Faculty of Electrical Engineering

EFFECT OF SLOT OPENING TO PERMANENT MAGNET LINEAR GENERATOR PERFORMANCE

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Bachelor of Electrical Engineering

2018

APPROVAL

I hereby declared that I have read this thesis entitles "*Effect of Slot Opening to Permanent Magnet Linear Generator Performance"* and in my opinion this thesis is sufficient in term of scope and quality as a partial fulfilment for awarding degree of Bachelor of Electrical Engineering with honour.

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Date : ………………………………………..

EFFECT OF SLOT OPENING TO PERMANENT MAGNET LINEAR GENERATOR PERFORMANCE

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A thesis submitted

In fulfilment of the requirement for the degree of Bachelor of Electrical Engineering with honour

Faculty of Electrical Engineering

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2018

DECLARATION

"I declare that this thesis entitled *"Effect of Slot Opening to Permanent Magnet linear Generator Performance"* is the result of my own research except as cited in the reference. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree".

Signature :……………………

Name : Eivan anak Kelvin

Date :……………………

DEDICATION

This thesis was dedicated, in thankful appreciation for support encouragement and understanding to my beloved parents, Mr Kelvin and Mrs Bawang.

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In the name of Jesus Christ, my only saviour and most merciful with deepest sense of gratitude to God the Almighty for giving me strength and ability to complete this final year project for my degree in Bachelor of Electrical Engineering with honour. First and foremost, I would like to take this opportunity to express my sincere appreciation to my supervisor Dr. Fairul Azhar Bin Abdul Shukor for his essential supervision, support and encouragement towards the completion of this research. Then, my appreciation goes to lovely family. I would like to thank particularly to my parents, Mr Kelvin and Mrs Bawang for giving me support for entire time during finishing this research.

ABSTRACT

This project were present to compare effect of slot opening to permanent magnet linear generator performance under the three phase and five phase topology. This generator use neodymium iron boron (NdFeB) as a permanent magnet (PM) where it attached to the mover. This arrangement of permanent magnet is called Halbach configuration. Objective of this research are to analyse the 15 slot 14 pole PMLG using FEM software and compare the performance of 15 slot 14 pole using three and five phase system. In order to accomplish the objective, modelling of 15 slot 14 pole of the PMLG need to be draw using the SolidWork with different size of slot opening. After that, all the model will be transfer to the FEM software to undergo simulation. The speed of the PMLG that been set inside simulation is from 0.5m/s to 2.0m/s with unloaded condition. For this FYP, the result and simulation is tested on different size of slot opening with unloaded condition for three phase and five phase. The parameter size of slot opening height, ht are 0mm to 1mm while for slot opening length, lt are tested from 1mm to 12mm. Based on the result, PMLG produced different flux linkage at different phase system but show same reading of flux linkage at different speed condition. In aspect of cogging force, PMLG with different speed condition and different phase will show almost similar reading of cogging force but this cogging force will be different if the slot opening of the PMLG is change. For output voltage (Vrms), three phase PMLG will produced higher voltage compare to five phase PMLG and the voltage produce by the both PMLG will decrease if the slot opening length is increase. Lastly, lower reading of THD that been produced by the PMLG can be achieved if the slot opening length set at 7mm and 8mm.

