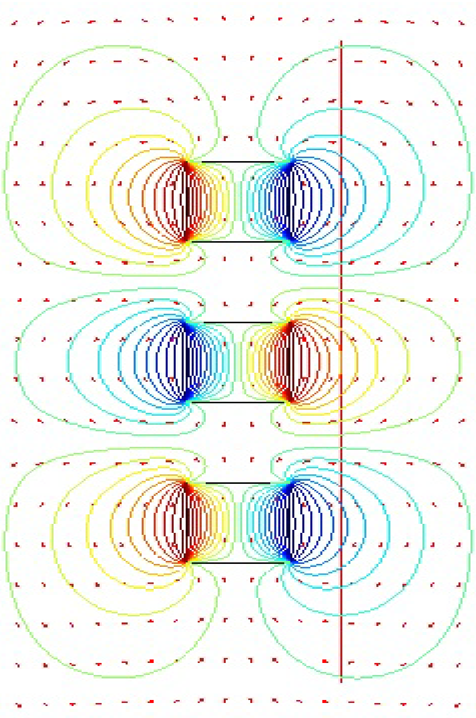
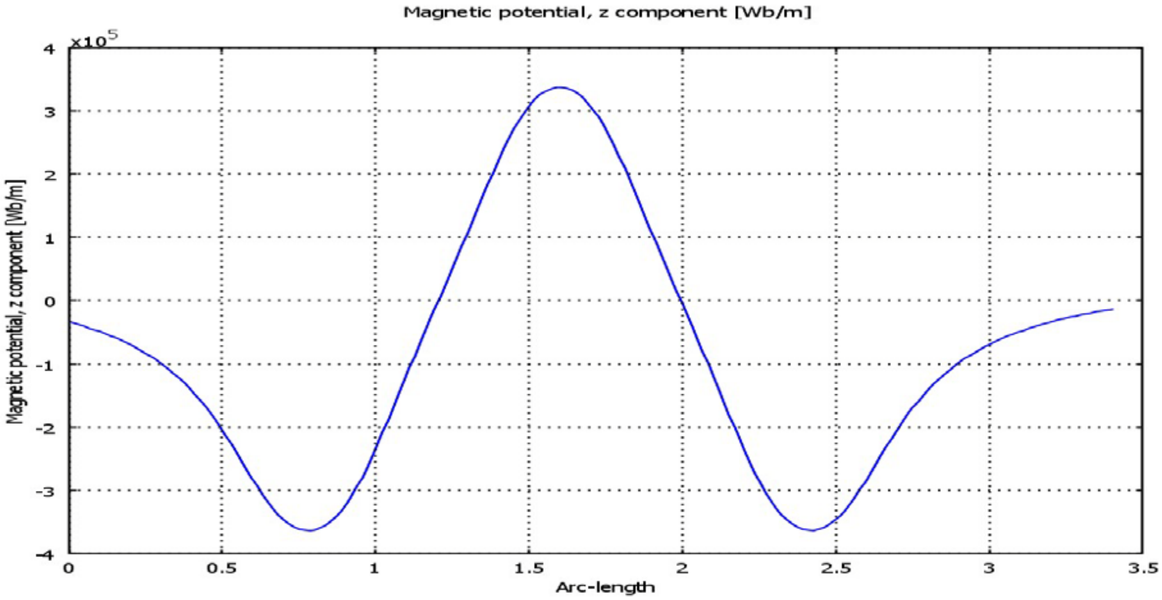


FIGURE 9B: LEFT FAR GRAPH



<u>FIGURE 10A</u>:RIGHT CLOSE



<u>FIGURE 10B</u>: RIGHT CLOSE GRAPH

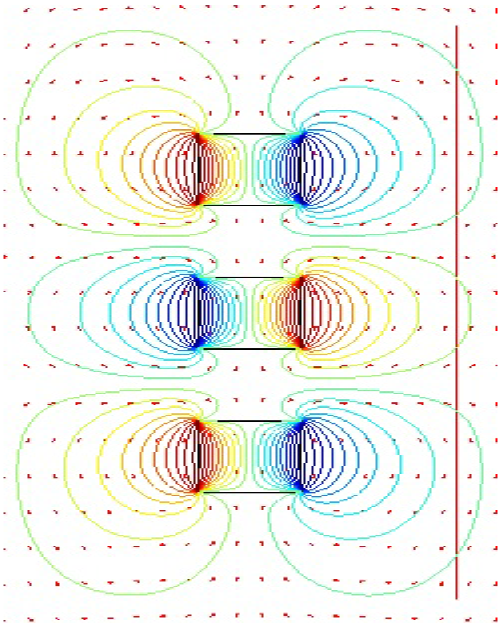


FIGURE 11A: RIGHT FAR

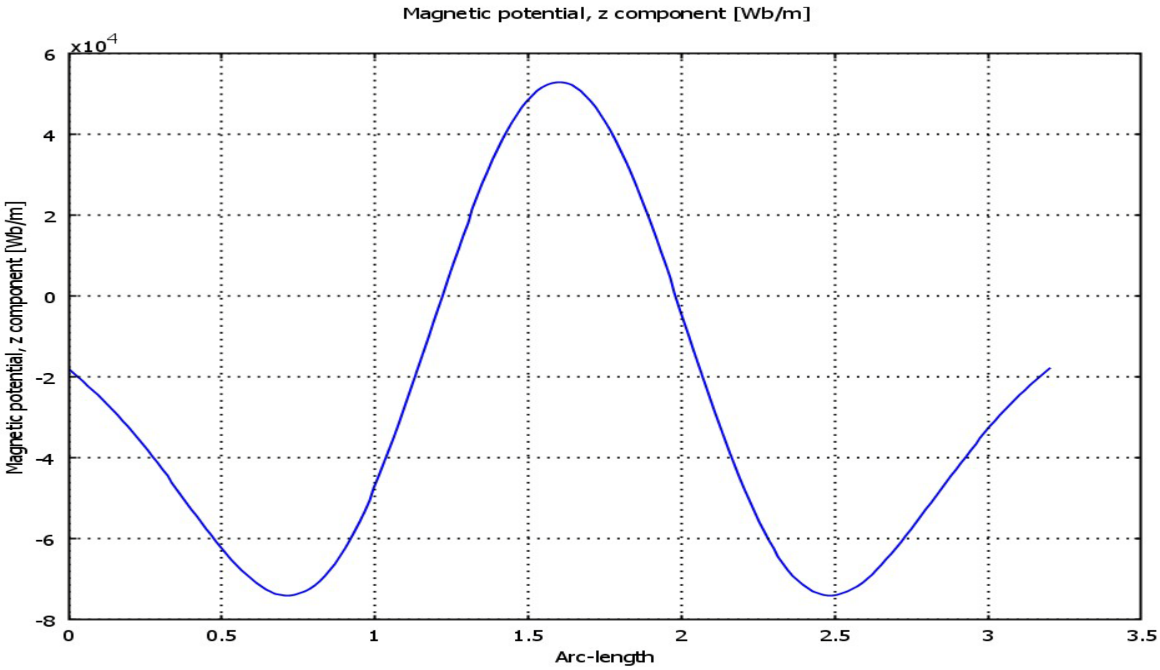
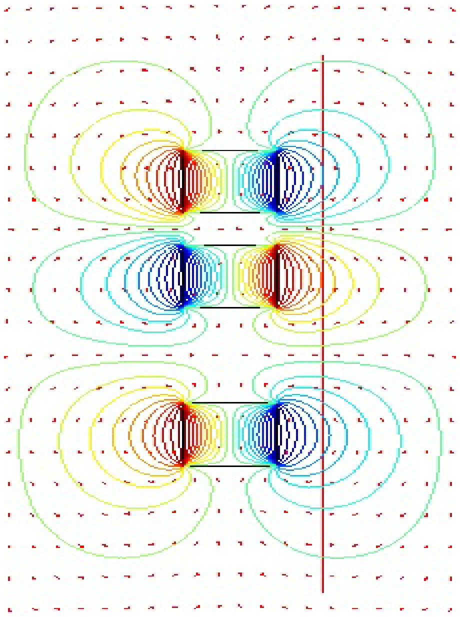
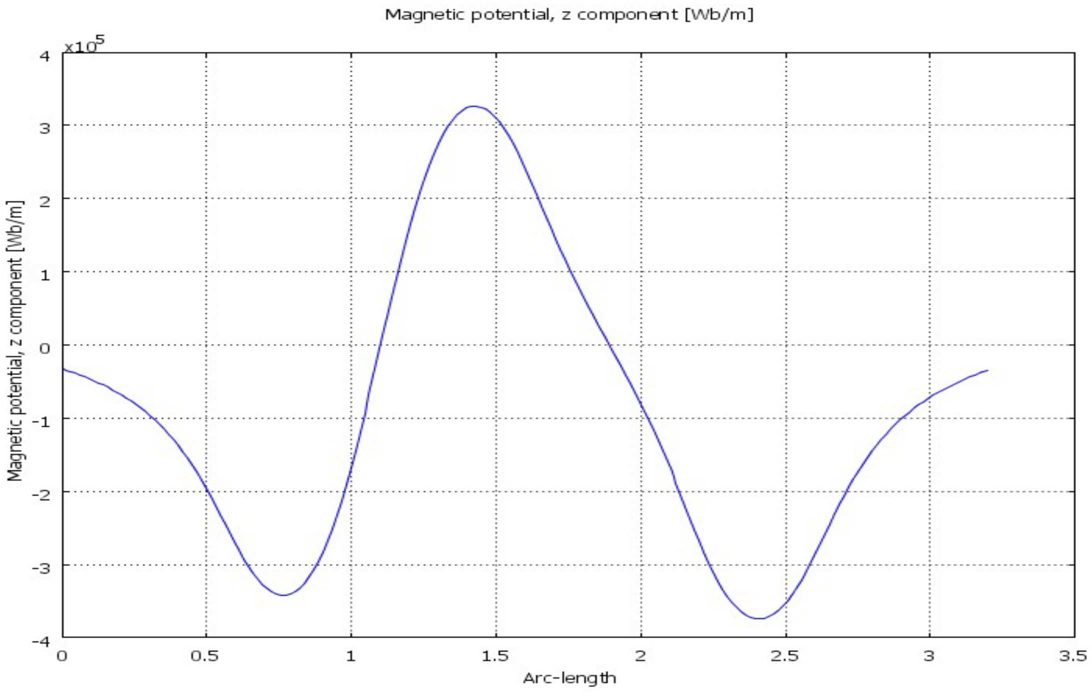


