ANALYSIS OF OPTIMUM COIL PARAMETER OF PERMANENT MAGNET GENERATOR FOR ENERGY HARVESTING APPLICATION

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A report submitted in partial fulfillment of the requirements for the degree of Electrical Engineering in Power Electronic and Drive

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ABSTRACT

With the increasing demand of electricity all around the globe, the importance of portable electrical energy supply cannot be taken lightly. As we know, electricity is very important to us nowadays. Our daily life depends on electric-powered devices. Thus, a portable energy source seems like the great solution to the problem. This is where this project becomes handy. In this project, a permanent magnet generator (PMG) is designed for motion energy harvesting application. The harvesting mechanism was driven by human motion as it can be wear on and the energy that was produced will be stored into battery. The design process of the PMG for motion energy harvesting includes several steps. The design focused only on the optimizing coil parameter of the PMG. Firstly, the PMG are modeled by using GMSH software and analyzed using Finite Element Method. All data gained from the Finite Element Method are then analyzed to ensure that the PMG are able to produce the desired output. After the analysis, it was found out that the PMG is able to produce 50W of output power with certain setting of the coil parameter. Previously, a lot of energy harvester has been introduced such as solar panel, tidal harvester and wind harvester. This project is the new variation of energy harvester which uses the motion energy to generate electricity and it is hoped to help other researcher or provide useful guide to produce a much better portable energy harvesting device in the future.

ABSTRAK

Dengan pertambahan permintaan terhadap tenaga elektrik di seluruh dunia, keperluan terhadap punca tenaga elektrik mudah alih amat dititikberatkan. Seperti yang kita tahu, tenaga elektrik amat penting dalam kehidupan seharian kita. Kita bergantung kepada perkakasan yang menggunakan tenaga elektrik. Oleh itu, punca tenaga elektrik mudah alih adalah penyelesaian terbaik bagi permasalahan ini. Projek ini boleh membantu untuk menyelesaikan permasalahan ini. Dalam projek ini, penjana magnet kekal (PMK) telah direka untuk kegunaan penuaian tenaga gerakan. Mekanisma tuaian digerakkan oleh pergerakan manusia kerana peranti tersebut boleh dipakai dan tenaga yang terhasil akan disimpan didalam bateri. Proses mereka PMK untuk kegunaan penuaian tenaga gerakan dijalankn melalui beberapa langkah. Pertama sekali, PMK direka menggunakan perisian GMSH dan dianalisis menggunakan kaedah unsur terbatas. Kesemua data yang diperoleh dari kaedah unsur terbatas kemudiannya dianalisis untuk memastikan PMK berupaya menjana hasil yang dikehendaki. Setelah melakukan analisis, didapati bahawa PMK berupaya menjana 50W kuasa melalui penyesuaian tertentu terhadap parameter gegelung. Sebelum ini,banyak penuai tenaga telah diperkenalkan seperti panel solar, penuai air pasang, dan penuai angin. Projek ini adalah variasi penuai tenaga dimana ia menggunakan tenaga gerakan untuk menjana elektrik and diharapkan supaya projek ini mampu membantu penyelidik dan memberi bimbingan untuk menghasilkan penuai tenaga yang lebih baik di masa hadapan.

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CHAPTER 1

INTRODUCTION

1.1 Project Background

Electrical energy is a form of energy that can be generated by using generator. The generator converts mechanical energy to electrical energy. The generator was first discovered by the famous Michael Faraday in 1831 based on the principle of electromagnetic induction. While the conventional generator uses petroleum and gas to generate electricity, it has become a major concern to know that the supply for the essential ingredients in conventional electrical generators are depleting. Petroleum reserve that exists on earth was expected to run out in the next 50 years.

In a modern fast moving world, researchers have put a lot of energy and effort to overcome the problem of increasing electrical tariff and knowing the fact that the electrical energy supply will run out in line with the last consume of petroleum supply. A lot of ways to overcome this problem has emerged. Among them are the generation of electricity from solar, wind, thermal and etc. The latest technology to be implemented to generate electricity is by using kinetic energy from any moving body. The generation technique was called motion energy harvesting.

Human being is subjected to moving since we were born until the end of our lifetime. Human move to work, get to another place and to communicate. By implementing the dynamic of human movement into the motion generator we can generate electrical energy simply by manipulating the motion energy created when we are moving. This type of generation is suitable for small power application.

To generate energy that produces high output, the generator needs an external force or a 'prime mover' acting as a shaft to move the rotor. This prime mover is connected to a pendulum to act as a motion harvester since a pendulum is a very conventional and easier method for this task.

1.2 Problem Statement

With the depletion of petroleum and gas which is the main source of electrical power generation, researcher has come out with new way to generate electrical power. This includes harvesting of free and renewable source of energy that can last for a long period of time. One of the famous renewable energy is the solar energy but implementation of photovoltaic cell is very expensive. So, researcher have move on to a new energy source which are free and much cheaper to realization. Motion energy can be implemented on any moving body and this means anything that moving. As we know, energy cannot be generated by its own. It can only be converted from one energy to another. Thus, it is a literally a waste of energy when people move around without knowing that they can actually generate power from just walking down the street or doing house chores.

In the future, all devices were expected to be powered by electrical power. As we can see in this millennium, the electricity and human cannot be separated. Electricity is essential to human as the entire world runs on it. This goes to the small and portable gadget. The main source of power for these small and portable gadgets is battery. Even though battery seems to be the ideal source of energy to empower the gadget or other electrical device, it has its own drawback. The battery cannot last forever. As the electrical charge inside it runs out, the battery must be replaced with a new one. This is applied to a non-rechargeable battery. As for the rechargeable battery, a huge time must be spent to charge the battery to the full until it can be used again.

This energy harvester device proposes a portable mechanism so that it can be carried anywhere. This energy harvester gives an output of 50W which is very suitable for low power application such as lighting, radio, charger and small power fan. This motion energy harvester has an output of 24V and 2A current which is stored inside two 24 volt batteries connected to the generator.

1.3 Objectives

The main aim of this project is to design a portable generator for energy. The performance of the generator design is analyzed. The following objectives are considered for this project:

a) To simulate and propose the design of generator for 50W motion energy harvester
b) Analysis the output power of the generator for motion energy harvester

1.4 Scope of Work

This project covers the scope of designing the permanent magnet generator as the device to harvest the motion energy and convert it to electrical energy. The generator then, are be examine and analysis. The result of the analysis is be computed.

This project can be divided into several parts or stages. The first is to study the basic principle of the Permanent Magnet Generator (PMG). The next step is to develop, design and analyze the PMG based on the best design computed. All the results of the analysis are computed to propose the best design for the generator for motion harvesting.

The limitation for this Final Year Project is only the design, analysis and proposal for the generator of the motion harvesting are done which is using advanced software tools such as GMSH software for finite element analysis, Origin8 for data computation and Solidworks for modeling the design. Others limitation is the study for mechanical elements such as stress and tension are not included. The fabrication process are also postponed because of the fabrication process requires high resources.

1.5 Report Outline

This thesis consists of 5 chapters. The first chapter covers the introduction, problem statement and the objective of this project. The scope of study and report outline also included in this chapter.

The second chapter stressed out on the overview of electrical energy generation from renewable source and evolution of energy harvesting in Malaysia. It also emphasize on the new motion harvesting principles. Besides, chapter two will also state the overview of energy harvesting device that been proposed and the overview of related published result of energy harvesting device.

The next chapter is the methodology which explains in detail the procedures and steps for this research and project. Design and simulation software which are used to complete this project also explained in this chapter.

The fourth chapter will be discussing about the result which is the model of the energy harvesting device. The generator structure will also be discussed. Lastly, the fifth chapter will be a conclusion for the project. A suggestion and recommendation was presented as guidelines for other researcher in future.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview of Electrical Energy Harvester from Renewable Source

This chapter will be discussing about the overview of electrical energy harvester from renewable source such as solar, wind, geothermal, and ocean. Besides that, basic operation of permanent magnet generator, overview of the energy harvesting device and the related result by other research will also be discussed.

2.1.1 Solar

The sun, as we know it is our nearest star. Without it, life would not exist on this planet. The sun's energy was harvested every day in many ways. For example, when we hang our laundry outside to dry in the sun, we are using the sun's heat to do work that is drying our clothes. All plants use the sun's light to make food using photosynthesis. Animals, in the other hand eat plants for food. And as we have learned, production the coal, oil and natural gas that we use today comes from decaying plants hundreds of millions of years ago. So, fossil fuels are actually sunlight stored millions of years ago.

Indirectly, the sun or other stars are our energy source. Even nuclear energy comes from a star because the uranium atoms used in nuclear energy were created in the fury of a nova – a star exploding. Among the most usage of solar energy is for the solar water heater. The solar water heaters were being used all over the United States in 1980s. It was proved to be a big improvement from coal-burning stoves and wood. We can use artificial gas made from coal to heat water, but it cost much more the price we pay for natural gas today.

Many houses used solar water heaters. As much as 30 percent of the homes east of Los Angeles, were equipped with solar water heaters, in 1897. Solar systems were used in Arizona, Florida and many other sunny parts of the United States as improvement to mechanical were made. Tens of thousands of solar water heaters had been sold on 1920s. However, large deposits of oil and natural gas were discovered in the western United States which makes these low cost fuels to replaced heaters from solar source.

But today, solar water heaters are making a huge comeback. There are more than half a million of them in California alone and they were used to heat water for use inside homes and businesses. Panels on the roof of a building, contain water pipes which when the sun hits the panels and the pipes, the sunlight warms them. That warmed water can then be used as home usage or even for swimming pool.

Figure 2.1 shows the solar water heater. The flat plat collector will collect the heat from the sun. Antifreeze liquid is used as the heat storage element. It then will be flow to the heat exchanger chamber. This chamber is used to contain the water to be supplied. The cold water will be supplied into the chamber. Heat exchange process wills occurs which cause the cold water to heat up according to the collected temperature from the flat plat collector. The heated water will be supplied to the house.

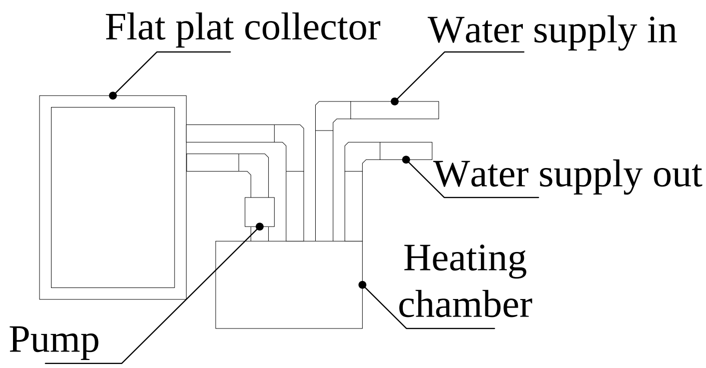


Figure 2.1: Solar Water Heater

Solar energy can also be used to generate electricity. Some solar power plants use a highly curved mirror called a parabolic trough to focus the sunlight on a pipe running down a central point above the curve of the mirror such as one in the California's Mojave Desert. The mirror focuses the sunlight onto strike the pipe, forcing the water to be steam. That steam can then be used to turn a turbine to generate electricity.

There are huge rows of solar mirrors in Mojave Desert arranged in what's called "solar thermal power plants" that use this idea to generate electricity for more than 350,000 homes. However, the problem with solar energy is that it works only when the sun is shining. Therefore, on cloudy days and at night, the power plants can't generate electricity. A "hybrid" technology has been developed so that during the daytime they use the sun. At night and on cloudy days they burn oil and natural gas to boil the water so they can generate electricity.

Another form of solar power plants to make electricity is called a Central Tower Power Plant, where sunlight is reflected off 1,800 mirrors circling the tall tower. The mirrors are called heliostats and it can move and turn to face the sun all day long. The reflected light is focused onto the top of the tower at the centre of the circle where a fluid is turned from liquid to steam. This steam can be used to turn the turbine and eventually generates electricity.

This solar harvesting technology was first built in the year 1980s and it was rebuilt in California as the experimental power plant given the name Solar II. This experimental power plant uses the sunlight to change heat into mechanical energy. This power plant was said to make enough electricity to power about 8,000 homes. Scientists say larger central tower power plants however can generate electricity for 50,000 up to 200,000 homes.

Figure 2.2 shows the solar thermal electricity circuitry. The parabolic trough like in the **Figure 2.3** will be used to collect the sun heat [9]. By using a curve-shaped glass or aluminum, the parabolic trough will focus the heat energy from the sun, towards the liquid container. The heated liquid then will be pumped to the heat exchanger chamber and turbine. The turbine will rotate the generator, thus producing electricity. Cooled water will be rotated back to the parabolic through or other chamber where other heating process using different source of heating, occur. The heated liquid will be channeled back to the turbine.