ABSTRAK

Projek ini dibentang untuk membandingkan kesan pembukaan celah kepada prestasi penjana lurus magnet kekal di bawah tiga fasa dan topologi fasa lima. Penjana ini menggunakan neodymium iron boron (NdFeB) sebagai magnet tetap (PM) di mana ia melekat pada penggerak. Susunan magnet kekal ini dipanggil konfigurasi Halbach. Objektif kajian ini adalah untuk menganalisis 15 celah 14 kutub PMLG menggunakan perisian FEM dan membandingkan prestasi 15 celah 14 kutub menggunakan sistem tiga dan lima fasa. Untuk mencapai matlamat, pemodelan 15 celah 14 kutub PMLG perlu dilukis menggunakan SolidWork dengan saiz pembukaan celah yang berbeza. Selepas itu, semua model akan dipindahkan ke perisian FEM untuk menjalani simulasi. Kelajuan PMLG yang telah ditetapkan dalam simulasi adalah dari 0.5m / s hingga 2.0m / s dengan keadaan yang tanpa beban. Untuk FYP ini, keputusan dan simulasi diuji pada saiz pembukaan celah yang berbeza dengan keadaan yang tanpa beban untuk tiga fasa dan lima fasa. Saiz parameter ketinggian pembukaan celah, ht adalah 0mm hingga 1mm manakala untuk panjang pembukaan celah, lt diuji dari 1mm hingga 12mm. Berdasarkan hasilnya, PMLG menghasilkan hubungan fluks yang berbeza pada sistem fasa yang berbeza tetapi menunjukkan pembacaan fluks yang sama pada keadaan kelajuan yang berbeza. Dalam aspek daya tarikan, PMLG dengan keadaan kelajuan yang berbeza dan fasa yang berbeza akan menunjukkan bacaan tarikan hampir sama tetapi daya tarikan ini akan berbeza jika pembukaan celah PMLG berubah. Untuk voltan keluaran (Vrms), tiga fasa PMLG akan menghasilkan voltan yang lebih tinggi berbanding dengan lima fasa PMLG dan voltan yang dihasilkan oleh kedua PMLG akan berkurangan jika panjang pembukaan slot meningkat. Terakhir sekali, bacaan THD yang lebih rendah yang dihasilkan oleh PMLG boleh dicapai jika panjang pembukaan celah ditetapkan pada 7mm dan 8mm.

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CHAPTER 1

INTRODUCTION

1.1 Project Background

Electrical machine is a device that convert the electrical energy to mechanical energy or in the other way around. There are three type of electrical machine which are generator, motor and transformer. Although transformer does not convert into another form of energy, but it convert alternating current of voltage level to another voltage level. Generator is one of the electrical machine. There are many research and study about generator which is rotary generator. But for permanent magnet linear generator (PMLG), the research is still in finding and the research in linear generator is not as much as permanent magnet linear motor (PMLG). The ordinary generator or the common one is called rotary generator. Linear generator is the same as the rotary generator but only the stator and rotor which is unfold to become linear. They are two type of generator which is synchronous and asynchronous generator (induction generator). Synchronous generator is generator that generate voltage waveform which is directly correspond to the rotor speed meanwhile, asynchronous generator is not. Asynchronous generator draw the excitation power directly from an electrical grid to operate and use the principal of induction motor to generate power. In term of efficiency and complexity, synchronous generator is better.

Before the linear generator, linear motor is the first research that has been found by Charles Wheatstone at King's College in London in 1840, but the invention is not so efficient due to large air gap. In 1845 he improve the motor which is lead to other researcher to explore in the linear motor field. Thus 1925 the research in linear generator has been continue by Eugene Jordan which is in France, but the invention of this electric generator is using gas and liquid expansion to move the piston which is armature. Research that has been done by Eugene Jordan has led to other researcher to contribute in this research such as Ralph James (USA) in 1960, Harold Kosoff in 1964 and many more. In 2008 the research has been carry by Chinese researcher which are Qing-Feng LI, Jin Xiao and Zhen Huang, Shanghai Jiao Tong University, China et al [1]. They propose that the flat-type permanent magnet linear alternator for free piston linear alternator (FPLAs) instead of the tubular one. Using the finite element method (FEM), they compare these two kinds of LAs. The FEM result shows that the flat-type permanent magnet LA has higher efficiency and larger output specific power than the tubular one, therefore more suitable for FPLAs, and that the alternator design can be optimized with respect to the permanent magnet length as well as the air gap [2]. This finding has been widely used in car industry such as Toyota Company and has been install to the engine part which it take the motion from the combustion piston to move the permanent magnet.

Linear generator offer great advantages for example, it used less moving part such as gear to harvest energy. Normally this system has been use by WEC (Wave Energy Converters) due to linear motion design which suitable for hydrokinetic energy. Marine hydrokinetic energy includes both wave and tidal power .Basic WEC classifications include the point absorber, oscillating water column, and hinged contour devices [3]. This linear generator design also lead to high reliability and low cost of generator due to less moving component such as gearbox. As already mention, this linear generator research development also been use in car industry to build hybrid car and will limit the uses of fuel which effect the environment. Not only that, the sources of fossil fuel will also decrease.