FIGURE 11B: RIGHT FAR GRAPH



FUGURE 12A: RIGHT CLOSE



FUGURE 12B: RIGHT CLOSE GRAPH

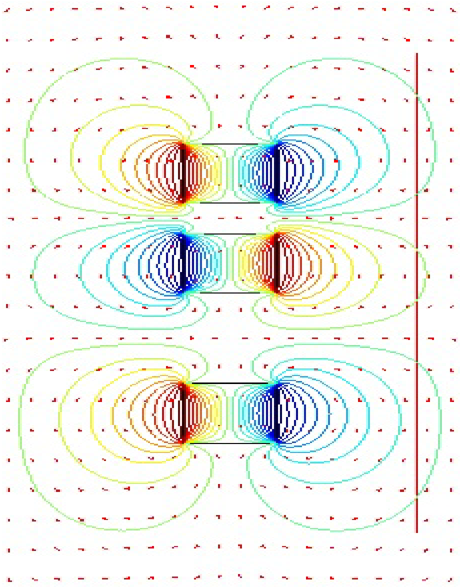


FIGURE 13A: RIGHT FAR

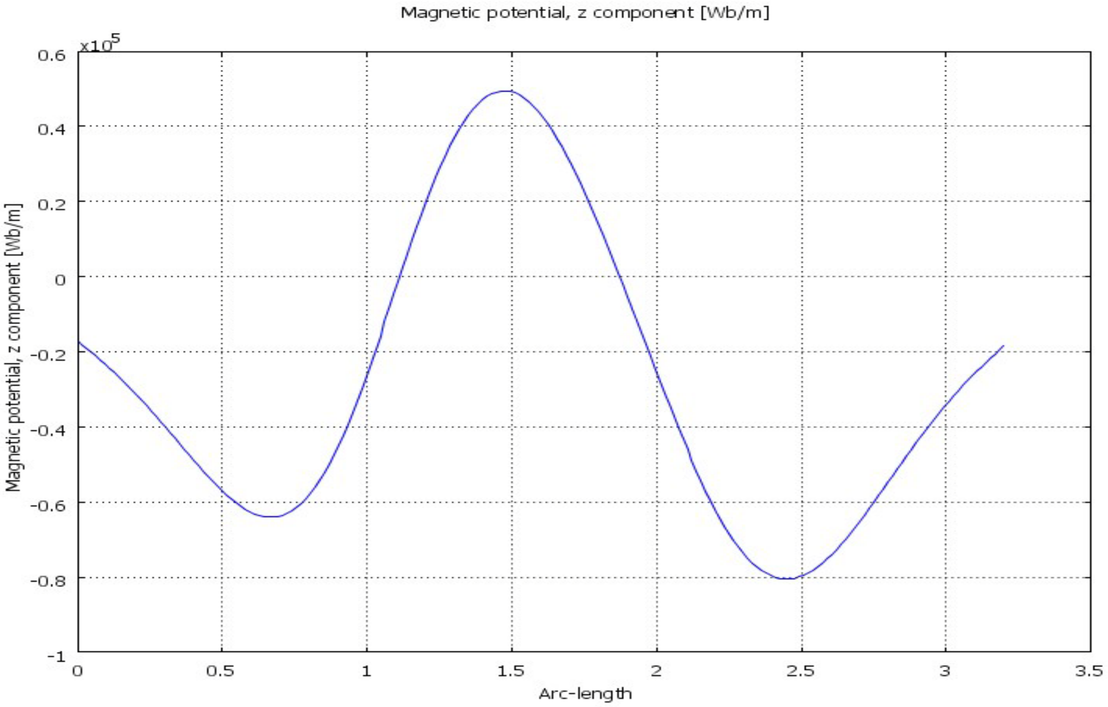


FIGURE 13B: RIGHT FAR GRAPH

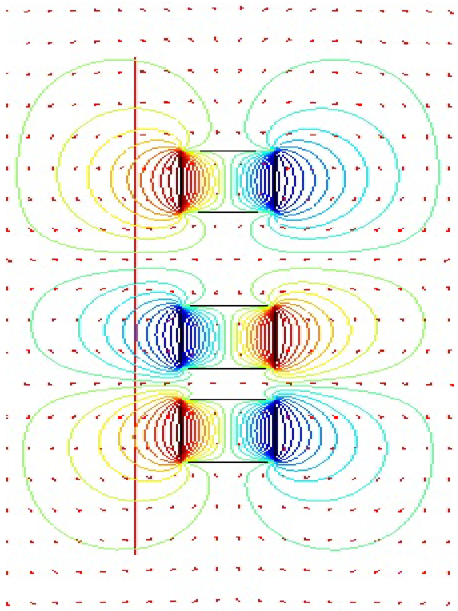


FIGURE 14A: LEFT CLOSE

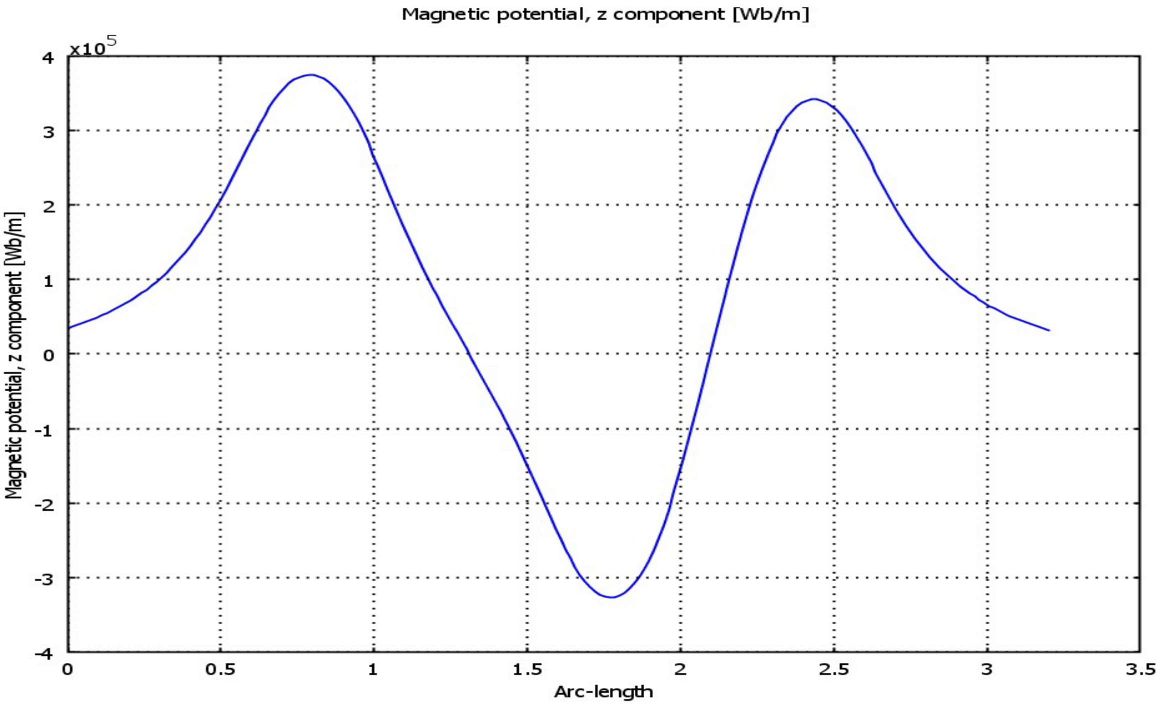


FIGURE 14B: LEFT CLOSE GRAPH

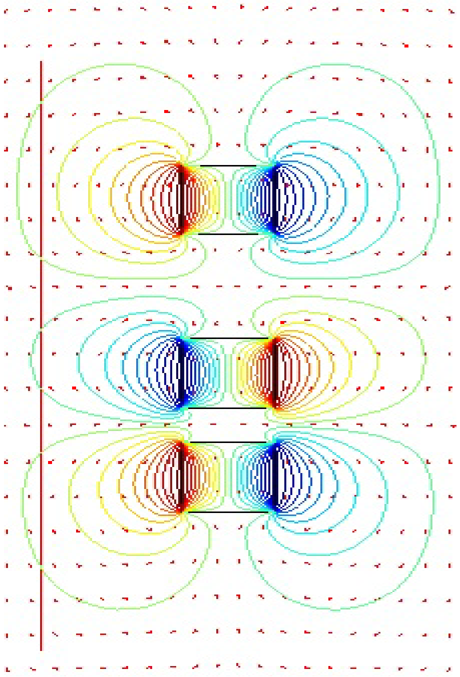


FIGURE 15A: LEFT FAR

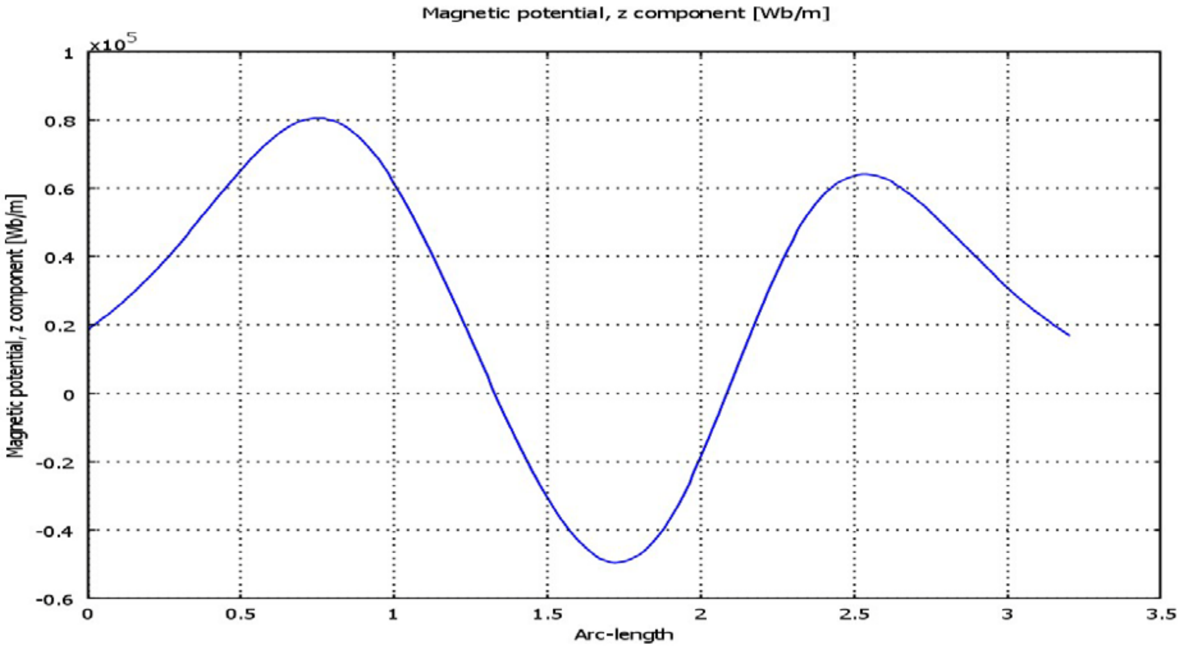


FIGURE 15B: LEFT FAR GRAPH

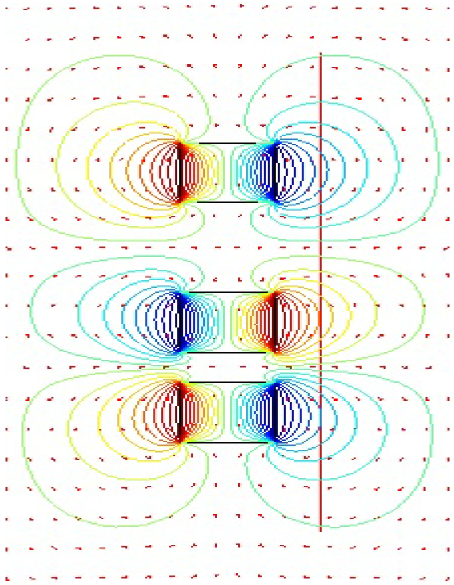


FIGURE 16A: RIGHT CLOSE

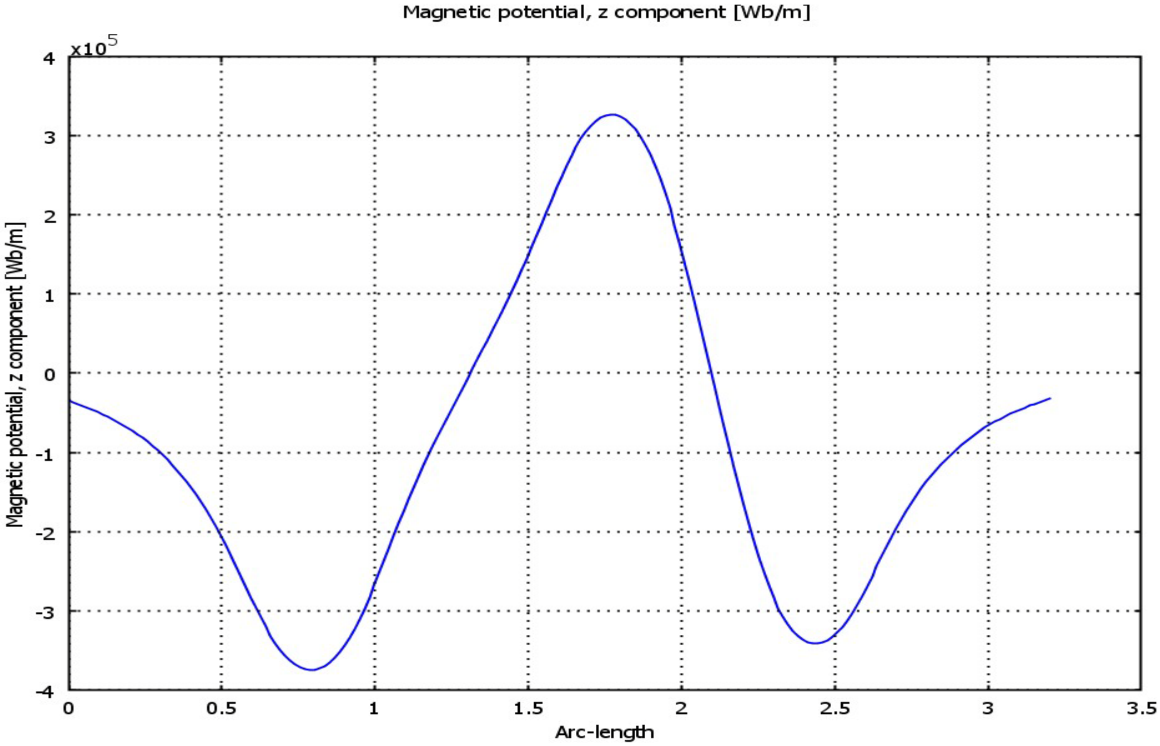


FIGURE 16B: RIGHT CLOSE GRAPH

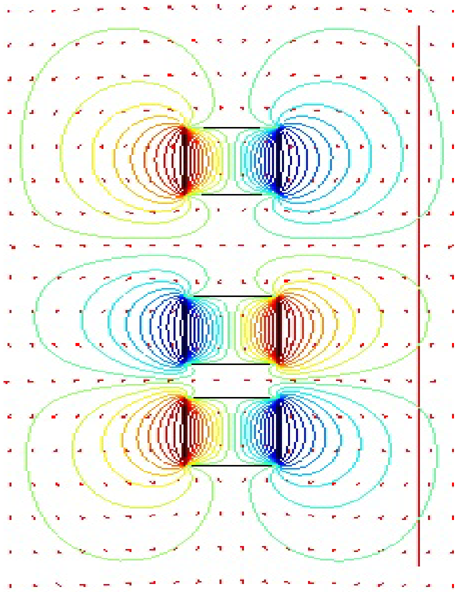


FIGURE 17A: RIGHT FAR

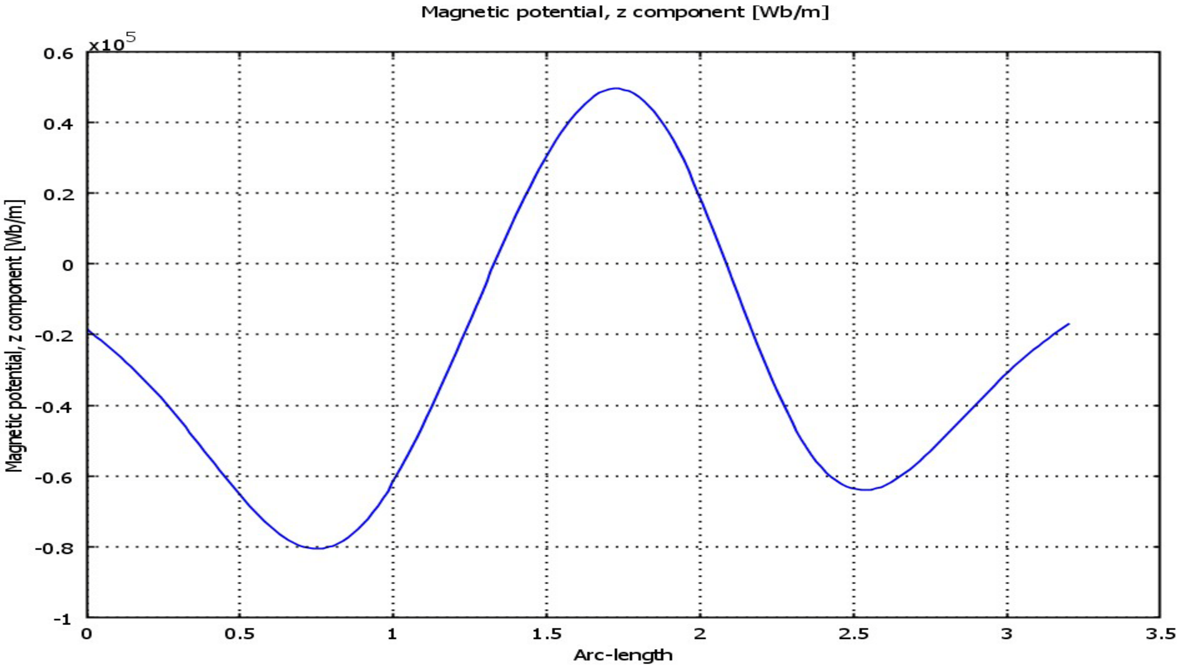


FIGURE 17B: RIGHT FAR GRAPH

2.3 RESULTS

Figure 7A shows the default of the virtual simulation of the magnet, the arc emitting from the magnet are the magnetic flux lines of the respected magnets. From figures (10A, 14A) we can see the movable magnet has changed its original position and moved to a different position vertically, we can also observe the magnetic flux lines has changed due to the movement of middle magnet and its interaction with the closed fixed magnets at various position.

Various curves are obtain due to the coil cutting the magnetic flux lines at various points as shown in figures (8A - 17A). The red line shows the point at which the coil cuts the flux lines for the following figures(8B – 17B).

CHAPTER 3

EXPERIMENT

3.1 CONSTRUCTION OF THE VIBRATIONAL GENERATOR

All external factors had to be taken into account when selecting the material for the tube of the vibrational generator. Any metal tube would produce eddy current which are electric currents induced within conductors by a changing magnetic field in the conductor. Hence we used polystyrene as the material for the tube. 4.5 inch of polystyrene hollow pipe of inner diameter 2.2 cm was cut out as smoothly to reduce friction as much as possible. An example of a vibrational generator is shown in Figure 18.

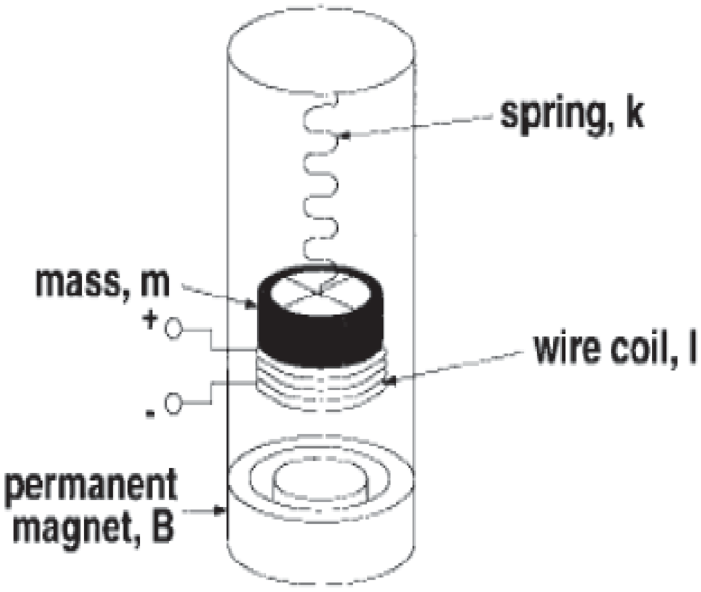


FIGURE18: TYPICAL MODEL OF A VIBRATIONAL GENERATOR