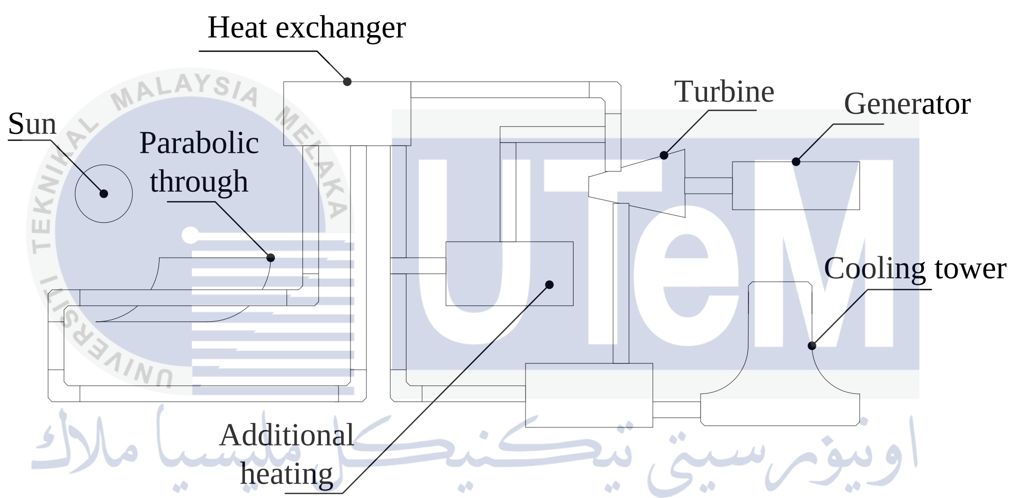


Figure 2.2: Solar Thermal Energy Harvesting

Figure 2.3: Parabolic trough

We can also convert the solar energy directly to generate electricity using solar cells. Solar cells or called photovoltaic cells or PV cells in short as shown in **Figure 2.4**. It can be found on many appliances as small as calculators, even on spacecraft. They were first developed in the 1950s for use on U.S. space satellites. They are made up of silicon, a special type of melted sand. Individual solar cells are arranged together in a module and then, these modules are grouped together in an array. Some of these arrays are set on special tracking devices to follow sunlight during the day to optimize the process of solar energy harvesting.

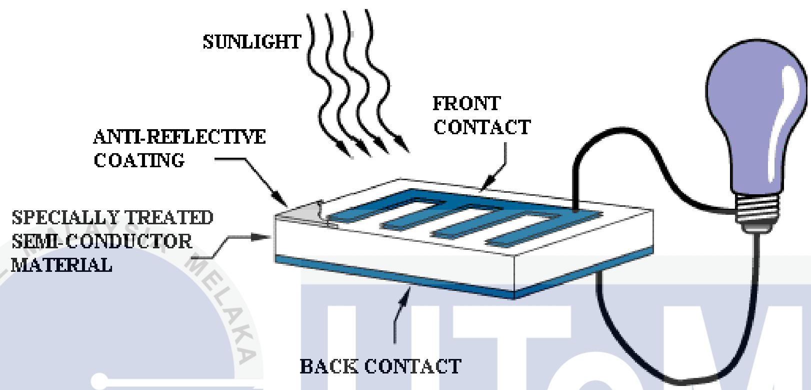


Figure 2.4: Build up of PV cells

The electrical energy generated from solar cells can be used directly in a home for lights and other appliances. Besides that, we can store solar energy in batteries to light a roadside billboard at night or for an emergency roadside cellular telephone when no telephone wires are around. PV cells have been installed in experimental cars which convert sunlight directly into energy to power electric motors on the car.

Figure 2.5 shows the process of solar energy harvested by using solar panel or photovoltaic (PV) cells. When sunlight strikes the solar cell, electrons are knocked loose. They move toward the treated front surface. An electron imbalance is created between the front and back. When the two surfaces are joined by a connector, a current of electricity occurs between the negative and positive sides. The current are fed to the controller to be stored using battery or inverted to AC power using inverter.

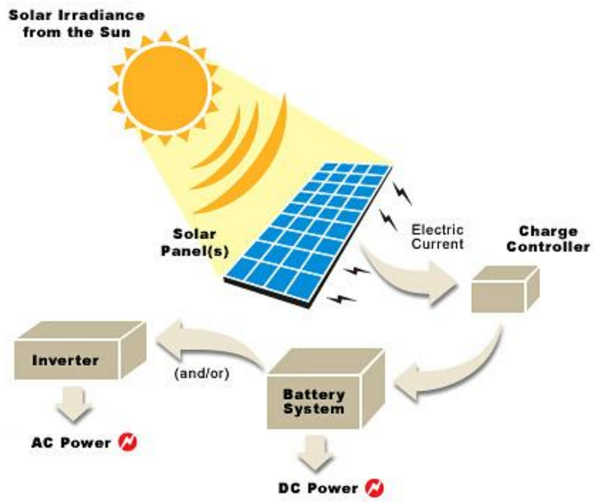


Figure 2.5: Solar energy harvesting

2.1.2 Thermal

From the first creation of the Earth, the geothermal has been existed. "Geo" in the geothermal means earth, and "thermal" means heat. Thus, geothermal means earth-heat. Below the top layer of the mantle or the Earth crust is a hot liquid rock called magma. The crust of the earth situated on this liquid magma mantle. This magma, when it breaks through the surface of the earth in a volcano called lava. 100 meters journey below the earth crust, the temperature of increases about 3 degrees Celsius. For, 10,000 feet below ground, the temperature of the rock will be hot enough to boil water.

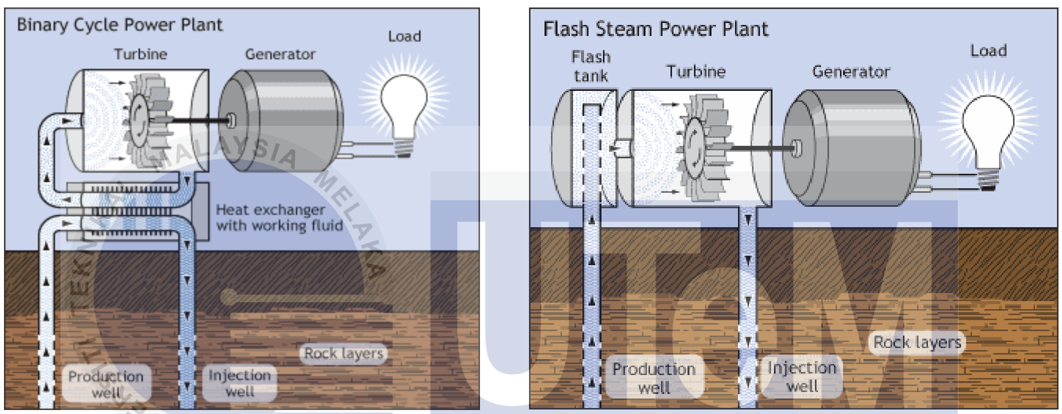
Deep under the surface, underground water sometimes makes its way close to the hot rock and turns into boiling hot water or into steam. The hot water can reach the temperatures of more than 148 degrees Celsius which is hotter than boiling water (100 degrees Celsius). This water does not turns into steam because it has no contact with the air in the surrounding. When this hot water comes up through a crack in the earth, it is called hot spring. Sometimes it explodes into the air as a geyser. The Paleo-Indians used hot springs in for cooking thousands of years ago. In other places around the world, people used hot springs for a place to joy and resting. The Romans built elevated buildings to enjoy hot baths while the Japanese have enjoyed natural hot springs for hundreds of years.

Nowadays, people use this geothermally heated hot water for swimming pools and in spa. The hot water from below the ground can also be used to warm buildings up to grow plants and vegetables indoor. In San Bernardino, in Southern California, hot water from below ground is used to provide heat to the buildings during the winter. Miles of insulated pipes were used to carry the hot water to dozens of public buildings. Animal shelters, retirement homes, state agencies, a hotel and convention center are some of the buildings which are heated using this method. Steam or hot water from underground can also be used to generate electricity using a geothermal power plant. Holes are drilled into the ground and pipes lowered into the hot water so that the hot steam or water comes up through these pipes from underground.

A geothermal power plant is like a regular power plant except that it has no fuel that was burned to heat water into steam. The hot water or steam in a geothermal power plant is heated by the earth. Then, it goes into a special turbine where the turbine blades spin and the shaft from the turbine is connected to a generator to generate electricity. The steam then gets cooled off in a cooling tower. When the steam or hot water was cooled off from the cooling process, a white smoke alike substance will appear. The cooled water can then be pumped back below ground to be reheated by the earth. This will ensure that the harvesting of geothermal energy can be continued.

Inside the power plant, hot water flows into turbine and out of the turbine. The cycle turns the generator, and the generated power goes out to the transformer and then to the transmission line that connect the power plants to our homes, school and businesses. The upper 10 feet below ground level stays the same temperature, almost everywhere in the Earth that is between 10 and 16 degrees C. In a basement of a building or in a cavern underground the temperature of the area is almost always cool. Heat pump system can be used to supply the heat to these underground building from hot steam source. The pipes of the pump system are buried near the building. Inside these pipes a fluid, like the antifreeze in a car radiator is circulated.

Thermal energy can be harvested using binary cycle and flash stem power plan. Both use the same source of energy which is the geyser which was among the free, renewable energy found on earth as shown in **Figure 2.6**. Production well will collect the hot water steam from the geyser. With binary cycle, the heat exchanger will be used to transfer the heat energy from the steam to the turbine while in flash steam, the hot steam will be used solely without other heat exchanger element. The turbine will be connected to the generator which when the turbine rotates, the generator will be able to produce electricity.



(a) (b)

Figure 2.6: Binary cycle power plant (a) and Flash steam power plant (b)

2.1.3 Wind

Wind can be used to do work. The kinetic energy of the wind can be changed into other forms of energy, either mechanical energy or electrical energy. When a boat lifts a sail, it is using wind energy to push it through the water. This is one form of work. Farmers have been using wind energy for many years to pump water from wells using windmills. In Holland, windmills have been used for centuries to pump water from low-lying areas. Wind is also used to turn large grinding stones to grind wheat or corn, just like a water wheel is turned by water power.

Today, the wind is also used to make electricity. Blowing wind spins the blades on a wind turbine just like a large toy pinwheel. This device is called a wind turbine and not a windmill. A windmill grinds or mills grain is used to pump water as shown in **Figure 2.7**.

Figure 2.7: Conventional wind energy harvesting

The blades of the turbine are attached to a hub that is mounted on a turning shaft as shown in **Figure 2.8**. The shaft goes through a gear transmission box where the turning speed is increased. The transmission is attached to a high speed shaft which turns a generator that makes electricity. If the wind gets too high, the turbine has a brake that will keep the blades from turning too fast and being damaged.

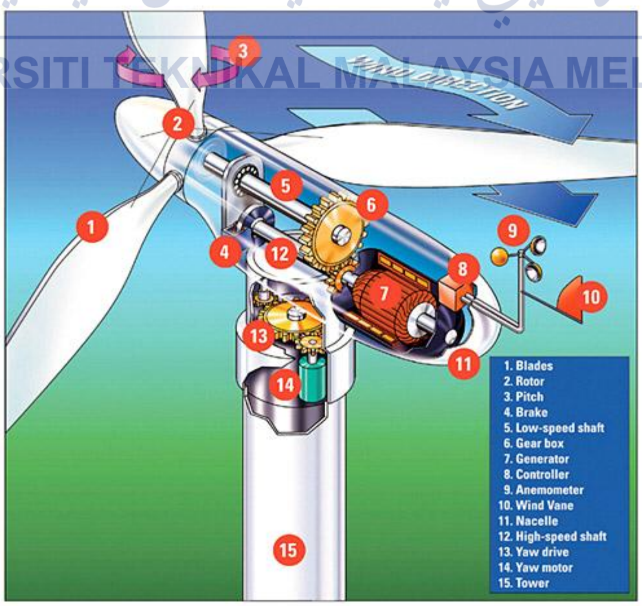


Figure 2.8: Parts inside the wind turbine

In order for a wind turbine to work efficiently, wind speeds usually must be above 12 to 14 miles per hour. Wind has to be this speed to turn the turbines fast enough to generate electricity. The turbines usually produce about 50 to 300 kilowatts of electricity each. You can light ten 100 watt light bulbs with 1,000 watts. So, a 300 kilowatt (300,000 watts) wind turbine could light up 3,000 light bulbs that use 100 watts.