To get a good efficiency and maximum power of the linear generator, the design parameter should be study and analyst so that it can be used widely in many field. In this project it will focusing on the design, analysis and performance of the permanent magnet linear generator (PMLG). The scope that going to study are 15 slot 14 pole. This scope will be operate under three phase and five phase system winding by changing the stator parameter and fix distance of air gap.

1.2 Problem statement

Nowadays many vehicle industry focusing on build hybrid electric vehicle (HEV) due to decrease the uses of fossil fuel to protect the environment. For examples, such pollutants include Carbon monoxide, Hydrogen, Nitrogen Oxide, particulate matter, Ammonia and Sulphur Dioxide will give damage to the environment and also toward human health. Besides that, the use of fuel in huge amount will lead to decreasing of fossil fuel resource. This problem can be overcome by create a hybrid electric vehicle (HEV). To create efficient hybrid electric vehicle, the vehicle must have simple generator that give high power output and voltage. For example the free piston linear alternator (FPLA), this linear alternator almost similar to the permanent magnet linear generator structure where the translator is attach to the combustion piston thus, this piston motion can generate electromagnetic forces which lead to flow of current. As another main part of FPLA the linear alternator is capable of directly utilizing the linear piston force without any need of the additional mechanical components that are necessary in a rotary configuration. FPLA is thus an effectively integrated energy conversion device. Permanent magnet linear generator is the basic structure of linear generator thus, by do the analysis and designing the permanent magnet linear generator, the value of output power, voltage and flux can be determine. Based on the analysis result outcome, the best design of permanent magnet linear generator that will be implement in variety type of energy harvesting machine can determine.

Hydropower system is a great source of energy but by implementing this hydropower system, many earth surface need to be sink under water. This will lead to destruction of forest and alter of natural landscape. Not only that, the implementing of this power plant will cause a lot of expenses to the developer and eventually lead to high maintaining cost to minimise the harmful incident at power plant. One of the solution to this problem is wave energy converter (WEC). Wave energy converter use the basic structure design of linear permanent magnet generator and Basic WEC classifications include the point absorber, oscillating water column, and hinged contour devices. To get a good and efficient WEC, the good design and parameter of permanent magnet generator is needed. By implement this project, the best characteristic design to implement in this WEC can be made. This project also can contribute toward a new energy harvesting system which help to preserve our environment and mankind.

In the current generator production, most of the generator system use three phase system. But in this research, the design are five phase linear generator and three phase linear generator. Many of the previous research said that the multiphase generators offer additional degrees of freedom that can be used for fault-tolerant operation. In fact, under fault conditions, their remaining healthy phases can be used to compensate the faults. The five-phase permanent magnet synchronous generator (PMSG)-based MCT generated power is very smooth even though in fault condition[4]. Not only that, three-phase PMSG currents increase is quiet huge compared to the five-phase one during fault. In this context, multiphase generators seem to be interesting alternative to classical three-phase generators [4].

1.3 Objective

The objective of this research are:

i. To design and analyse the 15 slot 14 pole PMLG performance characteristic using FEM software.

ii. To compare the performance of 15 slot 14 pole PMLG using three and five phase topology.

1.4 Scope

There are limitation of scope that has been set in order to achieve the objective, which are involve only modelling and simulation without prototype development. Firstly, the model of PMLG are design for 15slot 14 pole with the winding of three phase and five phase system. This simulation will run for unloaded with variation speed from 0.5m/s to 2.0m/s. The main parameter is the opening size of the slot. The size slot opening of stator will be vary in term of height, *ht* and length, *lt*. The height will be set from 0mm to 1mm whereas length will be set from 1mm to 12mm. After all of the parameter been set, the result will show in performance aspect of cogging force, voltage output (Vrms) and total harmonic distortion (THD).

1.5 Thesis outline

This research is consist of 5 chapters which are introduction, literature review, methodology, result analysis and discussion and last but not least conclusion and recommendation.

In chapter 1 will briefly about introduction of the project which are project background, problem statement, objective, scope and limitation. Besides that, this chapter also explain general information about current development of permanent magnet linear generator and three and five phase system.

In chapter 2, theoretically about introduction of PMLG, the working principle, and basic structure. Besides that, it also mention about the research that present by other researcher and related theory toward performance of PMLG such as magnetic material.

In chapter 3 it will discuss about execution of the project from first until finish the simulation. Here the formula will be used and calculate to set up the setting in the FEM.