According to Faraday’s Law, change in magnetic environment of a coil of wire will cause a voltage to be induced in the coil either by changing the magnetic field strength, moving a magnet toward or away from the coil, moving the coil into or out of the magnetic field or rotating the coil relative to the magnet. Hence we used copper coils for the turns over the polystyrene tube. Neodymium magnets were used for providing the magnetic flux. To produce any type of energy we have to oscillate the magnets in such a way that the magnetic field lines cut the copper coils exactly at right angles. **Figure 19**shows the picture of the vibrational generator.

FIGURE 19: VIBRATIONAL GENERATOR BEFORE ATTACHING THE MAGNETS

3.2 TYPES OF MAGNETIC MATERIALS

Ferrites have been in production since 1950’s and are more commonly known as Ceramics. Primarily made through thecalcining process from Iron Oxide, Strontium and Barium, it ferrites are the least expensive of all magnetic materials and mostly used in motors and sensors.

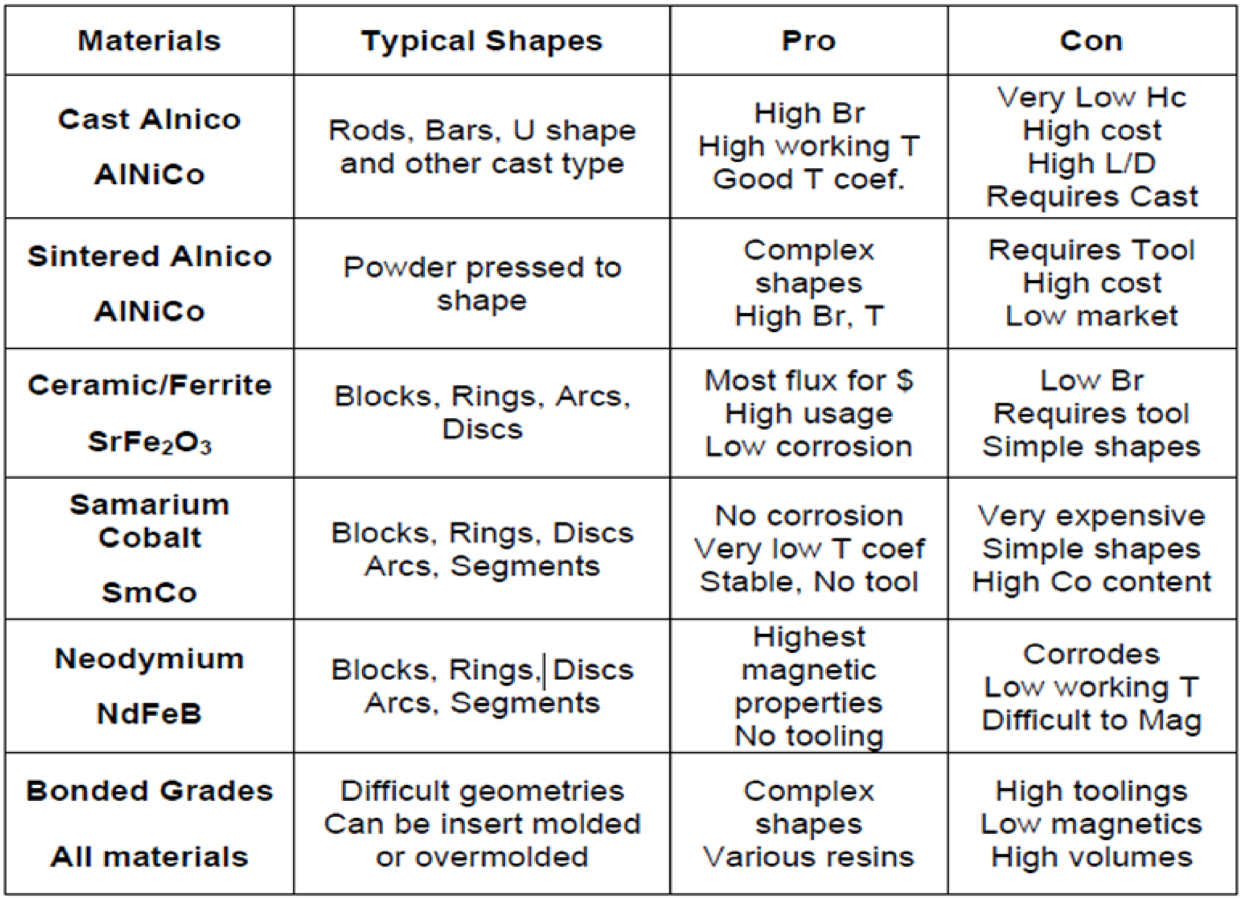
AlNiCo, as the name suggests, primarily composed of Aluminium, Nickel and Cobalt, andis one of the oldest commercially available magnets. Despite of their low magnetic values due to ease of demagnetization, they are preferred because of their high resistance to heat and good mechanical features. AlNiCo is mostly used in measuring instruments and high temperature processes.

Samarium Cobalt belongs to the rare earth family for their unique composition of Samarium and Cobalt. They have very high magnetic properties and good temperature characteristics, and hence are more expensive than other magnetic materials. Mostly found in two grades: SmCo5 (SmCo 1:5) and Sm2Co17 (SmCo 2:17), they are commonly used in aerospace, military and medical industries.

Neodymium is the strongest magnet in the rare earth family because of the Neodymium, Boron, Dysprosium and Gallium in their composition.

Bonded Magnets can be all of these above magnets bonded by different processes like extrusion, compression, calendaring or injection molding processes. Their magnetic properties however become lower due to these combining, but they can be made into complex shapes, inserted into, over-molded or co-molded with other materials.