2.1.4 Ocean

The world's ocean may possibly at some point provide us with energy to power our residences and businesses. At this time, there are very few ocean energy power plants and most are fairly small. There are three basic approaches to tap the ocean for its energy. We can use the ocean's waves, we can use the ocean's high and low tides, or we can use temperature differences in the water. Kinetic energy is present in the shifting waves of the ocean. That energy can be used to power up a turbine. For example, the wave will goes up into a chamber. The mounting water forces the air out of the chamber. The moving air spins a turbine which can turn a generator. When the wave goes down, air flows through the turbine and back into the chamber through doors that are normally closed.

This is only one type of wave-energy system. Others actually use the up and down action of the wave to power a piston that moves up and down within a cylinder. That piston could also rotate a generator. Most wave-energy systems are very small. But, they can be used to power up a warning buoy or a small light house. A different form of ocean energy is known as tidal energy. When tides come onto the coast, they can be contained in reservoirs behind dams. Then when the tide declines, the water behind the dam can be let out similar to in a regular hydroelectric power plant. Tidal energy has been utilized since about the 11th Century, when small dams were built alongside ocean estuaries and small streams. The tidal water behind these dams was used to cycle water wheels to mill grain.

As a way for tidal energy to perform well, a large grows in tides were needed. An increase of a minimum of 16 feet among the low tide to high tide is required. There are just a couple of places where this tide change happens around the earth. Some power plants are already running using this idea. One plant in France makes sufficient energy from tides (240 megawatts) to power about 240,000 homes. This facility is known as the La Rance Station in France. It began generating electricity in 1966. It generates about one fifth of a standard nuclear or coal-powered power plant. It is over 10 times the power of the next largest tidal station in the world, the 17 megawatt Canadian Annapolis station.

2.2 Basic operation of Permanent Magnet Generator

The permanent magnet generator is the device used to converts mechanical energy to electrical energy, generally using electromagnetic induction. In this project, the conversion of mechanical energy to electrical energy will be done.

2.2.1 Faraday's Law

The Faraday Law state that the induced voltage $Vemf$ in any closed circuit is the same to the time rate of change of the magnetic flux linkage by the circuit and can be expressed as:

$$V_{emf} = -N\frac{d\emptyset}{dt} \quad [\text{V}] \qquad (1.0)$$

Where V_{emf} is voltage induced in [V], N is number of turns and Ø is flux through each turns in [Wb]. Thus change in the magnetic environment of a coil of wire will cause a voltage to be induced in the coil. The voltage generated is depending on the rate of flux change. The change could be produced by changing the magnetic field strength, moving a magnet toward or away from the coil. Since the permanent magnets are buried into the rotor, thus the rotating magnetic field concept was used in designing the permanent magnet generator.

2.2.2 Voltage generation

Based on the operation principle of electric machinery, the output power is proportional to the machine speed. Therefore, PMG is more preferable in high-speed operation due to its simple structure and high power density. The PMG will be applied in various fields such as electro-mechanical battery, wind generation and etc. This is advantageous as the usage of gearbox that will make the system more complex as well as reduce the shaft speed can be abandoned. Usually magnetic field of the PMG is produced by the rotor of the machine. Thus, prime mover is used to rotate the rotor that will cause rotating magnetic field in the stator. Since the coil of wire at stator yoke will cut this rotating magnetic field, this will cause an induced voltage as stated in Faraday's Law.

2.2.3 Losses Mechanism

Under alternating flux condition, the total iron loss can be divided into two component which are eddy current and hysteresis. The following are the explanation of the two losses.

i) Eddy current

Motions of the magnet past the stator core periodically tend to induce eddy current at the surface core. This will cause flux density variation and tend to produce non-sinusoidal waveform that leads to harmonic. Usually, eddy current losses are significant and maybe dominant in high speed generator.

ii) Hysteresis loss

When there is an alternating magnetic field applied to stator, the flux traces out a different path from the previous one it followed. The flux in the core assume zero initially. As the flux density increase for the first time (rotor slot perpendicular with the stator yoke), the flux in the core traces out path **a-b**. However, when the flux density decrease, flux in the core traces out path **b-c-d-e** and suddenly take path **e-f-b** when flux density increase again as shown in **Figure 2.9**. This mean the flux present in the core depend the previous history of the flux in the core. Thus, the resulting failure to follow the old flux path is called hysteresis. The point **a** in Figure 2.9 shows the initial condition of a flux density inside a ferromagnetic material. After the ferromagnetic material is magnetized, the density will rise to point **b**. Then, the ferromagnetic material is demagnetized, forcing the magnetic flux to reverse to point **c**. The ferromagnetic material then will be magnetized again until it reaches point **b**. A repeated action of magnetizing and demagnetizing of ferromagnetic material will eventually leads to hysteresis loss.

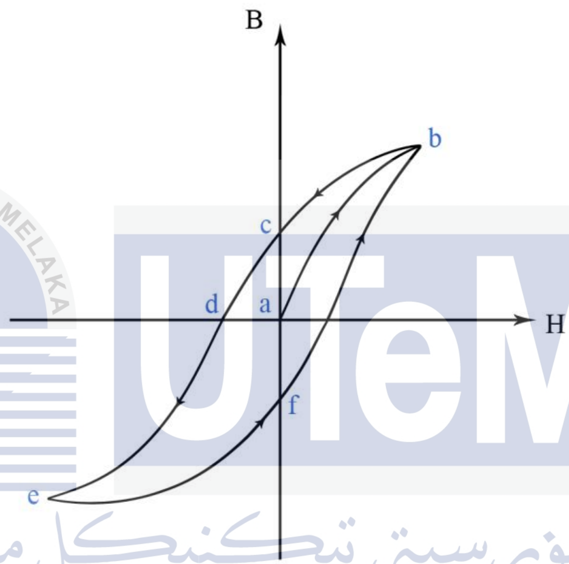


Figure 2.9: Graph of hysteresis curve

Another losses that occur in real PMG are copper losses and flux leakage. Copper losses are the resistive heating in the winding generator while flux leakage is fluxes which escape the core that contribute to self inductance in the winding PMG.

2.3 Overview of Energy Harvesting Device

This section will discuss about the overview of the energy harvesting device. The basic concept of the proposed energy harvester and the layout for the device are presented in this section. The previous work related to the energy harvesting device which has been developed by other researcher is also discussed in this section.

2.3.1 Basic Concept of Proposed 50W Energy Harvester

In this project, the energy harvesting device is expected to be portable. It was proposed that the energy harvesting device is made as pouch bag alike as shown in **Figure 2.10**. This energy harvesting device is able to generate a supply of 50 watt when activated. As stated before, the device manipulates the human motion to generate electricity.

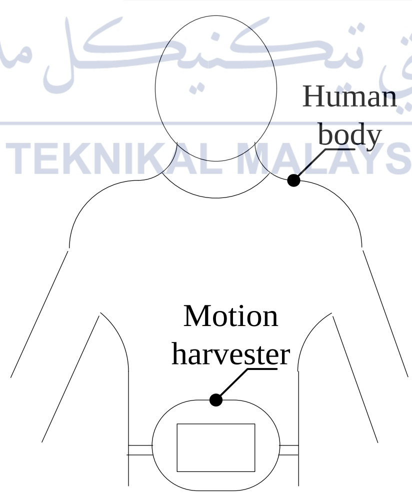


Figure 2.10: The application of the motion harvester

By referring to the figure above, we can see that the device is design so that it can be wear by the user. The device is attached to the wearer by using a harness and a simple bag. This is to ensure that the device moves together with the user movement. For example, when the user walks he generates vertical movement. This results in the vertical movement of the generator inside the device.

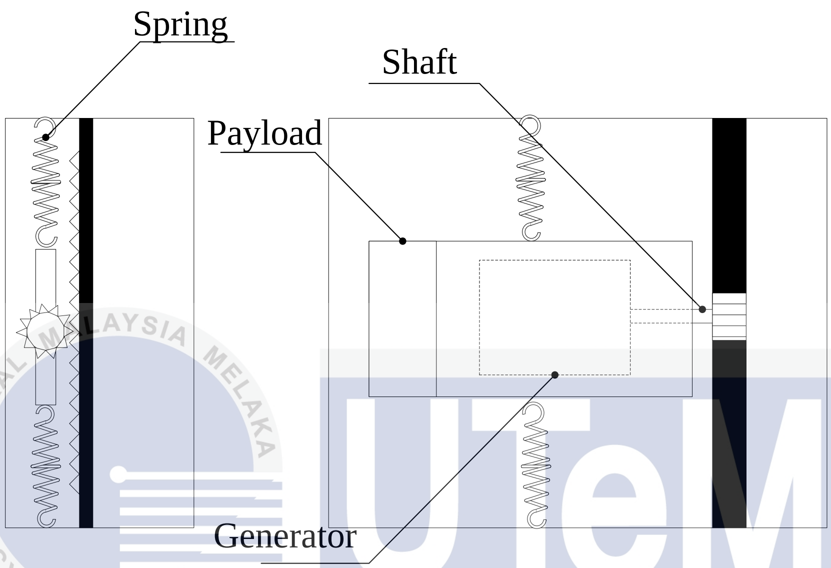


Figure 2.11: Motion harvester layout

Figure 2.11 shows the design of the motion harvester device. The device consists of the generator body which was attached to the spring. The purpose of the spring is to turn the generator to its original position when it was moved. It also reacts as a motion preserver which allows the generator to oscillate more when moved. This was helped by the payload which provide additional load to the generator.

2.4 Overview of Related Published Result of Energy Harvesting Device

Various experiment and result has been published for the motion energy harvesting device. A lot of ways can be used to harvest this type of energy. Firstly is the development of enhanced piezoelectric energy harvester induced by human motion [5]. This product is a development of a miniature size energy harvester to generate electricity using vibration which is caused by the human walking motion. It states that when we walk, a vibration will be formed. This motion can be harvested to generate electricity by using piezoelectric. **Figure 2.12** shows the piezoelectric energy harvester.

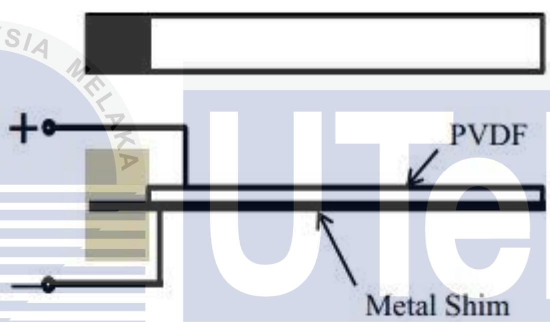


Figure 2.12: Piezoelectric energy harvester

By using this method, the energy can be harvested even when there is only small vibrations occur during the movement. This method can generate the maximum voltage of 6.3V. A large voltage can be generated continuously through the high frequency vibration. This will also be a drawback for the method. With high frequency vibration, human must be moving constantly, at a very fast pace. As human were entitled to tiredness, this motion harvester seems hard to employed.

The second method is a permanent magnet linear motion driven kinetic energy harvester [6]. Similar with the previous method, this method employ the use of permanent magnet to harvest motion energy into electrical generation as shown in **Figure 2.13**.

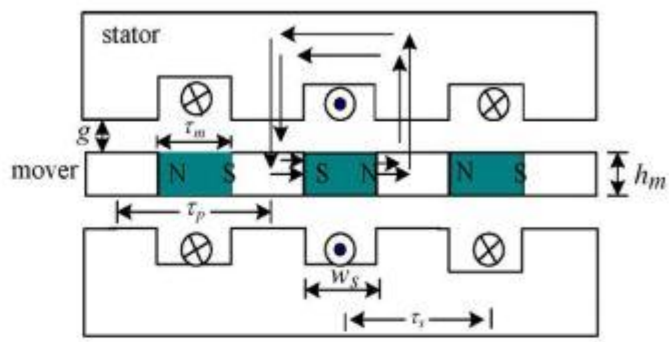


Figure 2.13: Permanent magnet linear motion harvester

The permanent magnet will move linearly along the axis. With the coil implanted on the stator of the device, it will induce the current by cutting the flux from the permanent magnet and thus, producing current. However, this is just a proof of concept done by the researcher which means the output is very low. Future research can be done to enhance the project.

The third method is a wearable piezoelectric rotational energy harvester [7]. This project consists of a pendulum swinging to harvest motion energy and generate electricity as shown in **Figure 2.14**. It use the concept of sensor in which when to body move, the pendulum inside the device will oscillate. This concept also has been used in the motion watch like the one developed by SEIKO company.