In chapter 4, all the analysis outcome will be show and based on the result of simulation. The simulation will focus on certain aspect, such as magnetic flux linkage, output voltage (Vrms), cogging force and total harmonic distortion (THD).

In chapter 5 it will show the conclusion base on the finding result. This chapter 5 also discuss about recommendation of this project.

CHAPTER 2

INTRODUCTION

2.1 Introduction of PMLG

The PMLG is similar like rotary generator but only the structure has been unfold. Linear generator is an alternative solution in providing an electrical supply with high efficiency [5]. This generator will be light weight and compact compare with rotary generator due to less rotary part if implement in any engine design. This generator design is needed when come to stand alone power generation, whether in industrial, commercial and personal purpose. It also can generate power for hybrid car or hybrid electric vehicle (HEV). This will reduce the emission a harmful gas particle into the air thus lead healthy environment. PMLG also act as the basic structure of wave energy converter (WEC) where it convert the marine hydrokinetic energy into electricity. Green energy is important nowadays thus this is one of the solution that will protect our environment and preserve it.

The basic PMLG structure consist of cylindrical stator shape, permanent magnet, translator and coil winding. The structure of PMLG is shown in figure 2.1. There are many type of permanent magnet linear generator, such as tabular PMLG, double sided PMLG, flat-type PMLG and etc. Furthermore, the PMLG can be specified as long translator type and long stator type. For the long translator generator, the stator is shorter compare to the translator and it vice versa for the long stator type. The translator of a long translator type always activates all windings in every generator motion, on other hand, in the long stator type, only a part of stator is activated [5]. There are several translator type that can be design with, for example the translator can become the moving coil, the moving magnet and the moving iron. All this translator design will provide magnetic field toward the generator coil. In this thesis, the moving magnet will be used as our mover and focus on tabular PMLG. In this thesis also we will focus on 15 slot 14 poles for three phase and five phase system. Figure 2.1 shows 15 slot 14 pole design where the stator slot hold the stator coil which the induce electromagnetic forces will be produce. The permanent magnet has attach to the translator for generation of magnetic field toward stator coil.

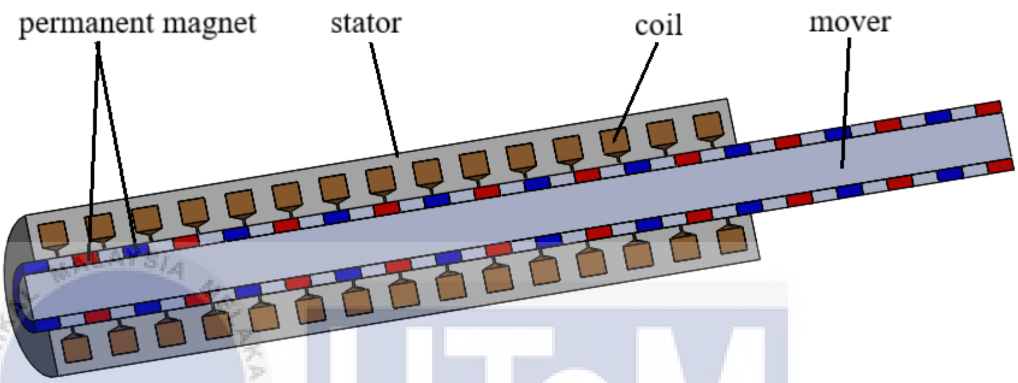


Figure 2.1: Structure of PMLG

2.2 The PMLG developed by others

There a quite a few research regarding on tabular type of PMLG. Many of the research has modified structure of the translator which is used double sided permanent magnet or use flat permanent magnet type. But this other research is based on tabular PMLG design. The title of the research is Permanent Magnet Linear Generator Design using Finite Element Method and has been carried by Hamzah Arof, *et.al* from faculty of electrical of University Malaya [6]. This paper show a general proposal design and finite element method has been used for calculate the performance of a tabular permanent magnet linear generator. By optimizing the linear generator dimension, the cogging force which is occurs due to the interaction between stator teeth and the permanent magnet can be reduce. The effect of armature reaction on the air gap flux density has been taken for analysed the generated voltage based on no load and load cases. To obtain the output voltage based on change of flux and speed of generator, the repetitive routine is followed. The generator design have the capability to produce 5.3kW of output voltage with efficiency of 96.8%. This research analysis is more about the voltage output and reduction of cogging forces on linear generator.