3.2.1 MAGNETIC PROPERTIES



Materials	Typical Shapes	Pro	Con
Cast Alnico **AlNiCo**	Rods, Bars, U shape and other cast type	High Br High working T Good T coef.	Very Low Hc High cost High L/D Requires Cast
Sintered Alnico **AlNiCo**	Powder pressed to shape	Complex shapes High Br, T	Requires Tool High cost Low market
Ceramic/Ferrite **$SrFe_2O_3$**	Blocks, Rings, Arcs, Discs	Most flux for $ High usage Low corrosion	Low Br Requires tool Simple shapes
Samarium Cobalt **SmCo**	Blocks, Rings, Discs Arcs, Segments	No corrosion Very low T coef Stable, No tool	Very expensive Simple shapes High Co content
Neodymium **NdFeB**	Blocks, Rings, Discs Arcs, Segments	Highest magnetic properties No tooling	Corrodes Low working T Difficult to Mag
Bonded Grades **All materials**	Difficult geometries Can be insert molded or overmolded	Complex shapes Various resins	High toolings Low magnetics High volumes

TABLE4:LIST OF BASIC MAGNETS AND THEIR PROPERTIES

3.3NEODYMIUM MAGNET

The Neodymium magnets were used in the practical part of this Thesis work, a **Neodymium magnet** (also known as **NdFeB**, **NIB** or **Neo** magnet), is a permanent magnet made from an alloy of neodymium, iron and boron to form the $Nd_2Fe_{14}B$ tetragonal crystalline structure. Developed in 1982 by General Motors and Sumitomo Special Metals, neodymium magnets are the strongest type of permanent magnet commercially available. They have replaced other types of magnet in the many applications in modern products that require strong permanent magnets, such as motors in cordless tools, hard disk drives and magnetic fasteners.

Some important properties used to compare permanent magnets are: remanence (B_r), which measures the strength of the magnetic field; coercivity (H_{ci}), the material's resistance to becoming demagnetized; energy product (BH_{max}), the density of magnetic energy; and Curie temperature (T_C), the temperature at which the material loses its magnetism. Neodymium magnets have higher remanence, much higher coercivity and energy product, but often lower Curie temperature than other types. Neodymium is alloyed with terbium and dysprosium in order to preserve its magnetic properties at high temperatures.

3.3.1The hazards of using Neodymium Magnets:

The greater force exerted by these magnets creates hazards that are not seen with other types of magnets. Neodymium magnets are larger than a few cubic centimeters, are strong enough to cause injuries to body parts pinched between two magnets, or a magnet and a metal surface, even causing broken bones.

Magnets which are allowed to come into contact with each other can strike with enough force to break and shatter the brittle magnets and the flying chips can also cause injuries in a number of ways.

3.4 RESULTS

After the magnets were attached to the tube and completely sealed using Sellotape to reduce external interruptions from noise etc, the vibrational generator was oscillated at different frequencies to measure the different output voltages. An Oscilloscope was used to view the changes in the waveform of the output voltage.

Later the numbers of turns of the coil were increased and the vibrational generator was oscillated through different frequencies. To reduce any electronic or manual anomalies the whole experiment was repeated several times and multiple readings were taken.

A digital oscilloscope was used to record all the data and all the waveforms.

The results of different waveforms are given in the following pages.

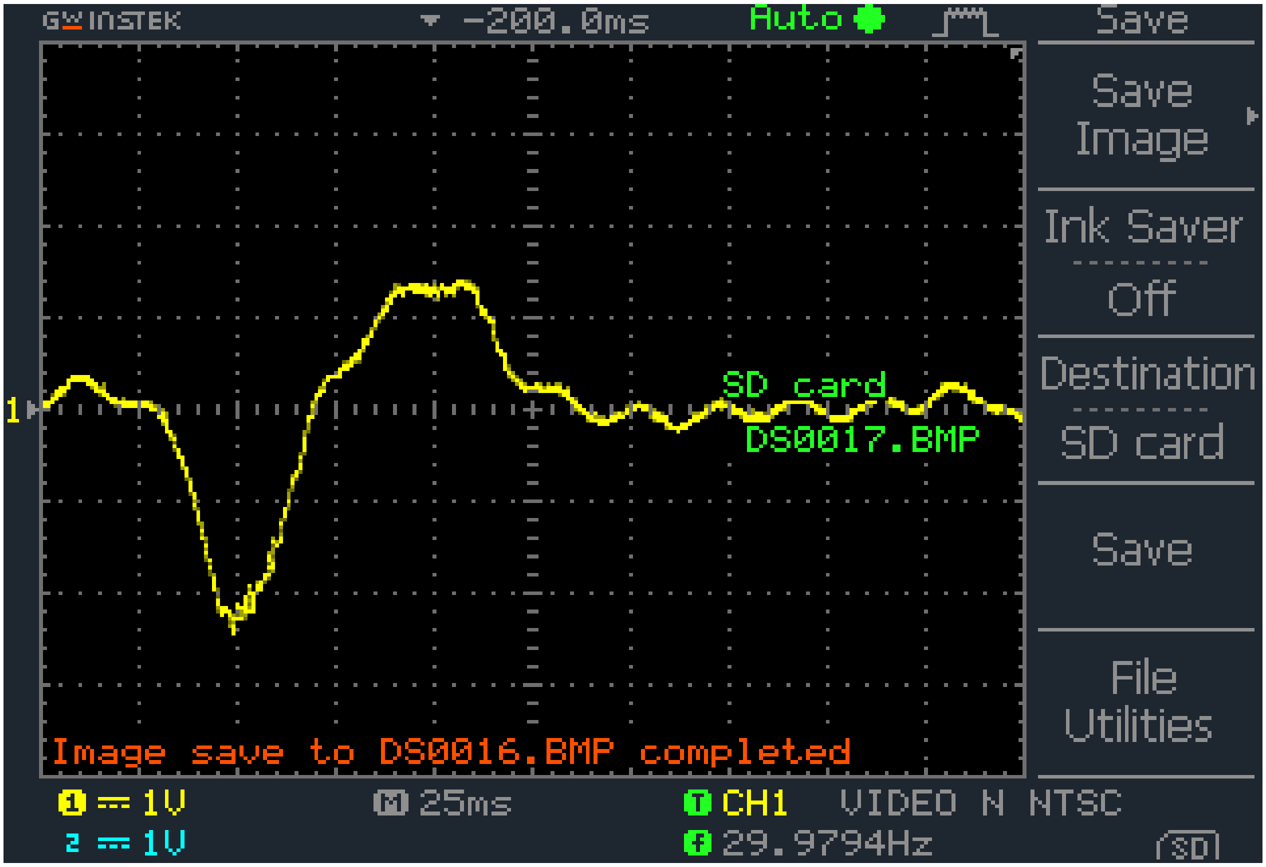


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FIGURE 20A: OSCILLOSCOPE OBSERVATION OF VIBRATIONAL GENERATOR

From this image of the oscillation we can see that the output voltage is approximately 1.25V.

The oscillating frequency is 29.97Hz

Time period = 25ms

The numbers of turns of coil = 150

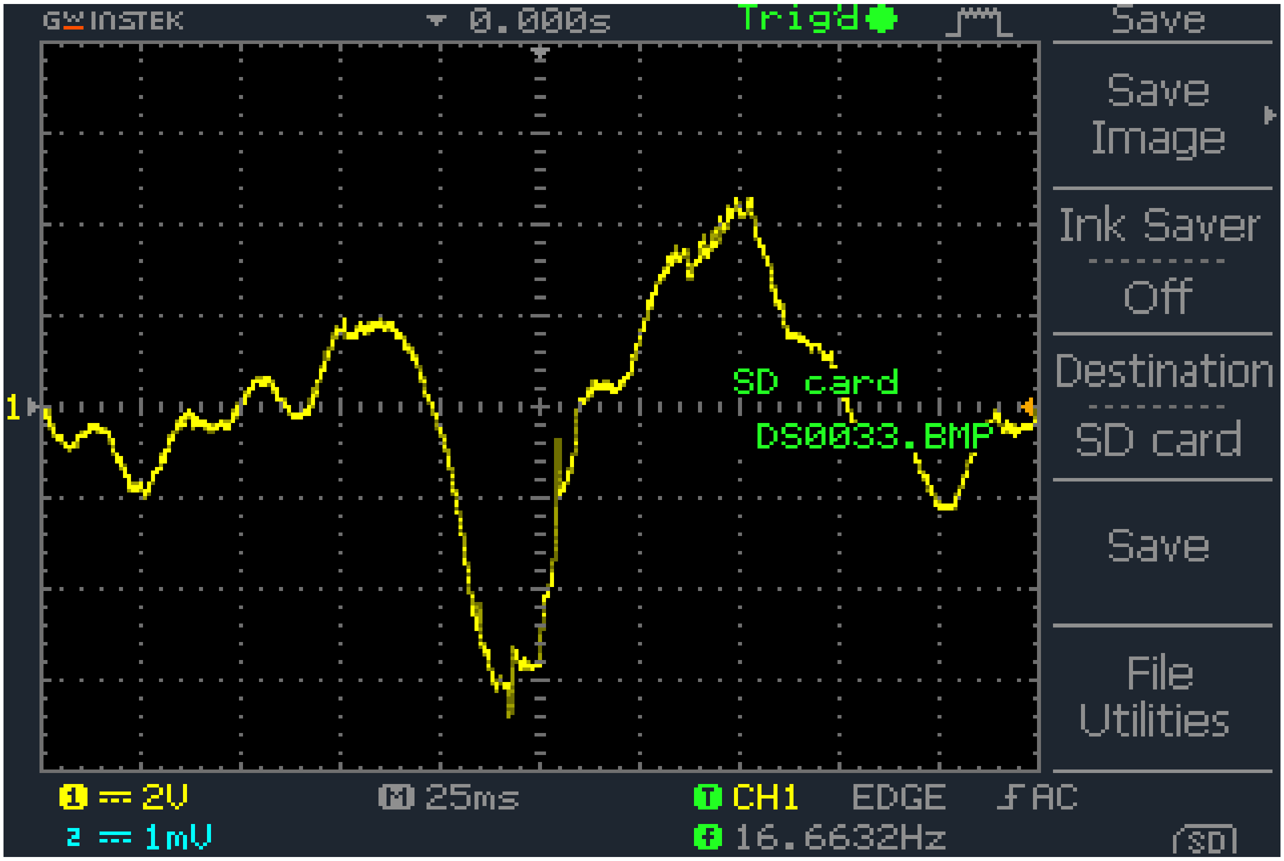


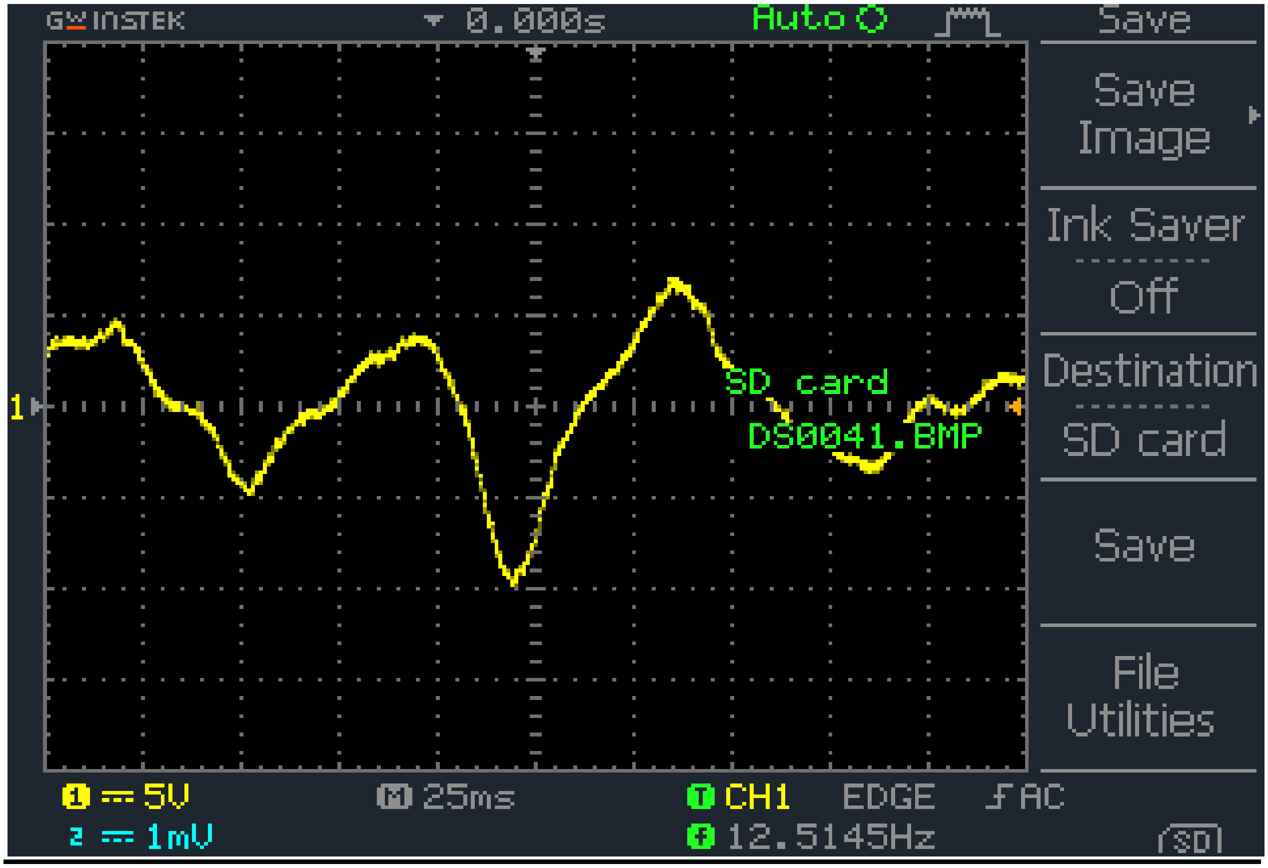
FIGURE 20B: **OSCILLOSCOPE OBSERVATION OF VIBRATIONAL GENERATOR**

When the number of turns were increased to 200, and the generator oscillated at about 16Hz this type of waveform was obtained. Now approximately 4V can be generated.