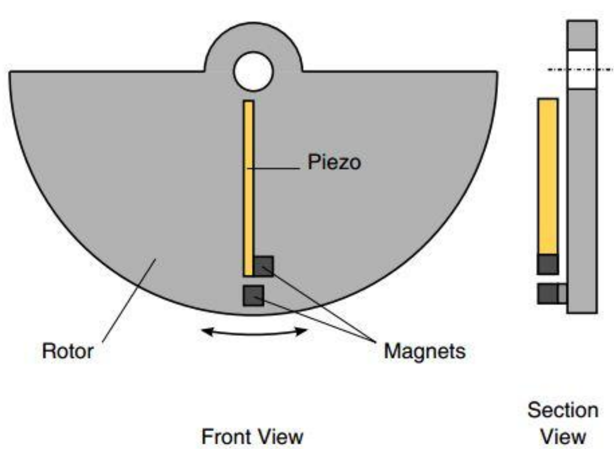


Figure 2.14: Rotational piezoelectric device

The harvester is less reliant on its positioning since it can function in a gravitational way, like a pendulum, as well as inertially. It allows rotational excitation all over its axis and linear excitation in two directions, making it proper for a human environment, where the orientation differs at random. The backlash for this project is that the experiments demonstrated that there are restrictions to the frequency up-conversion harvesting technique. In this case the piezoelectric beam was originally too rigid to allow good plucking and did not show any oscillation after actuation, which lead to a power output well below the capabilities of the technique.

Other motion energy harvesting that has been developed is a wearable system of micromachined piezoelectric cantilevers coupled to a rotational oscillating mass for on-body energy harvesting as shown in **Figure 2.15** [10]. This energy harvesting device applies small eccentric mass which portrays a hand watch movement to deflect the cantilevers mechanically to exert a low frequency motion to produce energy.

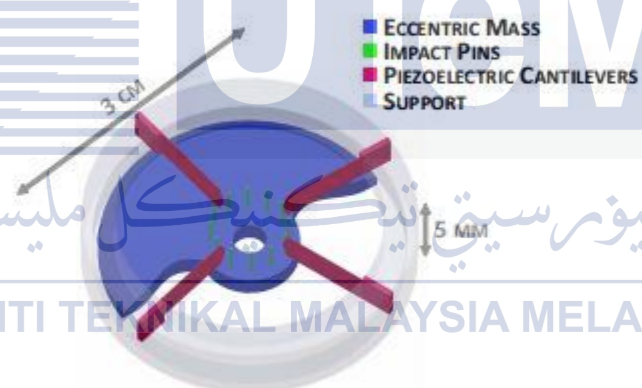


Figure 2.15: Micromachined piezoelectric cantilevers coupled to a rotational oscillating mass

The device will depends on the rotational direction of the eccentric mass. Since the piezoelectric cantilevers were attached to the eccentric mass, a slight rotational movement will deflect the cantilevers. The impact pins will block the movement of the cantilevers, hence enhancing the deflection. Since the piezoelectric can generate electricity, this seems to be very good energy motion harvester.

Another type of energy harvester is electromagnetic vibration energy harvester with non-linear vibration [11]. This type of energy harvester is very good to generate electrical energy from low frequency vibration with very less maintenance. The concept is shown in **Figure 2.16.**

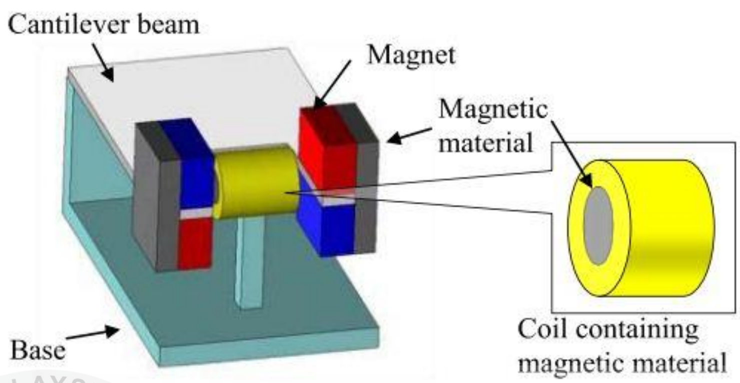


Figure 2.16: Concept of electromagnetic vibration energy harvester with non-linear vibration

The whole idea of this device is that the more changes of magnetic flux across the coil surface area, the more electromotive force are induced, thus generates more energy. The cantilever beam is attached with permanent magnet. If the cantilever beam moved due to the vibration from any source, the permanent magnet on the side will also move. The magnetic material will ensure the flux linkage path will always be in between both permanent magnets. Any flux that travels along the path will be induced by the coil, thus generating electricity.

CHAPTER 3

METHODOLOGY

3.0 Research Methodology

In completing this project, a few steps have been taken to ensure the swiftness of the project. The project uses the FEMAPH software to simulate and design the best machine to be selected as the generator. The first step in performing this final year project is by doing literature review for the project. Sufficient understanding is very important to ensure that the project runs well. Therefore, a literature review is a compelled way to ensure that the researcher have a good understanding on the project and have a picture of what the project covers. Research on related topic and field was done which includes journal, books and internet search.

The second step is the FEM training. As stated before, the FEM software was used to design the motor before it will be fabricated. The FEM software uses C language to model the stator and the rotor of the generator so that the design can follow the specification required. By using FEM, the size and measurement of the machine can be varied so that the result can be manipulated and the best design can be chosen.

Thirdly, the specification and limitation study is needed so that the project will never go out of the scope and the objective as stated in the Chapter 1. This specification and limitation study is based on the previous study. Besides, the specification and limitation study is used to plan on the structure of the harvester. The harvester must be in a good size so that it can be carry around without being a burden to its wearer. After that, the designing process is started by using FEM software, the best characteristic of generator to be implemented.

The analysis process comes after that. The analysis takes measure of the designed generator to check whether the designed is suitable to be proposed and implemented. The analysis was done with the use of FEM software by checking the flux linkage on the generator. The final procedure is to complete a technical report of the project. The report should contain the documentation of the project, the result, conclusion based on the project. The flowchart of completing this project is shown in **Figure 3.1**.

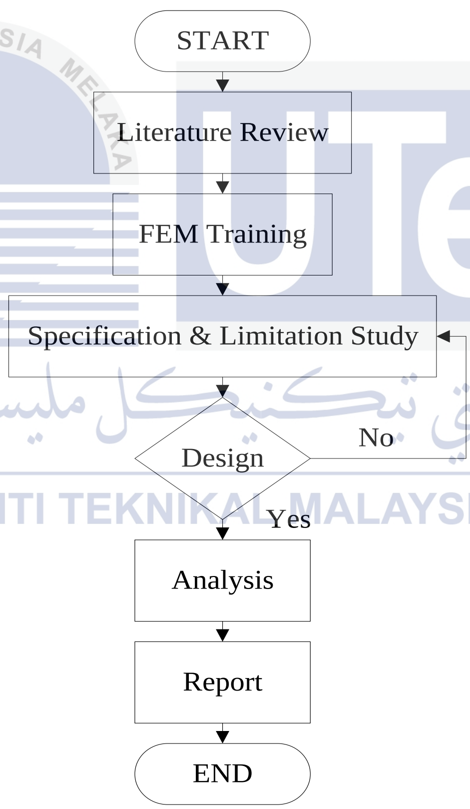


Figure 3.1: The flowchart of completing the project

3.1 Simulation Approach

For this project, the researcher use the Femaph software to do the designing process and the simulation purpose. By using Femaph software, the researcher can estimate the flux linkage of the machine, torque produce to determine the best design to be proposed for the energy harvester device.

The first step is the researcher can start to program the desired machine that is suitable with the application needed using Femaph. The program will be written in C language. The program will be saved in .geo file that is compatible with the software and can be open in Programmer's Notepad software.

After the program was done, the .geo file is imported to GMSH software. This is a well-known software for machine design purpose. This software is a 3D finite element grid generator with build in CAD engine and post-processor. The GMSH software will automatically calculate the nodal or mesh inside the machine structure as shown in **Figure 3.2**.

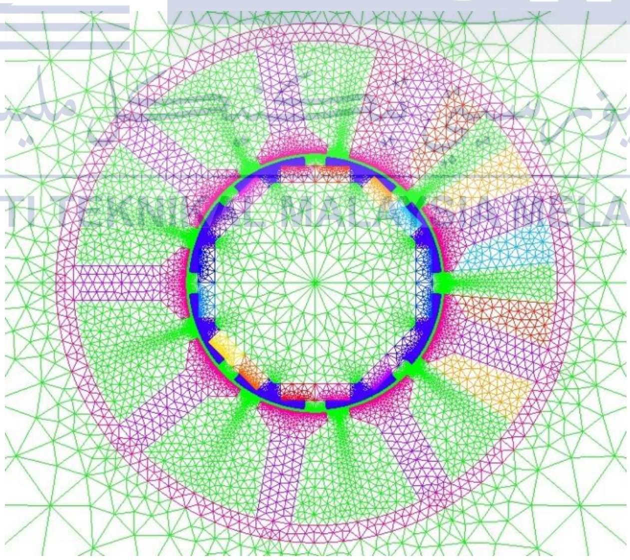


Figure 3.2: Mesh of Finite Element method

After the file was run, the mesh of the machine can be viewed to determine any misshape on the machine's structure. The mesh of the machine is saved afterward to .msh file.

Then, the command prompts are executed. The declaration of the address of the saved .msh file was done. Then, the .geo file is executed with gmsh2aph command. This is to determine flux density as shown in **Figure 3.3**, and flux linkage as shown in **Figure 3.4**. The relation of torque generated with the amount of current supplied can be analyzed. This process is repeated until the design satisfied the specification needed.

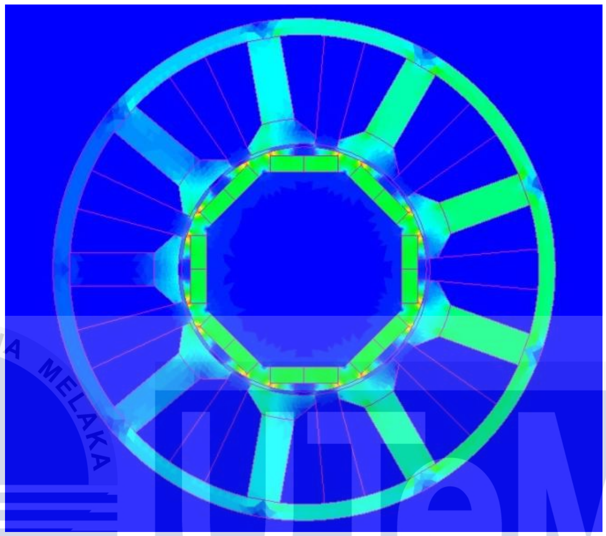


Figure 3.3: Flux density of the generator

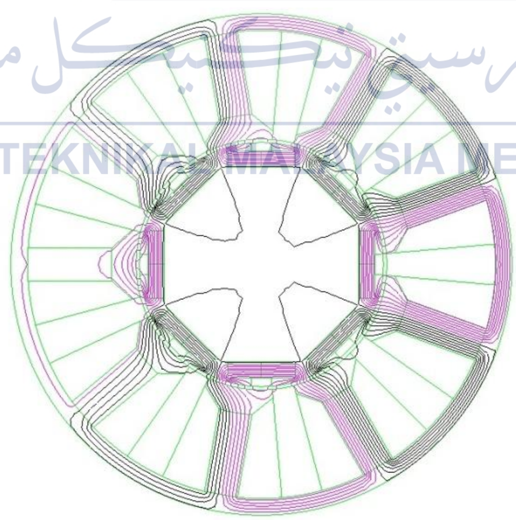


Figure 3.4: Flux linkage of the generator

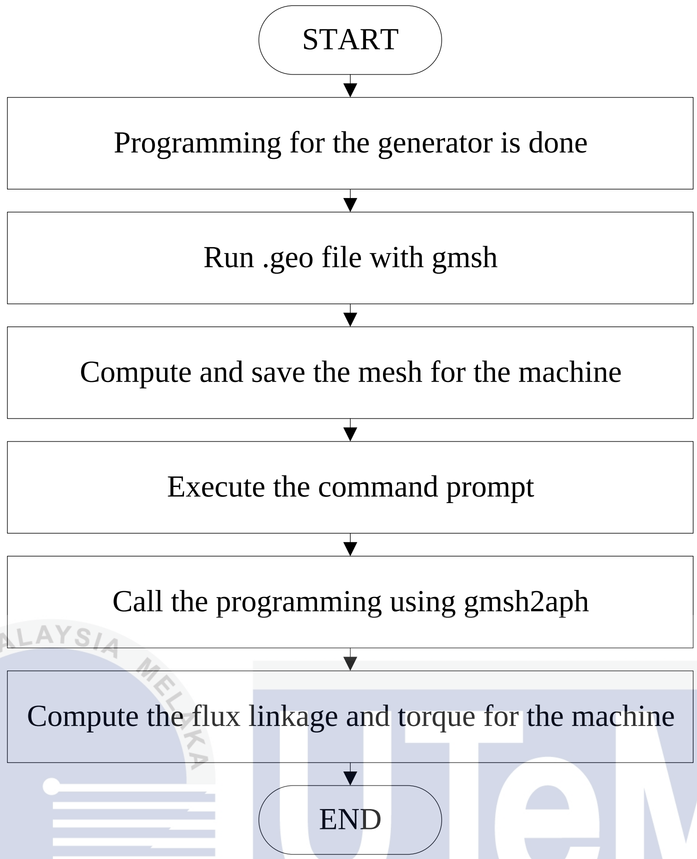


Figure 3.5: The flowchart of designing using Femaph

The Femaph software is able to compute the flux linkage of the generator which is in sine waveform. Thus the area under graph are determined to find the back emf of the generator using integration method. To do the analysis, the output voltage of the generator, V_{out} was determined by using formula (2.0);

$$V_{out} = \Phi * 4.44 * 3 * Z_{length} * \omega \qquad [V] \qquad (2.0)$$

Where Φ is the average flux linkage, Z_{length} is the generator thickness and ω is speed in rad/s.