The second research is about design of permanent magnet liner generator by Hew Wooi Ping, et.al from Department of Electrical Engineering, University of Malaya [5]. This paper shown the experience of designing permanent magnet linear generator which is generate three phase electrical current. The generator consist of long translator and permanent magnet mover as magnetic field source. Propose of this generator design is for attached with free piston internal combustion linear engine which operated using a dual chamber. This product later will be implement in a hybrid car to generate electricity to charge the batteries and run the motors. 2D finite element analysis is been used to perform the machine design and this generator be able to generate three phase voltage with the output power of 7kW. The fabrication of this prototype also been presented in this research. Parametric simulation and transient simulation are two types of simulation that been performed in the design get the output parameter such as induced voltage and flux linkage. The permanent magnet for this linear generator using Halbach permanent magnet arrangement and be mounted on an aluminium shaft. The generator generate 7kW of power by using a wire that has current capacity of 7 Ampere with the speed of 3000 cycle per minute. Figure 2.2 shown the induced voltage been produce by the linear generator.

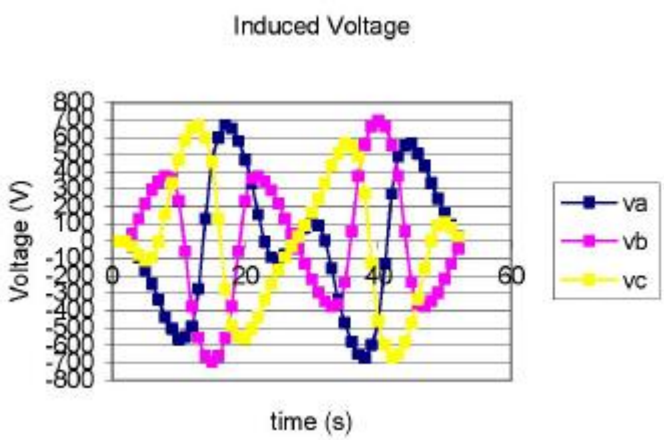


Figure 2.2: Three phase induced voltage produced by the linear generator

2.3 Basic principle of PMLG

PMLG consist of permanent magnet as the mover and the stator that hold the coil winding. The movement of the mover will generate the induce voltage due to the principle of Faraday’s law. Figure 2.3 show the basic principle of PMLG.

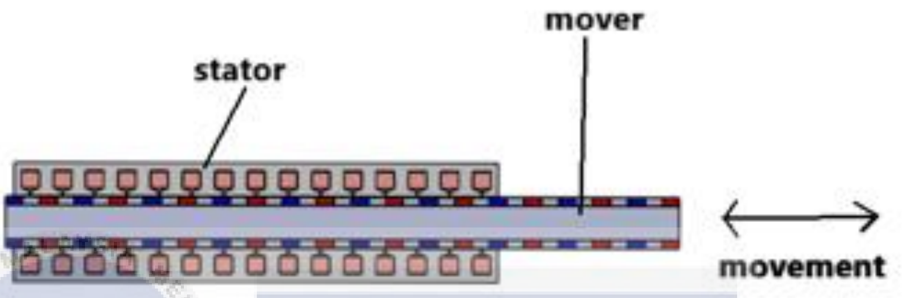


Figure 2.3: Basic principle of PMLG

2.3.1 Basic structure design

Figure 2.4 show 15 slot 14 pole type of generator. The coil of stator will tested in five phase and three phase of system. Figure 2.5 show the PM magnetization direction which using Halbach permanent magnet configuration.