Therefore, time period= 25ms

Volts/Div= 2V

Frequency= 16Hz



<u>FIGURE 20C</u>: OSCILLOSCOPE OBSERVATION OF VIBRATIONAL GENERATOR

When the number of turns were increased to 250, and the generator oscillated at about 12Hz this type of waveform was obtained. Now approximately 6.5V can be generated.

Therefore, time period= 25ms

Volts/Div= 5V

Frequency= 12Hz

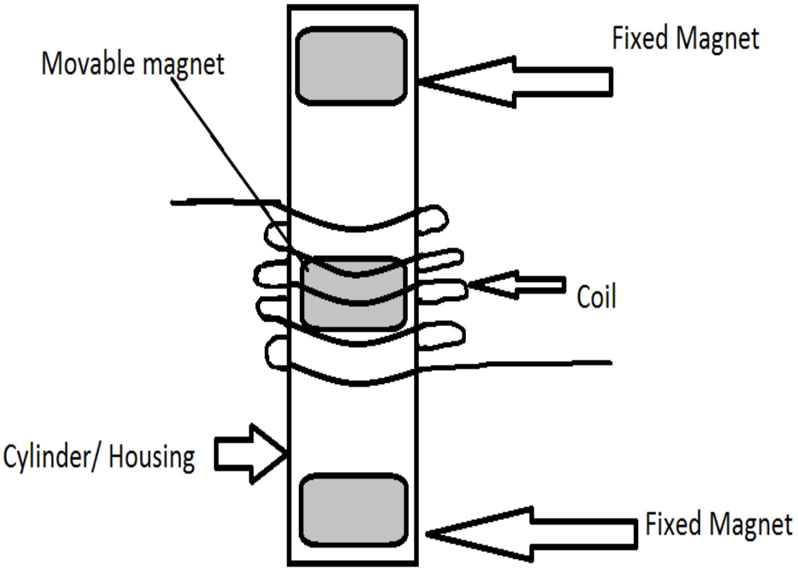


FIGURE 21: A SCHEMATIC DIAGRAM OF THE VIBRATIONAL GENERATOR

The figure above shows the schematic diagram of our exact electromagnetic generator.

3.5 CALCULATIONS

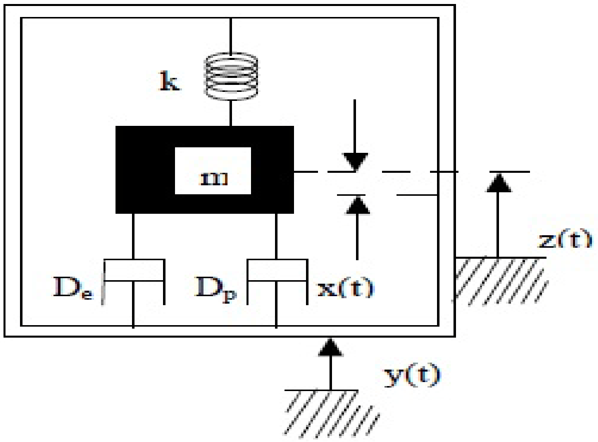


FIGURE 22: SCHEMATIC REPRESENTATION OF THE VIBRATIONAL GENERATOR

Equations of the magnet parameters, coil parameters, beam parameters and damping (D) parameters are important in order to develop and study the model.Variables z and $y$are the displacements of the generator mass and housing, respectively. For a sinusoidalexcitation:

$$y = Y_0 \sin(\omega t)$$

where, Y_0 = the vibration amplitude

ω= the frequency of vibration.

The equation of motion for the mass relative to the housing at no load condition(no electromagnetic forces considered) can be defined by the following equation:

$$m\frac{d^2x}{dt^2} + D_p\frac{dx}{dt} + kx = -ma(t) = F_0 sin\omega t$$

where, m = the moving mass of the generator

x = the relative movement between the mass and the housing

D_p = the parasitic damping

$F_0 = m\omega^2 a$

The parasitic damping of the generator is commonly known as mechanical loss and can consist of air resistance loss, surface friction loss, material hysteresis loss, etc. It depends on material properties, the size and shape of the generator, external force, frequency, and vibrational displacement. Kisthebeam spring constant where the natural resonant frequency $\omega_n$is given by:

$$\omega = \sqrt{k/m}$$

The displacement for the no-load conditionisgiven by the following equation:

$$x_{no-load} = \frac{F_0 \sin(\omega t - \phi)}{\sqrt{(k - m\omega^2)^2 + (D_p \omega)^2}}$$

where, $\phi = tan^{-1}(\frac{D_p \omega}{k - m\omega^2})$

This parasitic damping can be calculated from the open circuit quality factor and the damping ratio of the system, which can be expressed by:

$$Q_{oc} = \frac{m w_n}{D_p}, \quad \xi_{Oc} = \frac{D_p}{2m\omega_n}$$

The displacement at resonance is given by:

$$x_{no-load} = \frac{-F_0 \cos(\omega_n t)}{D_p \omega_n}$$

The phase angle (ϕ) between displacement and the forcing signal is 90^0.

When a load is connected to the generator coil terminal, an electromagnetic force will be generated between the magnet and the coil due to the current flow through the load; this opposes the movement of the generator. Thus, the equation of motion of the generator mass includes an extra term due to the magnetic force and becomes:

$$m\frac{d^2x}{dt^2} + D_p\frac{dx}{dt} + kx = F_0 sin\omega t - F_{em}$$

where, F_{em} = the electromagnetic force

The conductor moves along the X axis at velocity U in magnetic field B that varies with the position x. In this case, the force experienced on the current-carrying conductors in the loop is:

$$F_{em} = \int IBdl = \int IBdx = I[\int_{(0,0,0)}^{(\Delta x,0,0)} Bdx + \int_{(\Delta x,0,0)}^{(\Delta x,\Delta y,0)} Bdx + \int_{(\Delta x,\Delta y,0)}^{(0,\Delta y,0)} Bdx + \int_{(0,\Delta y,0)}^{(0,0,0)} Bdx]$$

$$F_{em} = I[\Delta x\{B(\Delta x) - B(0)\} + \Delta y B(\Delta x) + \Delta x\{B(0) - B(\Delta x)\} - \Delta y B(\Delta x)] = I\delta y(B(0) - B(\Delta x))$$

$$F_{em} = I\frac{d\phi}{dx}$$

Assuming the magnetic field B to be constant with the position x, then:

$$F_{em} = BlI$$

where l = coil mean length

The equation of how magnetic flux density (B) varies with the coil movement is:

$$F_{em} = \frac{V}{R_c + R_l + j\omega L}\frac{d\phi}{dx}$$

$$= \frac{1}{R_c + R_l + j\omega L}\left(\frac{d\phi}{dx}\right)\left(\frac{dx}{dt}\right)\left(\frac{d\phi}{dx}\right)$$

$$= \frac{(\frac{d\phi}{dx})^2}{R_c + R_l + j\omega L}\frac{dx}{dt}$$

where, V = the generated voltage

R_c = the coil resistance

L = the coil inductance

R_l = the load resistance

Assuming the individual flux linkage gradients are equal, the total electromagnetic force is given by:

$$F_{em} = \frac{N^2(\frac{d\phi}{dx})^2}{R_c + R_l + j\omega L}\frac{dx}{dt}$$

$$= D_{em}\frac{dx}{dt}$$

The electromagnetic damping, $D_{em} = \frac{N^2(\frac{d\phi}{dx})^2}{R_c + j\omega L + R_l}$

$$m\frac{d^2x}{dt^2} + D_p\frac{dx}{dt} + D_{em}\frac{dx}{dt} + kx = F_0 sin\omega t$$

$$x_{load} = \frac{F_0 \sin(\omega t - \theta)}{\sqrt{(k - m\omega^2) + [(D_p + D_{em})\omega]^2}}$$

where, $\theta = tan^{-1}[\frac{(D_p + D_{em})\omega}{(k - m\omega^2)}]$

Hence the displacement under load at resonance is given by:

$$x_{load} = \frac{-F_0 cos\omega t}{(D_p + D_{em})\omega}$$

The mechanical power is therefore:

$$P_{mech}(t) = F(t)U(t)$$

$$= F_0 \sin(\omega t)\frac{dx_{load}}{dt}$$

$$= \frac{{F_0}^2 sin^2(\omega t)}{(D_p + D_{em})}$$

where, *F(t)* = the applied sinusoidal force of the moving mass

U(t) = velocity of the moving mass due to the sinusoidal movement

ANALYTICAL & MATHEMATICAL

Let the mass of mobile magnets be m and elasto-magnetic constant be k_{em}. Then the elasto-magnetic constant is obtained by:

$$k_{em} = \frac{\Delta F}{\Delta x}$$

where, F = force of repulsion resulting from mobile and fixed magnets

Δx = displacement of mobile magnets.

The repulsion force can be expressed as:

$$F = k\left[\frac{1}{(x+h)^2} + \frac{1}{(x+2d)^2} - \frac{2}{(x+d)^2}\right]$$

where, k and h = constants

x = distance between the magnets

d = axial length of the magnets.

A variable y is considered for moving the housing. For sinusoidal excitation:

$$y = Y\sin\omega t$$

where, Y = amplitude of vibration

ω = pulsation vibration.

Hence we get the differential equation of motion:

$$mz + cz + k_{em}z = m\omega^2 Y sin\omega t$$

where, z = the relative displacement of mass [$z = (x - y)$]

c = the damping coefficient.

The equation above rearranged for the value of z is:

$$z = \frac{m\omega^2 Y}{k - m\omega^2 + j\omega c} sin\omega t$$

The instantaneous power generated by the system is:

$$P_i = c_e z^2$$

where, c = part of the damping assigned to electromagnetic force interaction, mobile magnets-coil currents

So the magnitude of generated power, $|P_i|$, is:

$$|P_i| = c_e \left| \frac{mY\omega^3}{(k - m\omega^2) + j\omega c} \right|^2$$

The generated power can then be written as:

$$P = \frac{m\varsigma_e Y^2 \left(\frac{\omega}{\omega_n}\right)^3 \omega^3}{\left[1 - \left(\frac{\omega}{\omega_n}\right)^2\right]^2 + \left[2\varsigma\left(\frac{\omega}{\omega_n}\right)\right]^2}$$

where, $\omega = \sqrt{\frac{k}{m}}$ is the natural pulsation of the system

$\varsigma_e = {}^{c_e}/_{2m\omega_n}$ is the electromagnetic damping factor

The overall damping of the system, , includes losses due tofriction, ς_f , air resistance, etc. and is given by:

$$\varsigma = \varsigma_e + \varsigma_f = \frac{c}{2m\omega_n}$$

The voltage, *e,* and current, *I,* generated by the system are described by the equations:

$$e = \phi z - R_c + j\omega L_c I\ ()$$

$$F_e = \phi i$$

where, F_e = the force generated by the electromagnetic coupling

R_c&L_c = the resistance and inductance of the coil

ϕ =*NBl,* the transformation factor

where, *N* = the number of turns

B = the magnetic induction

l = the average length of a spiral coil (πD)

If the current is through a load of resistance R_L, the electrical generated force will be:

$$F_e = \frac{\emptyset^2 z}{R_L + R_C + j\omega\, L_C}$$

Hence the electrical damping will be:

$$C_e = \frac{\emptyset^2}{R_L + R_C + j\omega\, L_C}$$

For the frequencies where the inductive impedance is much lower than resistive impedance, the electromagnetic damping factor will be:

$$\varsigma_e = \frac{\phi^2}{2m\omega_n(R_L + R_C)}$$

For the case when $\omega=\omega_n$, the maximum power generated will be:

$$P = \frac{\phi^2 Y^2 {\omega_n}^2}{8\varsigma^2(R_L + R_C)}$$

Chapter 4

Conclusion

4.1 SUMMARY

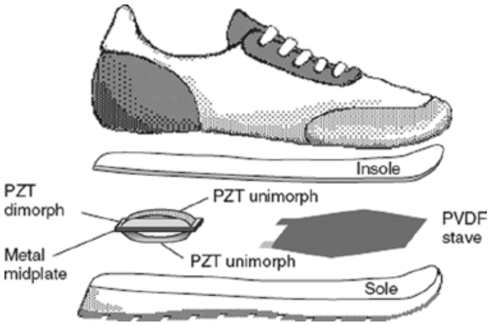
A vibrational energy harvesting system, harvests or extracts usable energy from ambient vibrations or oscillations. The usable energy is this case can usually be used for only a specific purpose – to charge small electronic devices. In short the main objective of this research was to establish an energy harvester that will be able to convert transient vibration to electrical energy. To make the device as efficient as possible the virtual design of the device was simulated using computer software called COMSOL Multiphysics. The exact design of the device was enacted in a virtual state and simulated to get results and to minimize errors as much as possible. The virtual simulation was further studied to learn more about the working mechanism and to realize the theoretical limitations. The errors that were found were scrutinized and consequently solved. All the problems from the start to finish including the final implementation required several modifications and were all duly completed. Special attention was required during the virtual simulations as the software was completely new to us and needed a few trial runs before we could actually go through with the project.