3.2 Analysis Parameter

The PMG is expected to be small in size. It was designed to be as small to be fit into a pouch bag. This is to make the PMG to be convenient to be carried anywhere. The PMG can be attached to human body which will provide the motion when it is moving. This PMG is designed using hollow rotor model with coil size of 0.35mm.

From the structure in **Figure 3.6**, it is presumed that the generator moves by a shaft that is connected with a gear. The gear then is connected to the shaft of the rotor which will rotate and generates electricity from human body movement. The design of the generator structure was taken from other research which has been proven the best to produce a high flux linkage and output power [8].

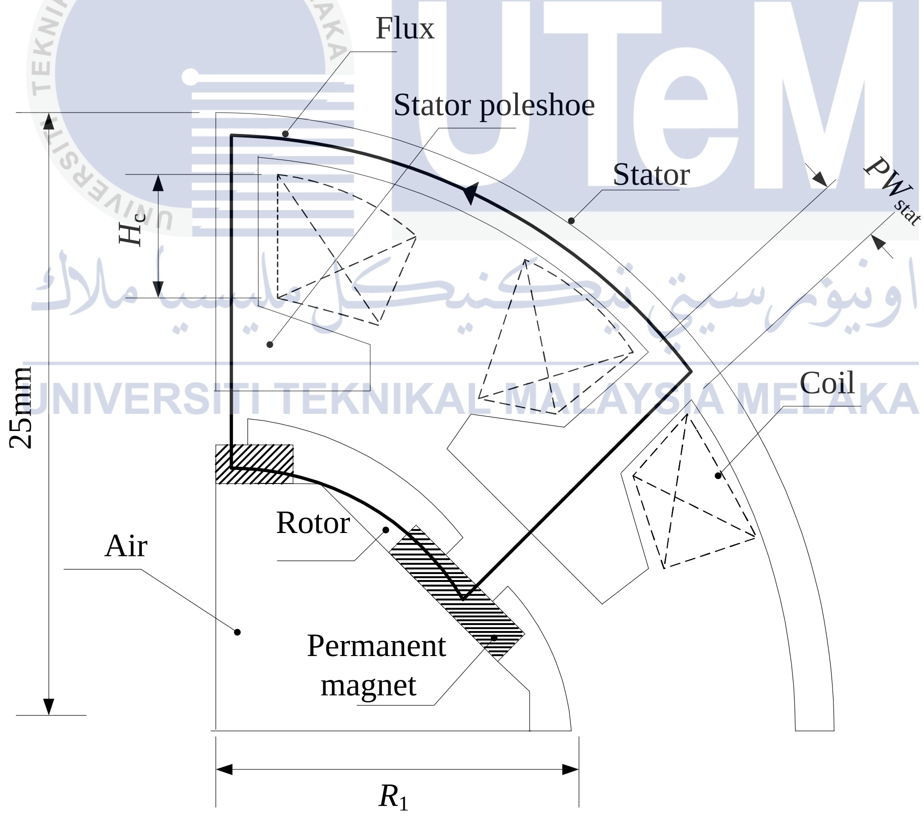


Figure 3.6: The generator structure

Table 3.1: Elements of generator

Elements	Value (mm)
Stator pole width, PW_{stat}	2, 2.5, 3, 3.5
Coil Height, H_c	4, 6, 8, 8.9
Rotor Radius, R_1	Varied with H_c
Permanent magnet	4 X 2

The analysis was done with a several steps to ensure that the output flux linkage is slightly similar to the desired value. The steps can be referred to **Figure 3.7**. The first step was to prepare the job list for the mesh to automatically calculate the flux linkage of the designed generator. The pole width of the stator was varied from 2 mm, 2.5 mm, 3 mm up to 3.5 mm. Then, the mesh was run with coil height, Hc varied from 4 mm, 6 mm, 8 mm, and 8.9 mm. All elements are tabulated in **Table 3.1**. After that the flux linkage was computed with the current varied of 2A and 4A. The output voltages were generated with the simulation. The output voltage is computed in proportional to the speed of the generator.

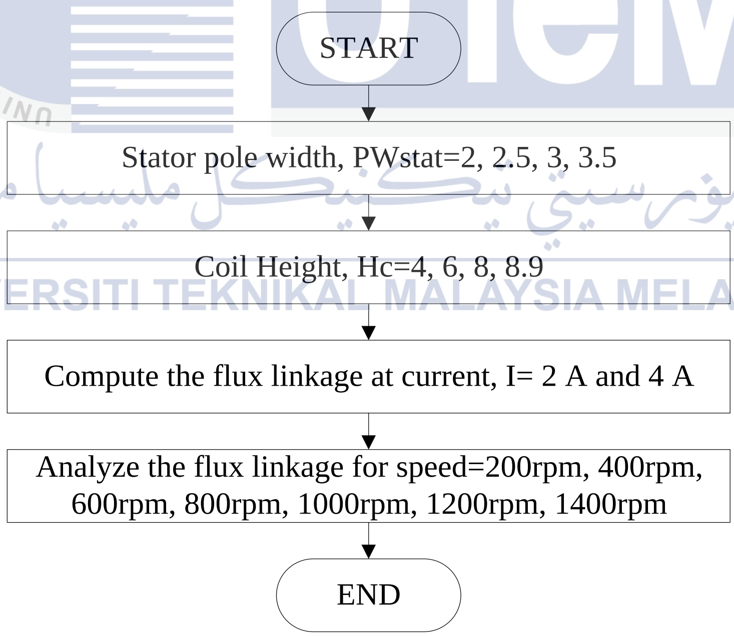


Figure 3.7: Flowchart of analysis parameter

3.3 Design Specification

The generator was designed so that it could have the output of 50W. The output then can be supplied to low power appliances or device. This output can be traced out from the battery that was used to store the electrical energy harvested from motion. The current that produced from the battery can be calculated with the formula (3.0) as below:

$$I = \frac{P}{V} \qquad [A] \qquad (3.0)$$

From this equation, a simple result of output current can be documented as in **Table 3.2**.

From **Table 3.2**, we can see that with the 4, 12 volt battery which gives the total of 48V, the output current is 1.0417 that is the lowest. This is reliable as high current will cause the output conductor to be large. By using a large conductor, it is a concern that the conductor would take a larger place in the energy harvesting device. The larger the conductor, the harder for winding to take place.

Table 3.2: The output current of the battery

Storage Device	Power (W)	Voltage (V)	Current (A)
1 battery	50	12	4.1667
2 batteries	50	24	2.0833
3 batteries	50	36	1.3889
4 batteries	50	48	1.0417

CHAPTER 4

RESULT

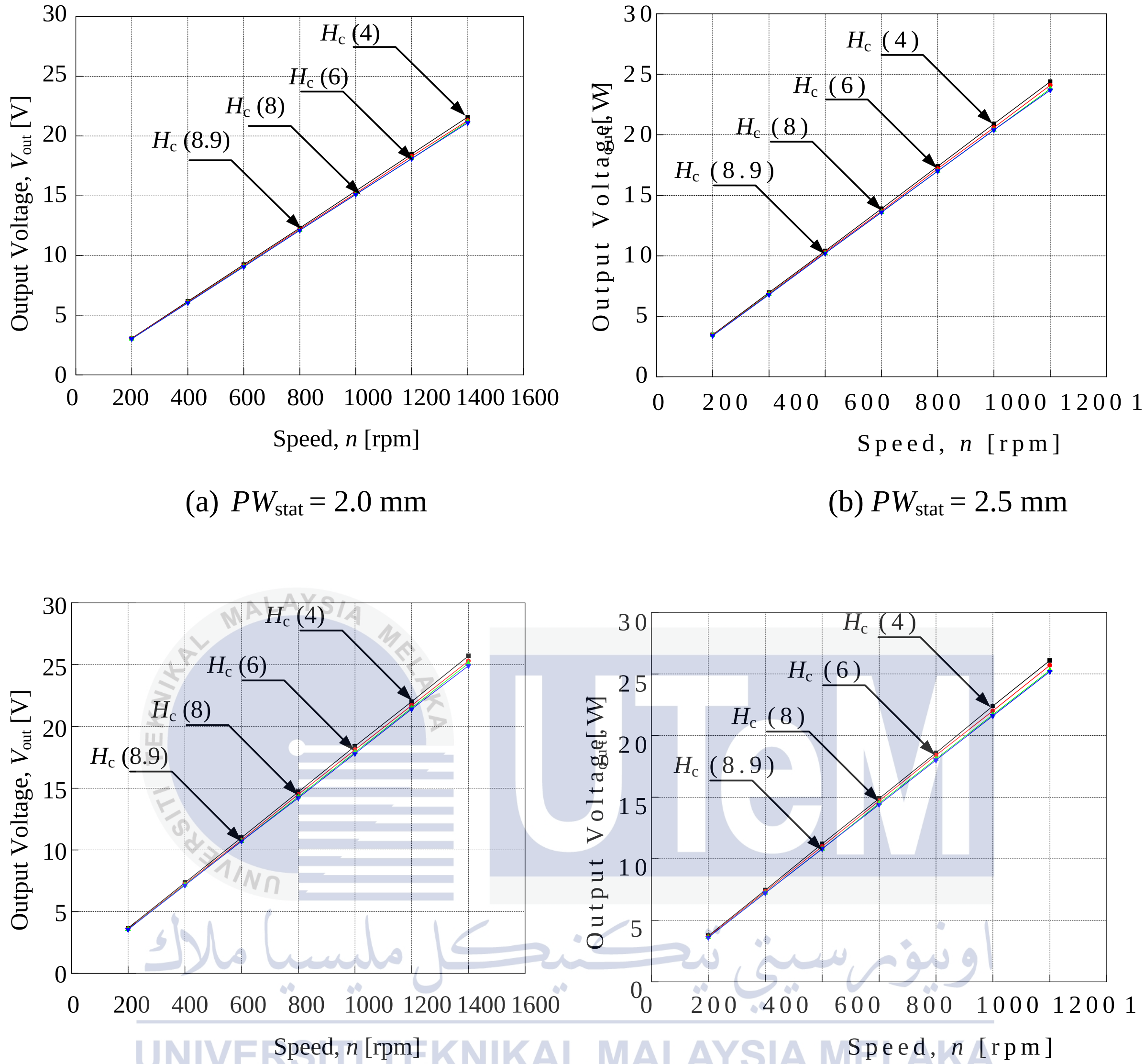
4.0 Analysis of Optimum Coil Parameter of Permanent Magnet Generator for Energy Harvesting Application

In this chapter, the outcome from the design process that took place earlier is observed and analyzed. The main point in this chapter is to see whether the design gives the desired outcomes as stated in the design specification. For the purpose of analysis, the value of the output voltage and the output power is reviewed. For both cases, the output voltage and output power are divided into two section based on the current which is 2 A and 4A. Then, both of them are divided into 4 section based on the stator pole width, PW_{stat} of 2.0mm, 2.5mm, 3.0mm and 3.5 mm. As stated before, the coil used in this project is of the size 0.35 mm. The calculation sample to obtain the output voltage is shown in the appendix section of this thesis. The output power is obtained from the multiplication of the output power with the respective current.

4.1 Analysis of Output Voltage for 2A of Load Current

From **Figure 4.1** the output voltage of 2A load current for PW_{stat} = 2.0 mm, 2.5 mm, 3.0 mm, and 3.5 mm are computed into graph. By referring to the graph from the **Figure 4.1**, the output voltage increases in proportional with the speed. The highest output voltage can be achieved when the speed is at 1400 rpm. From (a), the maximum output voltage obtained from the graph is about 22 V, from (b) the maximum voltage is about 24.5 V, from (c) the maximum output voltage is about 26 V and from (d) the maximum output voltage is at 27 V. All the maximum voltage is subjected at coil height, H_c equals to 4mm.