The practical part of the research was completed after the virtual simulations were completed. We were successful in creating an energy harvesting device which can provide up to 5V of electricity at any given time.

4.2TYPES OF VARIOUS MOTION BASED HARVESTERS:

Direct Force Generators:

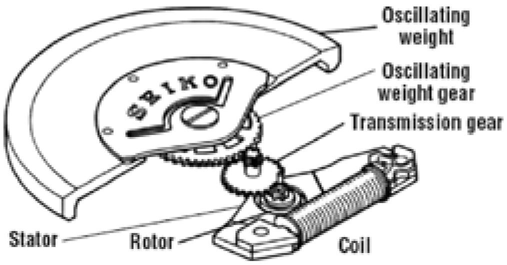
First proposed by Enger, he suggested a health-monitoring system powered by a piezoelectric bimorph, which could be driven by the movement of adjacent body tissue. The device consists of an RF transmitter, which would operate intermittently, at a rate depending upon the rate of power generation. But the first reported work on direct-force microgenerators in the research is by Umeda *and his team,* according to them that portable electronic equipment is often subjected to mechanical shock during transportation and investigated generation from such shock using a piezoelectric beam, which is clamped at both ends, when a steel ball is dropped onto it. Gonzales and his team addressed the problem associated with the device and suggested improvements, later Paradiso and his team of the MIT Media lab investigated power-harvesting running shoes and came up with the results that the piezoelectric solutions are better as it reduces power consumption of wearable devices, and power output is sufficient.



Electromagnetic Inertial Generators

Electromagnetic Inertial Generators

The concept was first used in an electrically operated self-winding watch, developed by the Seiko Epson Corporation. Used for making the Seiko Kinetic watch, this is now a commercial product. An asymmetric proof mass, freely rotating about a point some distance from its center of mass, is attached to a permanent magnet electrical generator, through high ratio gears. Further improvement was don by Tiemann who proposed the use of relative movement between magnets and coils in a mass-spring system to generate electrical energy from linear vibrational motion.



Exploded view of Seiko Kinetic watch (courtesy of Seiko Instruments Inc.).

Williams and Yates gave the first description of an inertial microgenerator was of an electromagnetic type driven by reciprocating vibration they researched their work based on material presented by Thomson. Some basic insights consists of are the choice of generator design parameters, e.g. operating the generator at its resonant frequency, and reducing the damping so that the mass moves to the limit of its travel, are both beneficial to power generation. The device is quite similar to a microphone. An average output of 0.33 μW was obtained from a 4.4 kHz input vibration.

COMMERCIALLY AVAILABLE MOTION HARVESTERS

Companies which are currently offering electromagnetic harvesters are Perpetuum and Ferro Solutions. Perpetuum offers devices such as its PMG17 and Ferro Solutions offers the VEH360.

Both are mechanically resonant devices with a relatively narrow bandwidth centered on the frequencies at which electrical machines are supplied. Advanced Cerametrics is known for making microgenerators using fiber composite materials for integrating into clothing or creating complex shapes. Kinetron offers rotational generators for energy harvesting. These use permanent magnets rotating within coils in a miniature variant of a conventional electrical generator. [16]

4.3 FUTURE IMPROVEMENTS:

Even though our research contains a lot of breakthrough, nonetheless there is a lot of room for improvements. As already mentioned COMSOL can be linked with other software, circuit made in PSpice can be used to link our model for further analysis. Like making a half-wave rectifier circuit schematics using PSpice, then save the schematic using the NETLIST feature available to save the circuit data in a word file. Then use the PSpice feature available in COMSOL to upload the schematic NETLIST data which can be used to embed with the model to get further data like how much Voltage can be generated as well as current, frequency values. Not to mention by changing the parameters what more different type of results we can expected. Moreover by linking with the rectifier circuit, we can generate a plot which can be used analyze how the half-rectifier circuit converts AC voltage to DC voltage with a capacitor filter.

MATLAB software can also be used for implementing computer programming language in the COMSOL model for any other new dimension of research in future, like making new type of functions or writing a program in MATLAB, then by using the Livelink For MATLAB feature in

COMSOL, we can transfer the functions or program created in MATLAB and use it in our COMSOL Model. This feature can be used if we encounter obstacles like if we need to introduce equations or laws which aren’t currently available with the current existing application modes in COMSOL. Then by using MATLAB we can overcome the problems.

4.4Can this device be used to replace batteries in future?

Simple thing like battery which we use for operating various appliances, devices; then later when their job is done in most they are not disposed properly, this creates a lot of nuisance to the environment like when they are disposed in trash and in local landfills harmful chemicals such as lead, lithium, cadmium and mercury are released to the environment. These substances pose serious threat to health issues for both humans and animals. Like other garbage, batteries also undergo photochemical reaction during decomposition which causes harmful gas emissions. Also they are responsible for water pollution as harmful chemical found in batteries can run off into local water supplies, not only its dangerous to people who drink, it can even kill plants and animals, thus putting the ecosystems of various water bodies in risk.

In recent years many battery industries are researching on making bio-degradable or eco-friendly batteries. Still it is neither yet up to par to make an impact nor cost effective. Since small solar panels are popularly used in small calculators and they don’t require batteries. Replacing the batteries on small handheld like cellphones, handheld games with the vibrational device can create a big impact. In future with the improvement of technology and discovery of new materials can be used to further improve the magnetic vibrational generator and they can be powerful enough to generate power currently possible with various batteries. It can easily replace them, like the way digital cameras replaced films, not only it will create a cost effective solutions, it will also create a great impact to the environment. [15]

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[11] (Torres & Rincón-Mora, 2005)

[12] (Sodano, Inman, & Park, 2004).

[13] (Skoog, Holler, & Crouch, 2006).

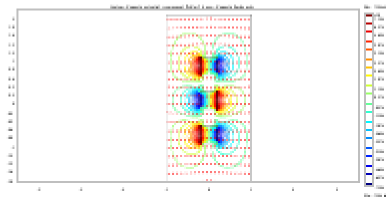
[14] (Meninger, Mur-Miranda, Amirtharajah,Chandrakasan, & Lang, 2001).

[15] https://www.sevacall.com/blog/2013/07/s/garbage-removal/environmental-problems-caused-by-disposal-of-batteries/

[16] http://ieeexplore.ieee.org/ieee_pilot/articles/96jproc09/96jproc09-mitcheson/article.html

Appendix

COMSOL Model Report



1. Table of Contents

2. Model Properties

Property	Value
Model name	

Author	
Company	
Department	
Reference	
URL	
Saved date	Apr 29, 2014 12:49:26 AM
Creation date	Nov 7, 2013 1:01:42 AM
COMSOL version	COMSOL 3.5.0.603

File name: C:\Users\Samsung\Desktop\MagnetMovement.mph

Application modes and modules used in this model:

- Geom1 (2D)
    - Magnetostatics

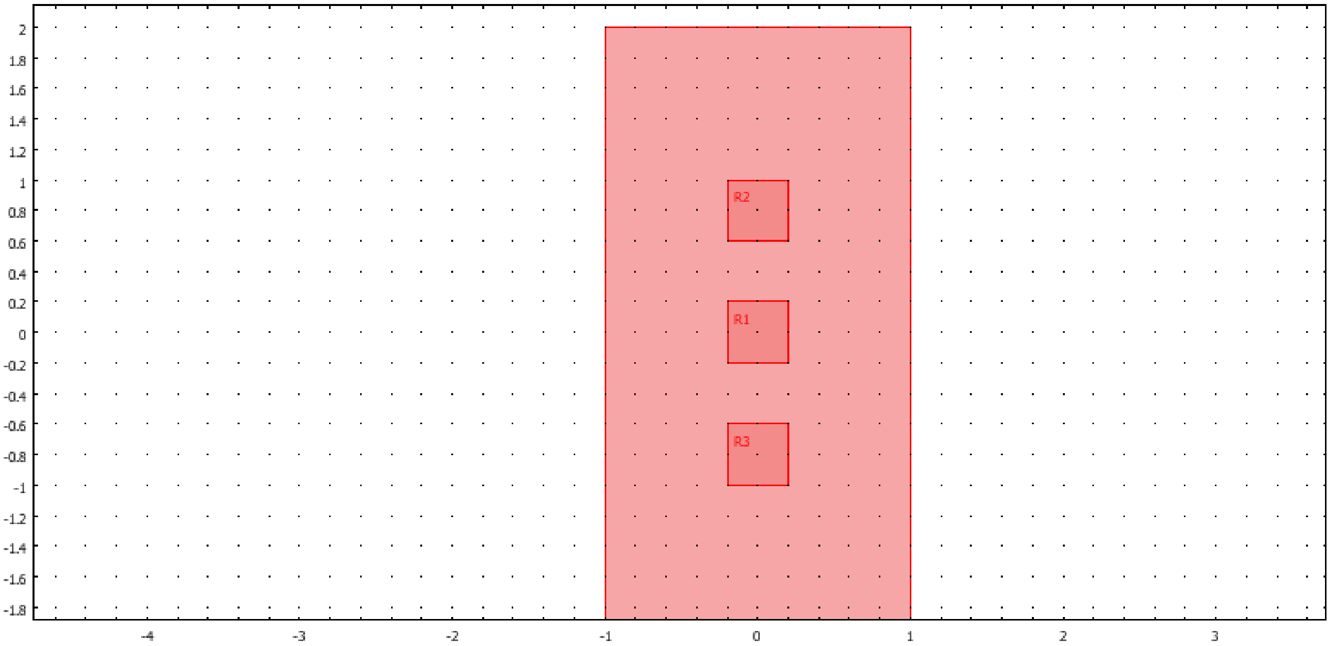
3. Constants

Name	**Expression**	**Value**	**Description**
Mpre	750000		Magnetization Of Magnet (A/m)

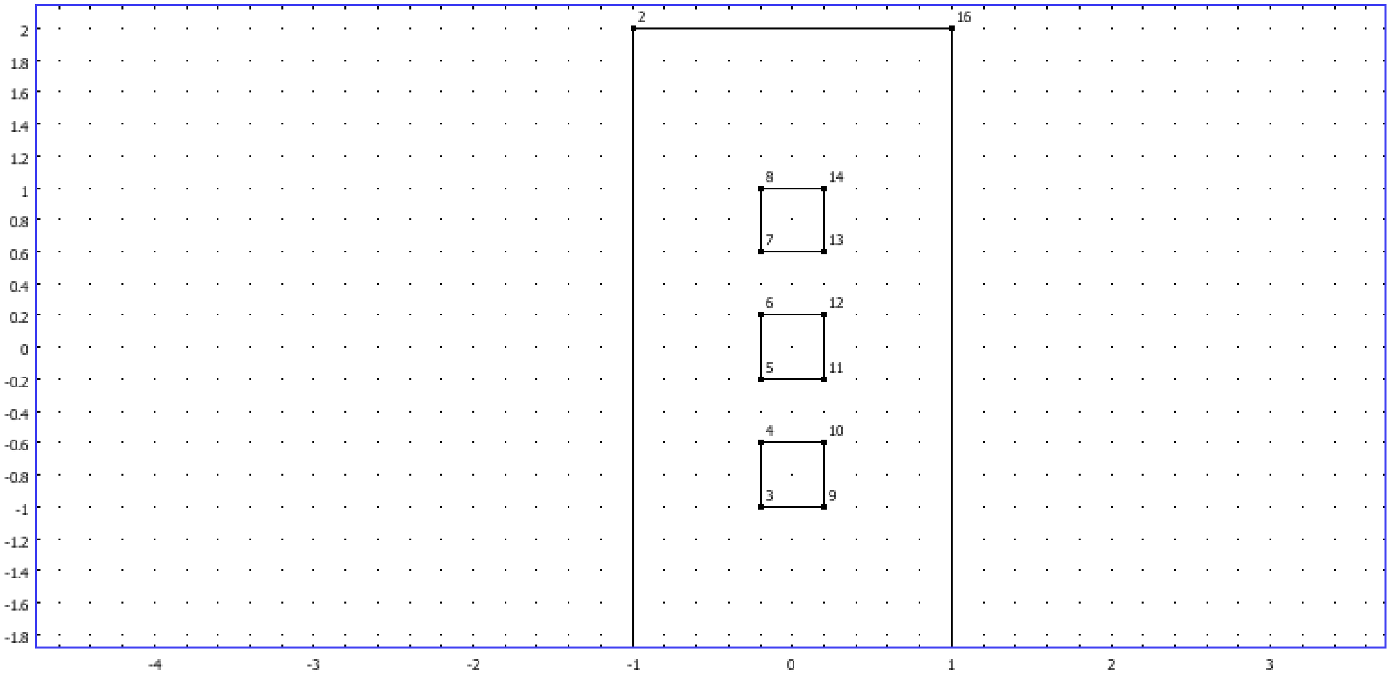
4. Geometry

Number of geometries: 1

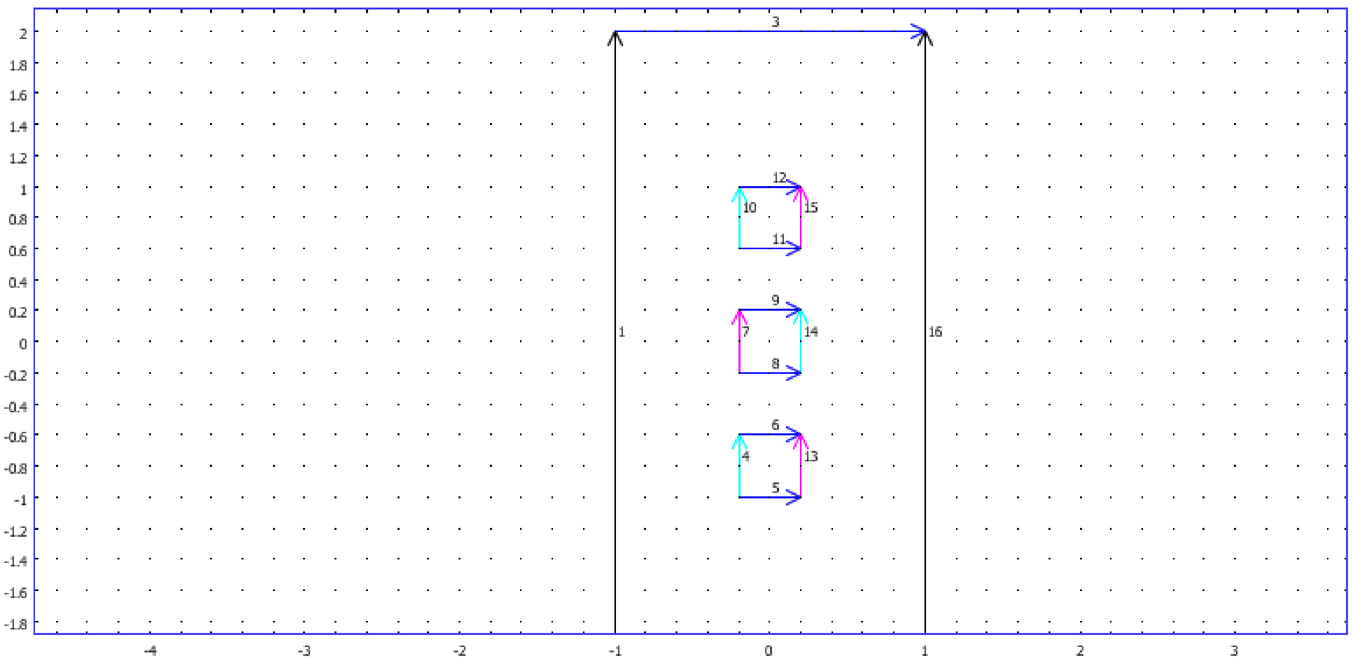
4.1. Geom1



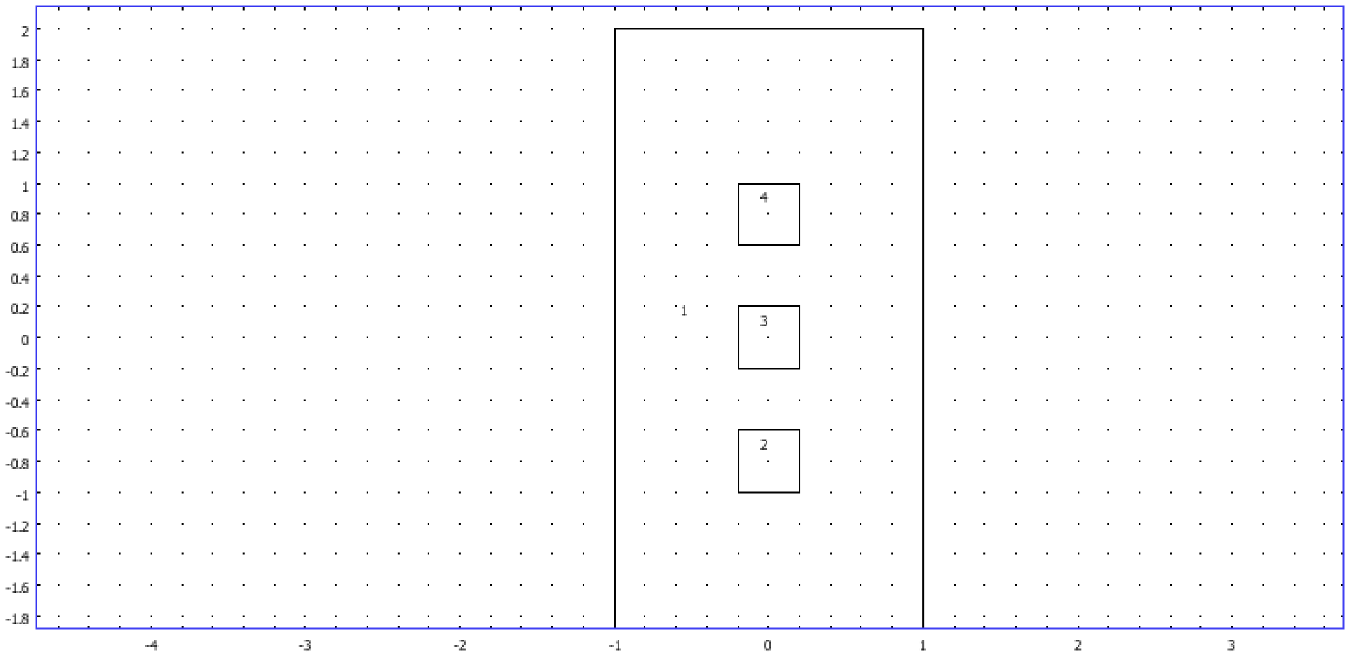
4.1.1. Point mode



4.1.2. Boundary mode



4.1.3. Subdomain mode



5. Geom1

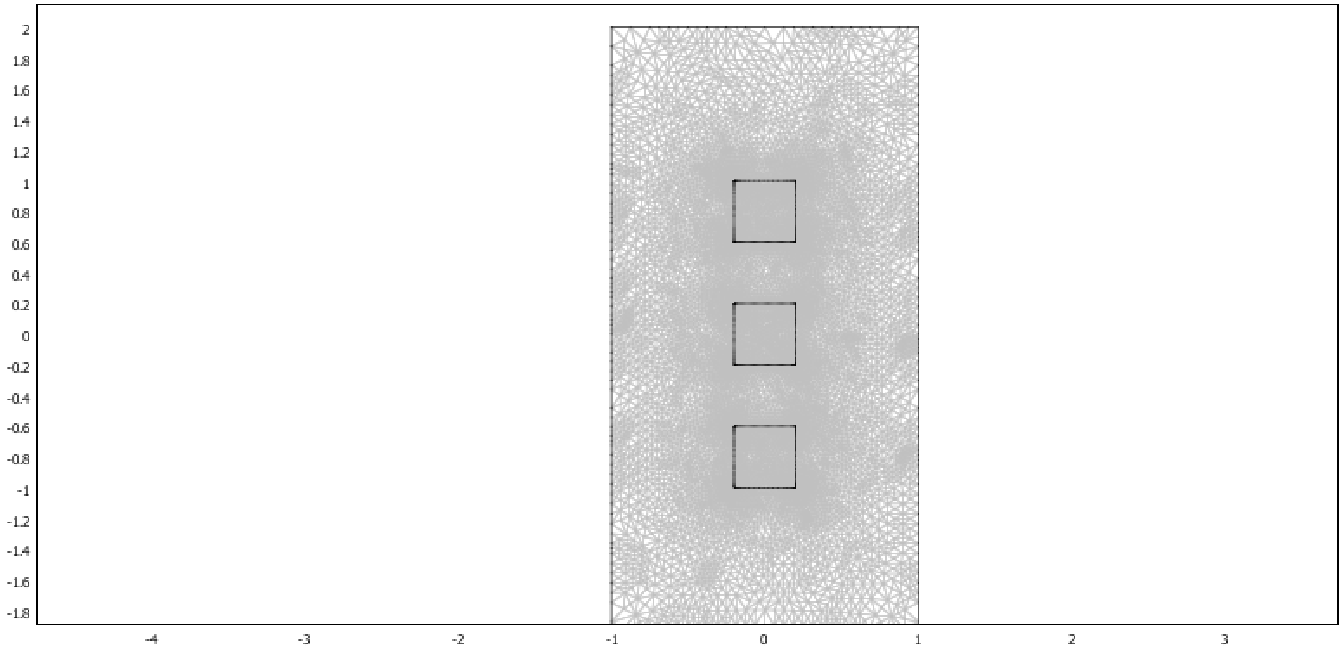
Space dimensions: 2D

Independent variables: x, y, z

5.1. Mesh

5.1.1. Mesh Statistics

Number of degrees of freedom	90432
Number of mesh points	22656
Number of elements	45121
Triangular	45121
Quadrilateral	0
Number of boundary elements	986
Number of vertex elements	16
Minimum element quality	0.583
Element area ratio	0



5.2. Application Mode: Magnetostatics (qa)

Application mode type: Magnetostatics

Application mode name: qa

5.2.1. Scalar Variables

Name	Variable	Value	Unit	Description
epsilon0	epsilon0_qa	8.854187817e-12	F/m	Permittivity of vacuum
mu0	mu0_qa	4*pi*1e-7	H/m	Permeability of vacuum

5.2.2. Application Mode Properties

Property	**Value**

Default element type	Lagrange - Quadratic
Analysis type	Static
Frame	Frame (ref)
Weak constraints	Off
Constraint type	Ideal

5.2.3. Variables

Dependent variables: Az, redAz

Shape functions: shlag(2,'Az')

Interior boundaries active

5.2.4. Boundary Settings

Boundary		1, 16	2-3, 5-6, 8-9, 11-12	4, 10, 14	7, 13, 15
Type		Magnetic insulation	Magnetic potential	Magnetic potential	Magnetic potential
Magnetic potential (A0z)	Wb/m	0	0	**Mpre**	**-Mpre**

5.2.5. Subdomain Settings

Subdomain		1	2	3	4
Relative permeability (mur)	1	{1,0;0,1}	{1,0;0,1}	**{murFe,0;0,murFe}**	**{Mpre,0;0,Mpre}**
magconstrel		$B = \mu_0 \mu_r H$	**$B = \mu_0 H + \mu_0 M$**	**$B = \mu_0 H + \mu_0 M$**	**$B = \mu_0 H + \mu_0 M$**
Magnetization (M)	A/m	{0;0}	**{Mpre;0}**	**{-Mpre;0}**	**{Mpre;0}**