From (a), the minimum output voltage obtained from the graph is about 3 V, from (b) the minimum voltage is about 3.5 V, from (c) the minimum output voltage is about 4.2 V and from (d) the minimum output voltage is at 4.5 V. In contrast with the maximum output voltage, the minimum output voltage is subjected to the coil height, H_c equals to 8.9mm. From all four graph (a), (b), (c) and (d) in **Figure 4.1**, it can be concluded that the output voltage increases when H_c increases. The small change in the PW_{stat} results in the small change of the output voltage.



(a) PW_{stat} = 2.0 mm

(b) PW_{stat} = 2.5 mm

(c) PW_{stat} = 3.0 mm

(d) PW_{stat} = 3.5 mm

Figure 4.1: Output voltage at 2 A of load current

4.2 Analysis of Output Voltage for 4A of Load Current

The output voltage of 4A load current for PW_{stat} = 2.0 mm, 2.5 mm, 3.0 mm, and 3.5 mm are in **Figure 4.2**, increases in proportional with the speed. When the speed is at 1400 rpm, the generator gives the highest output voltage. All the maximum voltage is subjected at coil height, H_c equals to 4mm. From (a), the maximum output voltage obtained from the graph is about 21 V, from (b) the maximum voltage is about 23 V, from (c) the maximum output voltage is about 25 V and from (d) the maximum output voltage is at 26 V.

Differ from the maximum output voltage, the minimum output voltage is achieved when the coil height, H_c equals to 8.9mm. From (a), the minimum output voltage obtained from the graph is about 2.9 V, from (b) the minimum voltage is about 3.3 V, from (c) the minimum output voltage is about 4 V and from (d) the minimum output voltage is at 4.3 V. From all four graph (a), (b), (c) and (d) in **Figure 4.2**, it can be concluded that the output voltage increases when H_c increases. The small change in the PW_{stat} results in the small change of the output voltage.

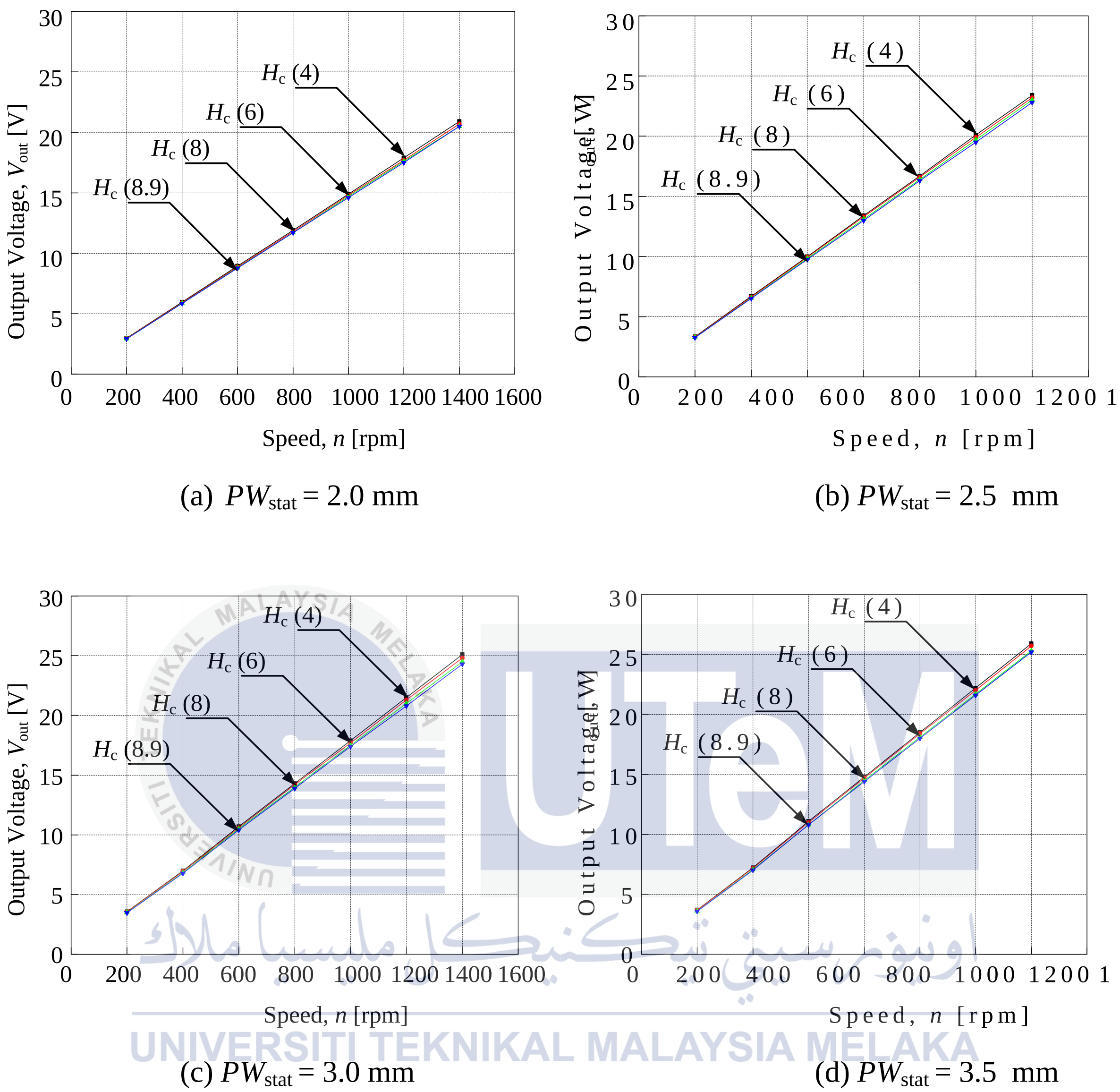
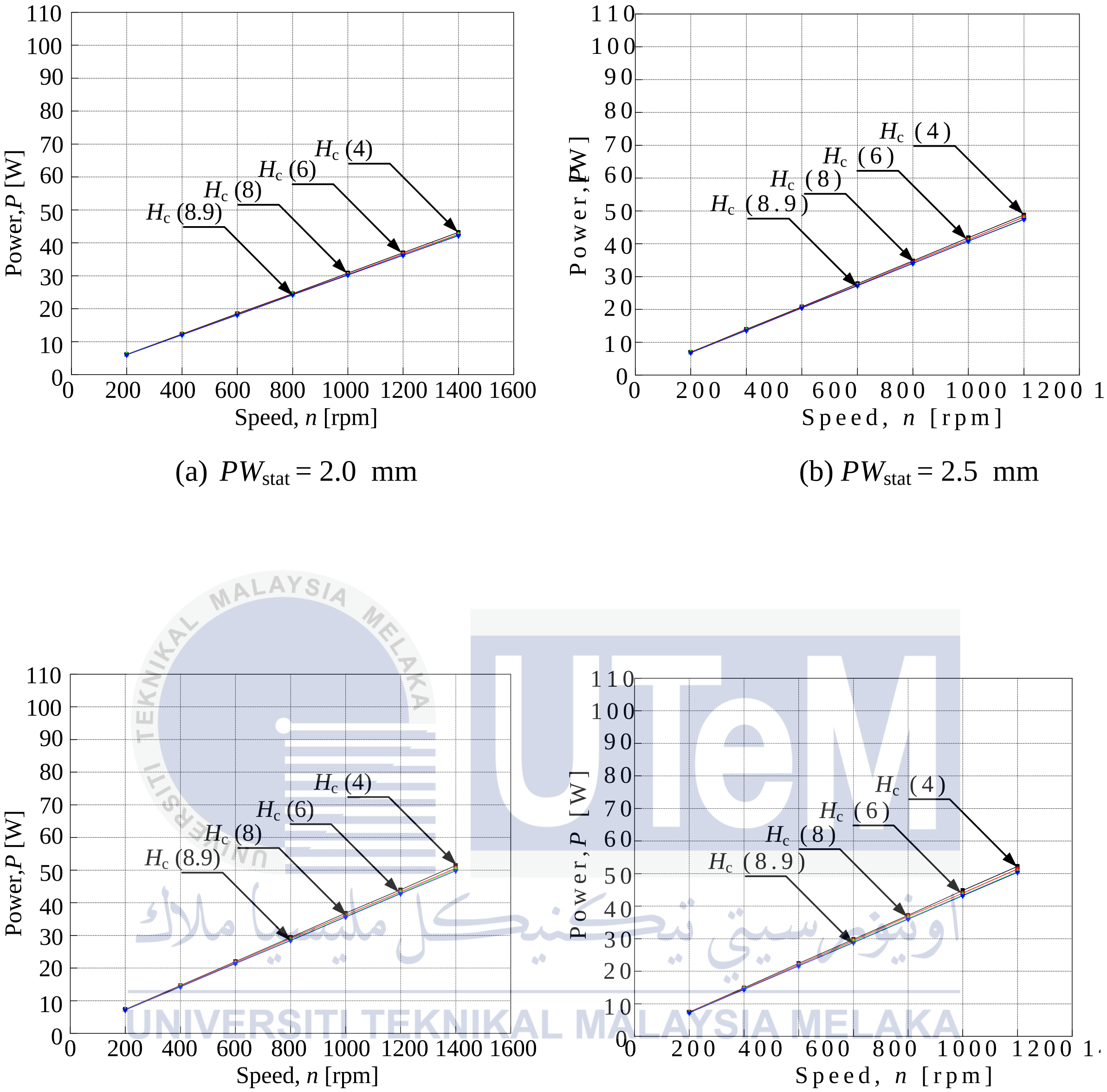


Figure 4.2: Output voltage at 4 A of load current

4.3 Analysis of Output Power for 2A of Load Current

Figure 4.3 shows the output power of 2A load current for PW_{stat} = 2.0 mm, 2.5 mm, 3.0 mm, and 3.5 mm. By referring to the graph from the **Figure 4.3**, it can be conclude that the higher the speed, the higher the output power. The highest output power can be achieved when the speed is at 1400 rpm. From (a), the maximum output power obtained from the graph is about 44W, from (b) the maximum power is about 49W, from (c) the maximum power voltage is about 52W and from (d) the maximum output power is at 54W. All the maximum power is subjected at coil height, H_c equals to 4mm.

The minimum output power obtained from the graph is about 6 W for (a), from (b) the minimum power is about 7 W, 8.4 W from (c) and from (d) the minimum output power is at 9 W. In contrast with the maximum output power, the minimum output power is subjected to the coil height, H_c equals to 8.9mm. From all four graph (a), (b), (c) and (d) in **Figure 4.3**, it can be concluded that the output power increases when H_c increases. The experiment is done by changing the PW_{stat} with the very small changes. Thus, the difference is very small.