6. Solver Settings

Solve using a script: off

Analysis type	Static
Auto select solver	On
Solver	Stationary
Solution form	Automatic
Symmetric	auto
Adaptive mesh refinement	On
Optimization/Sensitivity	Off
Plot while solving	Off

6.1. Direct (UMFPACK)

Solver type: Linear system solver

Parameter	**Value**
Pivot threshold	0.1
Memory allocation factor	0.7

6.2. Stationary

Parameter	**Value**
Linearity	Automatic
Relative tolerance	1.0E-6
Maximum number of iterations	25
Manual tuning of damping parameters	Off
Highly nonlinear problem	Off
Initial damping factor	1.0
Minimum damping factor	1.0E-4
Restriction for step size update	10.0

6.3. Adaptive mesh refinement

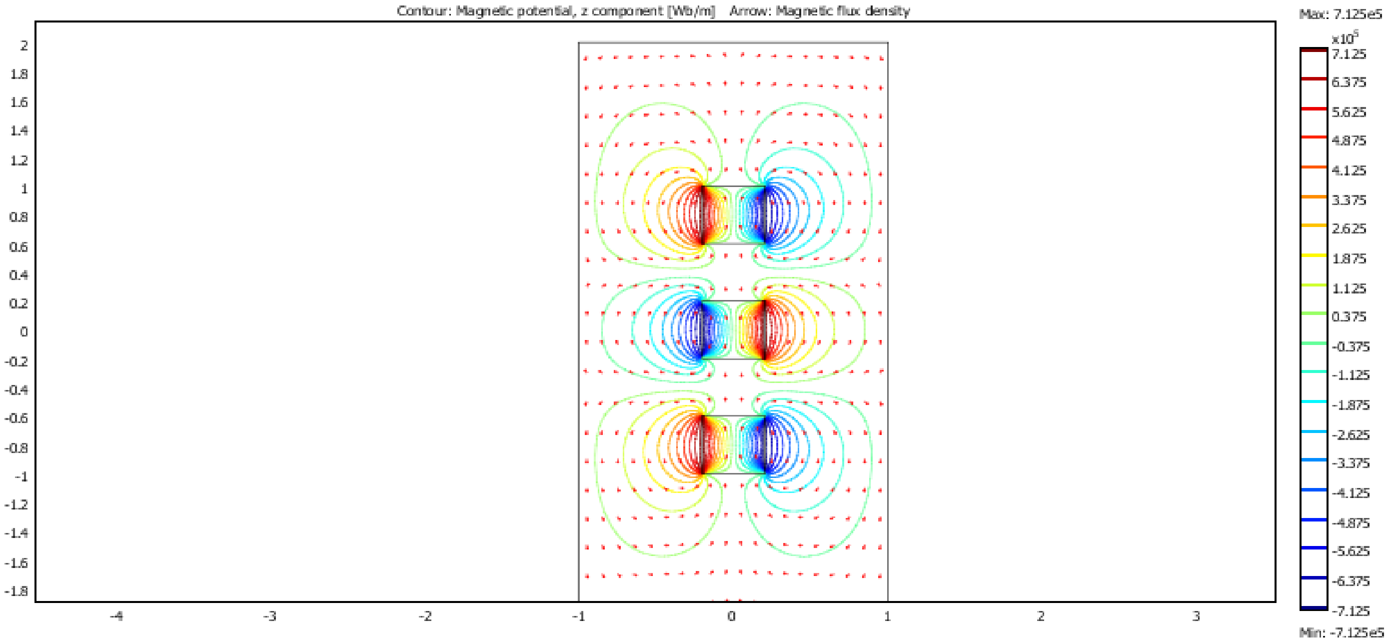
Parameter	**Value**
Use adaptive mesh refinement in geometry	Current geometry
Maximum number of refinements	2
Maximum number of elements	10000000
Refinement method	Longest
Residual order	0
Weights for eigenmodes	1
Scaling factor	1
Stability estimate derivative order	2

Element selection method	Rough global minimum
Increase number of elements by	1.7
Worst element fraction	0.5
Element fraction	0.5

6.4. Advanced

Parameter	**Value**
Constraint handling method	Elimination
Null-space function	Automatic
Automatic assembly block size	On
Assembly block size	1000
Use Hermitian transpose of constraint matrix and in symmetry detection	Off
Use complex functions with real input	Off
Stop if error due to undefined operation	On
Store solution on file	Off
Type of scaling	Automatic
Manual scaling	
Row equilibration	On
Manual control of reassembly	Off
Load constant	On
Constraint constant	On
Mass constant	On
Damping (mass) constant	On
Jacobian constant	On
Constraint Jacobian constant	On

7. Postprocessing



8. Variables

8.1. Boundary

Name	Description	Unit	Expression
dVolbnd_qa	Volume integration contribution	1	1
Jsz_qa	Surface current density	A/m	unx * (Hy_qa_down-Hy_qa_up)-uny * (Hx_qa_down-Hx_qa_up)
unTx_qa	Maxwell surface stress tensor, x component	Pa	-0.5 * (Bx_qa_up * Hx_qa_up+By_qa_up * Hy_qa_up) * dnx+(dnx * Hx_qa_up+dny * Hy_qa_up) * Bx_qa_up
dnTx_qa	Maxwell surface stress tensor, x component	Pa	-0.5 * (Bx_qa_down * Hx_qa_down+By_qa_down * Hy_qa_down) * unx+(unx * Hx_qa_down+uny * Hy_qa_down) * Bx_qa_down

unTy_qa	Maxwell surface stress tensor, y component	Pa	-0.5 * (Bx_qa_up * Hx_qa_up+By_qa_up * Hy_qa_up) * dny+(dnx * Hx_qa_up+dny * Hy_qa_up) * By_qa_up
dnTy_qa	Maxwell surface stress tensor, y component	Pa	-0.5 * (Bx_qa_down * Hx_qa_down+By_qa_down * Hy_qa_down) * uny+(unx * Hx_qa_down+uny * Hy_qa_down) * By_qa_down
FsLtzx_qa	Lorentz surface force contribution, x component	Pa	-Jsz_qa * By_qa
FsLtzy_qa	Lorentz surface force contribution, y component	Pa	Jsz_qa * Bx_qa
normFsLtz_qa	Lorentz surface force contribution, cycle average, norm	Pa	sqrt(abs(FsLtzx_qa)^2+abs(FsLtzy_qa)^2)

8.2. Subdomain

8.2.1. Subdomain 1

Name	Description	Unit	Expression
curlAx_qa	Curl of magnetic potential, x component	T	Azy
curlAy_qa	Curl of magnetic potential, y component	T	-Azx
dVol_qa	Volume integration contribution	1	1
Bx_qa	Magnetic flux density, x component	T	curlAx_qa
By_qa	Magnetic flux density, y component	T	curlAy_qa
Hx_qa	Magnetic field, x component	A/m	Bx_qa/(mur_qa * mu0_qa)
Hy_qa	Magnetic field, y component	A/m	By_qa/(mur_qa * mu0_qa)

mu_qa	Permeability	H/m	mu0_qa * mur_qa
muxx_qa	Permeability, xx component	H/m	mu0_qa * murxx_qa
muxy_qa	Permeability, xy component	H/m	mu0_qa * murxy_qa
muyx_qa	Permeability, yx component	H/m	mu0_qa * muryx_qa
muyy_qa	Permeability, yy component	H/m	mu0_qa * muryy_qa
Jpz_qa	Potential current density, z component	A/m^2	sigma_qa * deltaV_qa/L_qa
Jz_qa	Total current density, z component	A/m^2	Jpz_qa+Jvz_qa+Jez_qa
Q_qa	Resistive heating	W/m^3	Jz_qa * (vx_qa * By_qa-vy_qa * Bx_qa+deltaV_qa/L_qa)
W_qa	Total energy density	J/m^3	Wm_qa
dW_qa	Integrand for total energy	J/m^3	dVol_qa * W_qa
Wm_qa	Magnetic energy density	J/m^3	0.5 * (Hx_qa * Bx_qa+Hy_qa * By_qa)
FLtzx_qa	Lorentz force contribution, x component	N/m^3	-Jz_qa * By_qa
FLtzy_qa	Lorentz force contribution, y component	N/m^3	Jz_qa * Bx_qa
normFLtz_qa	Lorentz force contribution, norm	N/m^3	sqrt(abs(FLtzx_qa)^2+abs(FLtzy_qa)^2)
normM_qa	Magnetization, norm	A/m	sqrt(abs(Mx_qa)^2+abs(My_qa)^2)
normBr_qa	Remanent flux density, norm	T	sqrt(abs(Brx_qa)^2+abs(Bry_qa)^2)
normH_qa	Magnetic field, norm	A/m	sqrt(abs(Hx_qa)^2+abs(Hy_qa)^2)
normB_qa	Magnetic flux density, norm	T	sqrt(abs(Bx_qa)^2+abs(By_qa)^2)
normJ_qa	Total current density, norm	A/m^2	abs(Jz_qa)
Jvz_qa	Velocity current density, z component	A/m^2	sigma_qa * Evz_qa
Evz_qa	Lorentz electric field, z component	V/m	vx_qa * By_qa-vy_qa * Bx_qa

normEv_qa	Lorentz electric field, norm	V/m	abs(Evz_qa)
normv_qa	Velocity, norm	m/s	sqrt(abs(vx_qa)^2+abs(vy_qa)^2)

8.2.2. Subdomain 2-4

Name	**Description**	**Unit**	**Expression**
curlAx_qa	Curl of magnetic potential, x component	T	Azy
curlAy_qa	Curl of magnetic potential, y component	T	-Azx
dVol_qa	Volume integration contribution	1	1
Bx_qa	Magnetic flux density, x component	T	curlAx_qa
By_qa	Magnetic flux density, y component	T	curlAy_qa
Hx_qa	Magnetic field, x component	A/m	Bx_qa/mu0_qa-Mx_qa
Hy_qa	Magnetic field, y component	A/m	By_qa/mu0_qa-My_qa
mu_qa	Permeability	H/m	mu0_qa * mur_qa
muxx_qa	Permeability, xx component	H/m	mu0_qa * murxx_qa
muxy_qa	Permeability, xy component	H/m	mu0_qa * murxy_qa
muyx_qa	Permeability, yx component	H/m	mu0_qa * muryx_qa
muyy_qa	Permeability, yy component	H/m	mu0_qa * muryy_qa
Jpz_qa	Potential current density, z component	A/m^2	sigma_qa * deltaV_qa/L_qa
Jz_qa	Total current density, z component	A/m^2	Jpz_qa+Jvz_qa+Jez_qa
Q_qa	Resistive heating	W/m^3	Jz_qa * (vx_qa * By_qa-vy_qa * Bx_qa+deltaV_qa/L_qa)
W_qa	Total energy	J/m^3	Wm_qa

	density		
dW_qa	Integrand for total energy	Pa	dVol_qa * W_qa
Wm_qa	Magnetic energy density	J/m^3	0.5 * (Hx_qa * Bx_qa+Hy_qa * By_qa+Mx_qa * Bx_qa+My_qa * By_qa)
FLtzx_qa	Lorentz force contribution, x component	N/m^3	-Jz_qa * By_qa
FLtzy_qa	Lorentz force contribution, y component	N/m^3	Jz_qa * Bx_qa
normFLtz_qa	Lorentz force contribution, norm	N/m^3	sqrt(abs(FLtzx_qa)^2+abs(FLtzy_qa)^2)
normM_qa	Magnetization, norm	A/m	sqrt(abs(Mx_qa)^2+abs(My_qa)^2)
normBr_qa	Remanent flux density, norm	T	sqrt(abs(Brx_qa)^2+abs(Bry_qa)^2)
normH_qa	Magnetic field, norm	A/m	sqrt(abs(Hx_qa)^2+abs(Hy_qa)^2)
normB_qa	Magnetic flux density, norm	T	sqrt(abs(Bx_qa)^2+abs(By_qa)^2)
normJ_qa	Total current density, norm	A/m^2	abs(Jz_qa)
Jvz_qa	Velocity current density, z component	A/m^2	sigma_qa * Evz_qa
Evz_qa	Lorentz electric field, z component	V/m	vx_qa * By_qa-vy_qa * Bx_qa
normEv_qa	Lorentz electric field, norm	V/m	abs(Evz_qa)
normv_qa	Velocity, norm	m/s	sqrt(abs(vx_qa)^2+abs(vy_qa)^2)