(a) PW_{stat} = 2.0 mm

(b) PW_{stat} = 2.5 mm

(c) PW_{stat} = 3.0 mm

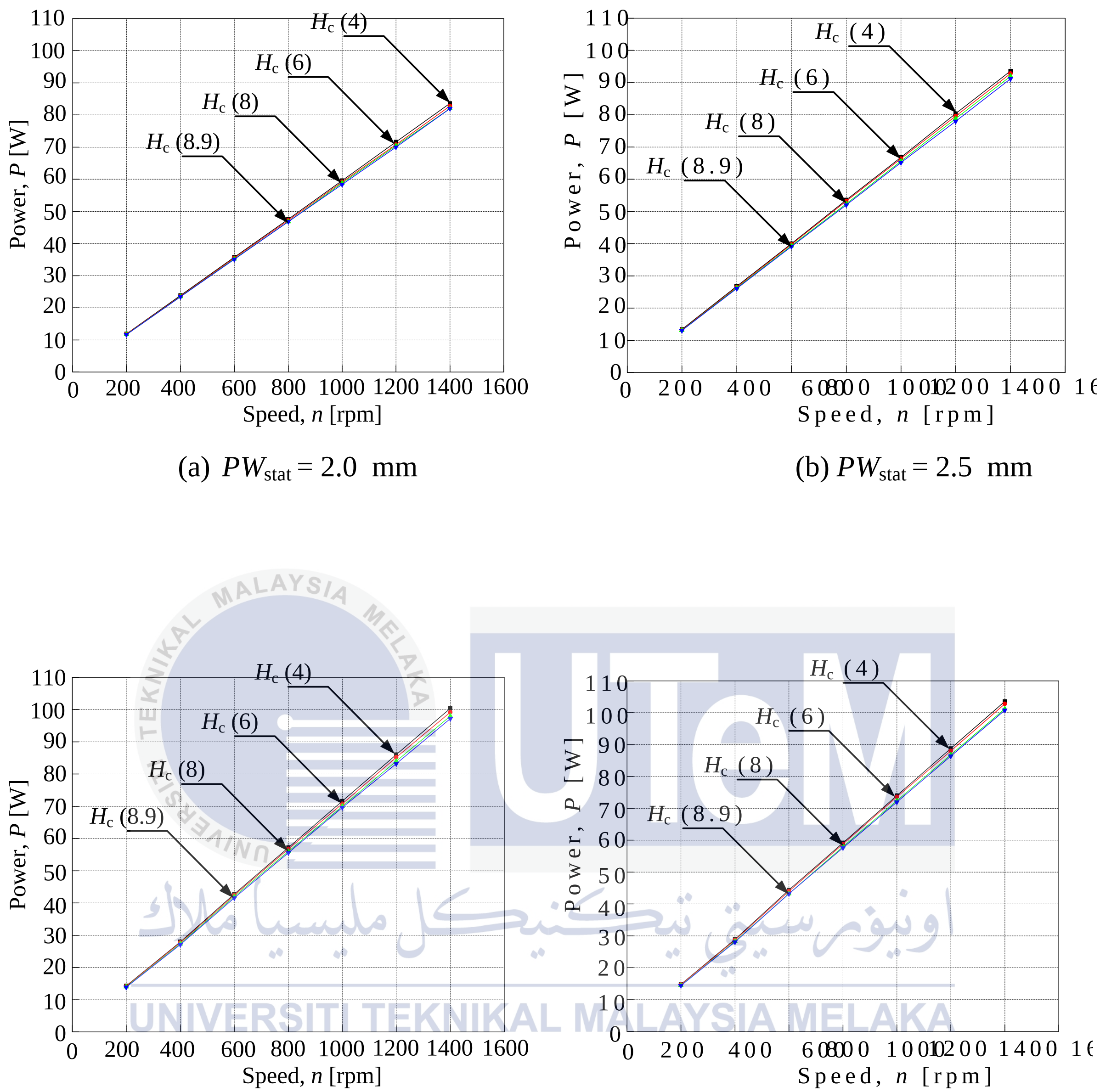
(d) PW_{stat} = 3.5 mm

Figure 4.3: Output power at 2 A of load current

4.4 Analysis of Output Power for 4A of Load Current

From **Figure 4.4** the output power of 4A load current for PW_{stat} = 2.0 mm, 2.5 mm, 3.0 mm, and 3.5 mm are computed into graph. By referring to the graph from the **Figure 4.4**, the output power increases when the speed increases. The highest output power can be achieved when the speed is at 1400 rpm. From (a), the maximum output power obtained from the graph is about 84W, from (b) the maximum power is about 92W, from (c) the maximum power voltage is about 100W and from (d) the maximum output power is at 104W. All the maximum power is subjected at coil height, H_c equals to 4mm.

We can see that for (a), the minimum output power obtained from the graph is about 11.6 W, from (b) the minimum power is about 13.2 W, from (c) the minimum output power is about 16 W and from (d) the minimum output power is at 17.2 W. In contrast with the maximum output power, the minimum output power is subjected to the coil height, H_c equals to 8.9mm. From all four graph (a), (b), (c) and (d) in **Figure 4.4**, it can be concluded that the output power increases when H_c increases. The small change of the output power is as the result of the small change in the PW_{stat} results in.



(a) PW_{stat} = 2.0 mm

(b) PW_{stat} = 2.5 mm

(c) PW_{stat} = 3.0 mm

(d) PW_{stat} = 3.5 mm

Figure 4.4: Output power at 4 A of load current

4.5 The Optimum Coil Parameter

Based on the analysis that has been done, the optimum coil parameter are achieved at the load current of 2A, when the coil height, H_c is 6mm, the stator pole width, PW_{stat} is 2.5mm and the speed is at 1400 rpm. With this setting, the generator gives an output of 24.1V. Therefore, at 2A of load current, the output power is 48.2W which is close to the aimed output power. **Figure 4.5** shows the fixed parameter for the optimize coil condition. The values are obtained from the simulation. All the values are varies except for the size of the permanent magnet which remains the same at 4 X 2 mm. The number of turn of the coil for this parameter setting is 193 turns. The fixed setting is computed in **Table 4.1**.

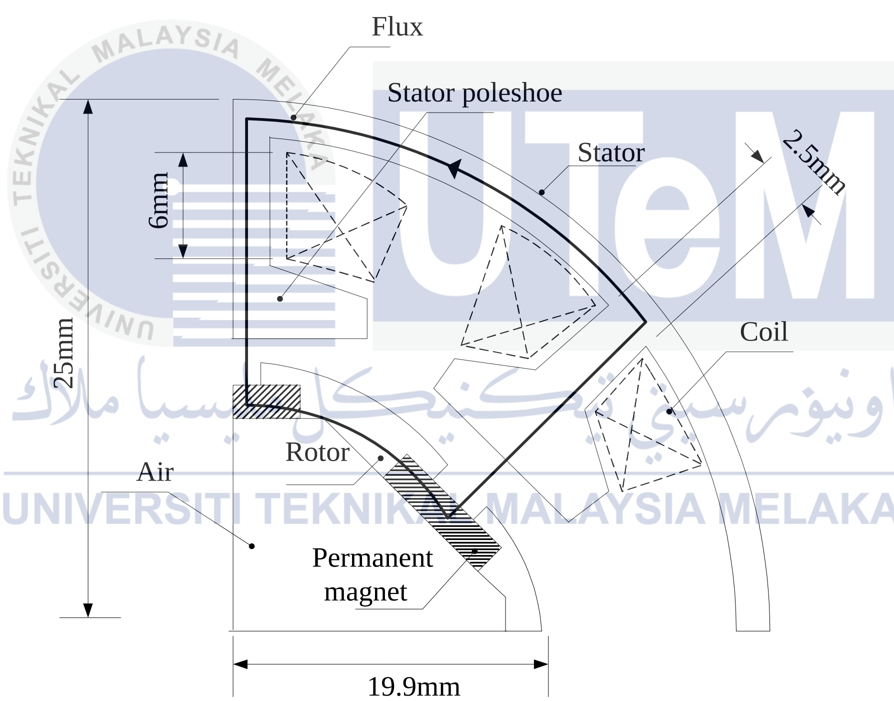


Figure 4.5: Parameter for coil optimization

Table 4.1: Fixed setting for optimum coil parameter

Elements	Value (mm)
Stator pole width, PW_{stat}	2.5
Coil Height, H_c	6
Rotor Radius, R_1	19
Permanent magnet	4 X 2

4.6 Proposed Energy Harvester Device

Finally, the sketch of the final model to be proposed for the energy harvester device was designed using Solidwork software. The model consists of the generator structure as in **Figure 3.6**, shaft, bearing and casing to hold the device in place. The final model of the PMG is shown in **Figure 4.6** below.

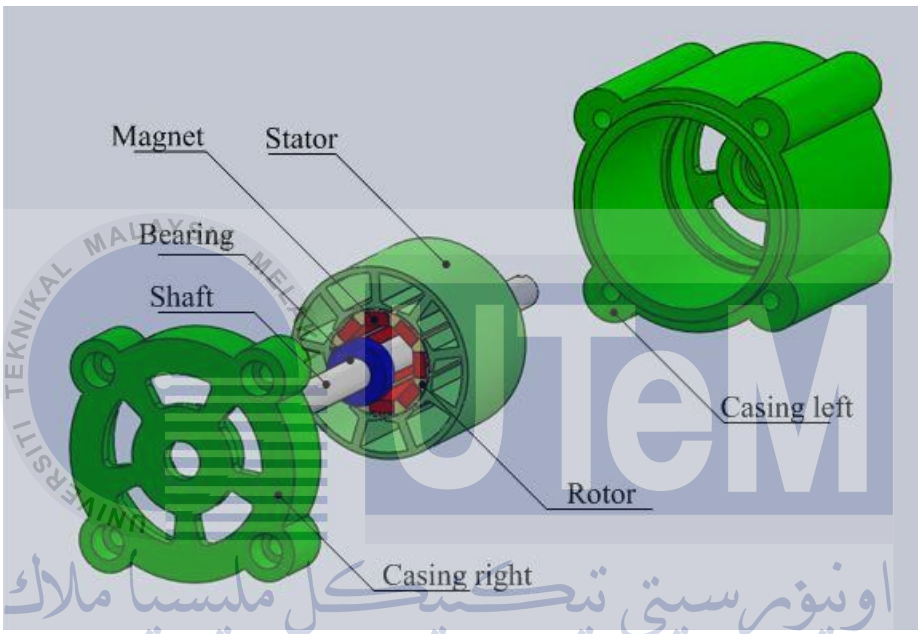


Figure 4.6: Structure of the proposed energy harvester device

The stator of the device is fixed onto the inner surface of the left casing. The shaft in the other hand is coupled with two sets of bearing to smoothen the rotational movement of the shaft. The casing has a set of holes to prevent the coil around the stator from getting too hot. The assembled model then can be attached in a pouch bag so that it can be carried everywhere.

CHAPTER 5

CONCLUSION

5.0 Conclusion

After a lot of work in the past two semesters, the proposed model of energy harvesting device has been completed. A generator for the energy harvesting device had been developed for this final year project.

The basic concept of a permanent generator and the theories are the main fundamentals in designing the perfect model for the generator of the energy harvesting device. It is very important to study the characteristic of the generator in order to design the best model which suits the application of portable energy harvesting device which includes the size optimization of the generator. In this project, a permanent magnet generator has been taken into consideration for the research.

In designing the generator, the magnetic flux is a main element to be considered in which the rotational motion of the generator and the output voltage depends on the magnetic flux characteristic. The best performance of the generator can be achieved when the abundance amount of magnetic flux pass through the stator and the coil. In the other hand, a flux leakage is the condition where the magnetic flux does not pass through the stator slot which is considered as a loss.

Design of generator using finite element method related software enables the deeper understanding regarding the characteristic of the generator including the path of magnetic flux and the structure of the generator affects the overall performance of the generator. Since the finite element method displays the graphical views of the simulation results, the effect of variables modification such as the stator pole width, PW_{stat} can be noticed instantly.

From this project, the objectives of the project are achieved as presented in this report. The design process was discussed as in chapter 3. The analysis are also done with the result was discussed in chapter 4. The proposed model are presented in chapter 4 in which the outcome is achieved as expected of 50W at current 2A as calculated in **Table 3.2** when the speed is 1400 rpm and PW_{stat} is 2.5 mm with H_c is 6 mm.

It can conclude that the basic of motion harvesting device that have been researched simply comes from the basic principle of the generator. What makes it differ from the generator is how the source of energy can be manipulated by using motion energy rather than oil and fuel from conventional generator. This project can be the stepping stone of the development of the energy harvester device as a clean and renewable energy.

5.1 Recommendation

A lot of new knowledge has been learnt regarding the permanent magnet generator. For this project, only the optimum coil parameter has been considered. There are other parameter that should be taken into consideration such as the size of magnet, type of rotor and size of coil. Hopefully more research can be conducted to further optimize the generator for the motion energy harvester.

Besides, it is recommended that the model in **Figure 4.6** is fabricated and analyze to determine whether the fabricated model will have expected performance as simulated. After the model is fabricated, the completed model can be assembled as an actual energy harvester device.

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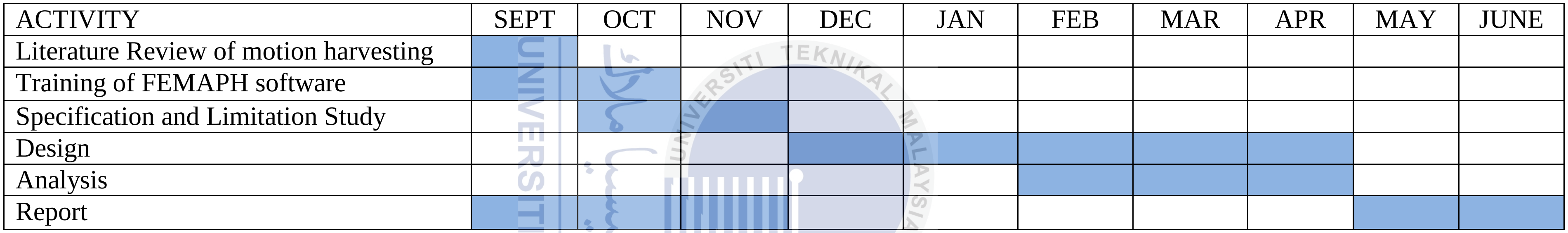
APPENDICES

APPENDIX A

Gantt chart



Milestone:

Activity	Progress
Literature Review of motion harvesting	Done on September 2013
Training of FEMAPH software	Done on October 2013
Specification and Limitation Study	Done on November 2013
Design	Done on April 2014
Analysis	Done on April 2014
Report	Done on May 2014

APPENDIX B

Sample calculation

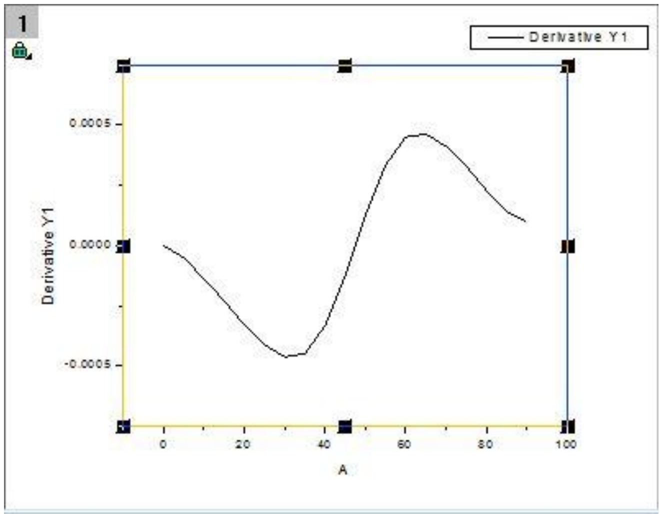
The raw data obtained from the Finite Element Method are transferred to Origin8 software.

	A(X)	B(Y)
Long Name		
Units		
Comments		
1	0	0.00682
2	5	0.00682
3	10	0.00632
4	15	0.00543
5	20	0.00403
6	25	0.00214
7	30	-8.49649E-5
8	35	-0.00249
9	40	-0.00458
10	45	-0.00582
11	50	-0.00582
12	55	-0.00458
13	60	-0.00249
14	65	-8.49048E-5
15	70	0.00214
16	75	0.00403
17	80	0.00543
18	85	0.00632
19	90	0.00682

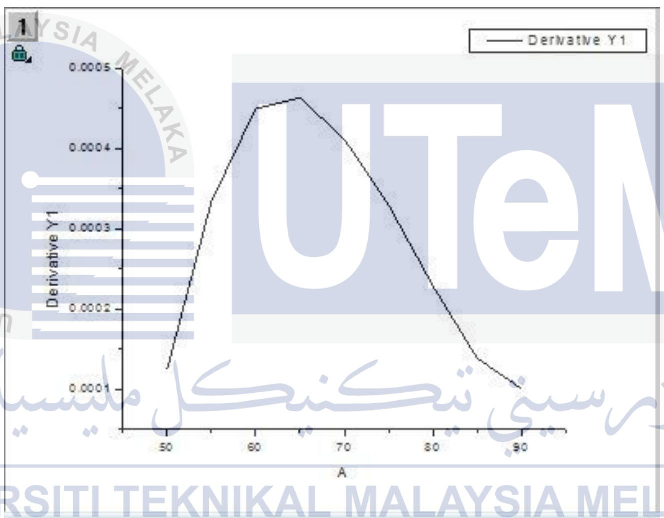
The X column on the left is the representation of the movement of the rotor with 5 degree increment while the Y column on the right is the flux linkage with every rotor movement.

	A(X)	B(Y)	C(Y)
Long Name			Derivative Y1
Units			
Comments			
1	0	0.00682	-8.78E-10
2	5	0.00682	-5.0178E-5
3	10	0.00632	-1.38481E-4
4	15	0.00543	-2.28783E-4
5	20	0.00403	-3.29493E-4
6	25	0.00214	-4.11245E-4
7	30	-8.49649E-5	-4.62599E-4
8	35	-0.00249	-4.4943E-4
9	40	-0.00458	-3.33143E-4
10	45	-0.00582	-1.24076E-4
11	50	-0.00582	1.24072E-4
12	55	-0.00458	3.33144E-4
13	60	-0.00249	4.49444E-4
14	65	-8.49048E-5	4.62601E-4
15	70	0.00214	4.11244E-4
16	75	0.00403	3.2949E-4
17	80	0.00543	2.28779E-4
18	85	0.00632	1.38477E-4
19	90	0.00682	1.00354E-4

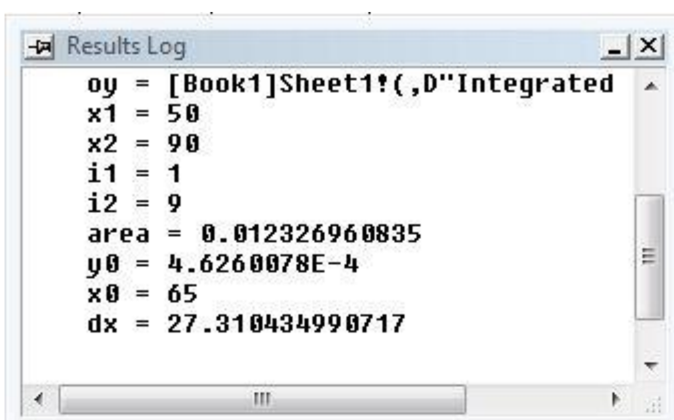
The flux linkage in Y column are differentiated.



The differentiated values are plotted. The value will present as a sinusoidal graph.



The positive curve of the sinusoidal graph is integrated to find the area under graph which is the average flux linkage. The integration will gives an output as below.



The area under graph is divided by x2-x1.

$$\Phi = \frac{0.012326}{90 - 50} = 3.0815 \times 10^{-4}$$

Using formula (2.0) with speed of 1400rpm;

$$V_{out} = \Phi * 4.44 * 3 * Z_{length} * \omega$$

$$V_{out} = 3.0815 \times 10^{-4} * 4.44 * 3 * 40 * 1400 * 2\pi/60$$

$$V_{out} = 24.07\, V$$

APPENDIX C

Sample coding for GMSH software

Mesh file coding for overall model build up, test_UTeM_rm.msh

```
SrotationAngle=0;
//SrotationAngle=180/12;
//SrotationAngle=-180/12;

RrotationAngle=0.0;
//RrotationAngle=180/3;
//RrotationAngle=-180/12;

Seccentricity_x=0.0;
Seccentricity_y=0.0;
Reccentricity_x=0.0;
Reccentricity_y=0.0;

/*********************************************************************
 *      motor.geo
 *      Triangle/Quadrangle (2D/ Quarter Model)
 *    Ver. 070126
 *********************************************************************/

/*********************************************************************/
/*** Definition of User Function Set ***/
Include "test_functions.geo";
```

```
/*** Definition of Specification of Motor Geometry ***/

Include "test_specification.geo";


/*********************************************************************/

/*** Set radious of fillet ***/


rc00=0.7e-3;

rc1 = 0.2e-3;

rc2 = 0.8e-3;

rc3 = 0.5e-3;


rc4 = 0.25e-3;

rc5 = 0.2e-3;

rc6 = 0.1e-3;


/* Characteristic Length / Control Mesh Size */

lc0 = 2.0e-3;  // for center

lc1 = 20.0e-3;

lc2 = 3.0e-3;

lc3 = 1.0e-3;  //for stator core

lc31 = 1.5e-3;

lc32 = 0.5e-4;

lc33 = 0.5e-4;
```

```
lc4 = 0.7e-3;  //for coil

lc41 = 0.5e-3;

lc5 = 5.0e-4;  //for Prim. Magnet

lc51 = 1.0e-3;

lc52 = 1.0e-3; // for Sec. Mag

lc53 = 5.0e-4;

lc6 = 1.2e-3;  //for rotor core, outer

lc61 = 1.0e-3;  // slit, outer

lc62 = 5.0e-4;

lc63 = 5.0e-4;

lc7 = 1.5e-3;  //for shaft core


/******************************************************************/

// ***** Definition of Counters *****


LineNum = 0;

Region = 0;

RegionAir = 0;

RegionSlotAir = 0;

RegionGapAir = 0;

RegionFerro1 = 0;

RegionFerro2 = 0;

RegionFerro3 = 0;

RegionCoil = 0;

RegionCoilSlot = 0;
```

```
RegionMag = 0;

RegionShaftAir = 0;

RegionRotorAir = 0;


/*********************************************************************/

// ***** Set Centers of Stator & Rotot ****


/*** Set Geometrical Points ***/


// Set the center of the stator

Scenter_x=Seccentricity_x;

Scenter_y=Seccentricity_y;

Scenter_z=0.0;


// Set the center of the rotor

Rcenter_x=Reccentricity_x;

Rcenter_y=Reccentricity_y;

Rcenter_z=0.0;


Scenter=newp;

Point(Scenter)={Scenter_x, Scenter_y, Scenter_z, lc0};


If (Rcenter_x!=Scenter_x || Rcenter_y!=Scenter_y)

  Rcenter=newp;

  Point(Rcenter)={Rcenter_x, Rcenter_y, Rcenter_z, lc0};
```

```
EndIf

If (Rcenter_x==Scenter_x && Rcenter_y==Scenter_y)

  Rcenter=Scenter;

EndIf


Zoffset=1.0e-3;


/*********************************************************************/

Geometry.AutoCoherence=0;


// ***** Outer Air Region ****

Include "test_outer_air.geo";


// ***** Air Region of Fringe of Rotor ****

Include "test_outer_stator.geo";


// ***** Stator Region/Yoke ****

Include "model_stator_yoke.geo";


// ***** Stator Region/Ple ****

Include "model_stator_pole.geo";
```

```
//Include "model_stator_pole_inner.geo";
//Include "model_stator_yoke_inner.geo";

// ***** Stator Region/ Pole ****
Include "model_stator_poleshoe.geo";


// ***** Stator Region/ Coil ****
Include "test_coil_outer.geo";
Include "test_coil_air_outer.geo";
//Include "test_coil_inner.geo";
//Include "test_coil_air_inner.geo";

// ***** Gap Region ****
Include "test_gap_air_outer.geo";
//Include "test_gap_air_inner.geo";


// ***** Rotor Region pole *****
//Include "test_rotor_outer_poleshoe.geo";
//Include "test_rotor_inner_poleshoe.geo";
Include "test_rotor_air1.geo";
Include "test_rotor_pole.geo";
```

```
// ***** Rotor Region/yoke *****
//Include "model_stator_poleshoe_inner.geo";



// ***** Rotor Region/shaft *****
Include "test_rotor_shaft_air.geo";

// ***** Rotor Region/shaft *****


// ***** Rotor Region/shaft *****


// ***** Rotor Region/shaft *****
//Include "test_magnet_A.geo";
Include "test_magnet_slot.geo";


/*** Define physical entities ***/

Propnum=1;
Physical Surface(Propnum) = {Air[{1:RegionAir}]};  // Air
```

```
For i In{1:RegionAir}
  Printf("Air[%f] %f",Air[i],Propnum);
EndFor


Propnum=2;
Physical Surface(Propnum) = {GapAir[{1:RegionGapAir}]};  // Air
For i In{1:RegionGapAir}
  Printf("GapAir[%f] %f",GapAir[i],Propnum);
EndFor


Propnum=3;
Physical Surface(Propnum) = {Ferro1[{1:RegionFerro1}]};  // Feromagnetic
For i In{1:RegionFerro1}
  Printf("Ferromagnetic[%f] %f",Ferro1[i],Propnum);
EndFor


Propnum=4;
Physical Surface(Propnum) = {Ferro2[{1:RegionFerro2}]};  // Feromagnetic
For i In{1:RegionFerro2}
  Printf("Ferromagnetic[%f] %f",Ferro2[i],Propnum);
EndFor


Propnum=5;
Physical Surface(Propnum) = {Ferro3[{1:RegionFerro3}]};  // Feromagnetic
```

```
For i In{1:RegionFerro3}
  Printf("Ferromagnetic[%f] %f",Ferro3[i],Propnum);
EndFor

For i In{1:RegionMag}
  Propnum++;
  Physical Surface(Propnum) = {Mag[i]};  // Manet
  Printf("Magnet[%f] %f",Mag[i],Propnum);
EndFor

For i In{1:RegionCoil}
  Propnum++;
  Physical Surface(Propnum) = {Coil[i]};  // Coil at right side of pole
  Printf("Coil[%f] %f",Coil[i],Propnum);
EndFor

For i In{1:RegionCoilSlot}
  Propnum++;
  Physical Surface(Propnum) = {CoilSlot[i]};  // Coil at right side of pole
  Printf("CoilSlot[%f] %f",CoilSlot[i],Propnum);
EndFor

/***********************************************************************/
// End of script
Show "*";
```