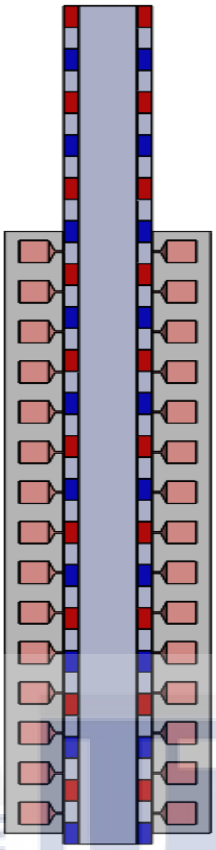


Figure 2.4: 15 slot 14 pole PMLG

The PMLG get the magnetic field source by using the permanent magnet at the mover. Compare to other mover type of same volume, it give high flux density in the air gap and become one of the most important aspect in performance of PMLG. A high cogging force is produced in the axial permanent magnet generator due to the interaction between permanent magnet and stator teeth. This cogging force becomes a serious problem, thus radial and axial permanent magnets is applied to reduce the cogging force. This arrangement of permanent magnet is called Halbach configuration. The use of the Halbach configuration also give some advantages such as, flux produce can be concentrated without the back iron at the mover and lead to lighter weight design of PMLG. The absence of the back iron at the mover also eliminate the eddy current and hysteresis effect thus the energy conversion efficiency can be improve.

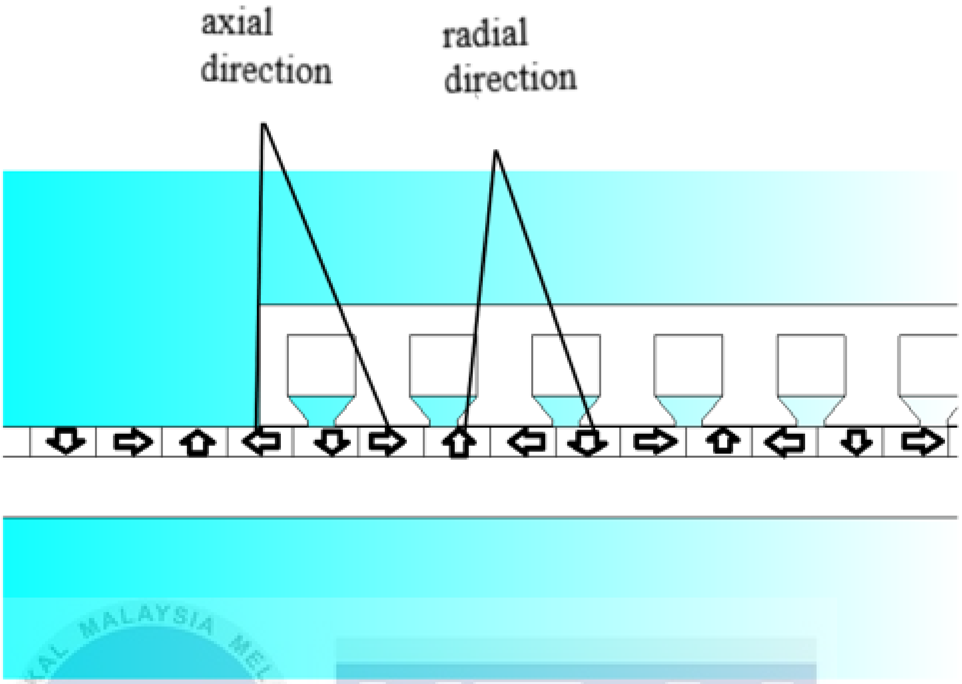


Figure 2.5: Halbach permanent magnet configuration

Linear generator of 15 slot 14 pole consist of two major structure which are stator and mover. There are important parameter in the stator that need to be highlight. The important parameter of the stator are number of coil, turn, stator length and resistance value of the coil. All of this parameter have its own specific value. For the stator parameter, it has 15 number of coil, 77 number of turns, 336mm of stator length and 0.427Ω of resistance. Whereas the mover part consist of three parameter components which are type of magnet, type of shaft and magnetic pole arrangement used. Type of magnet used is neodymium iron boron magnet (NdFeB), shaft consist of air, and magnetic pole arrangement is Halbach configuration. All of this parameter will be keep in constant throughout the simulation. All of this specification has been summarize in table 2.1.

Table 2.1: structure setting 15 slot 14 pole of stator and mover generator

Structure part	Parameter	14 pole
stator	Number of coil	15
	Number of turn	77
	Resistance (ohm)	0.427
	Stator length (mm)	336
mover	Type of magnet	NdFeB
	shaft	air
	Magnetic pole arrangement	Halbach

2.3.2 Working principle of PMLG

Generation of electrical in this PMLG is same theory as rotary generator where the moving permanent magnet will provide magnetic field toward the coil winding at the stator. Figure 2.6 show the magnetic field that been generate by permanent magnet.

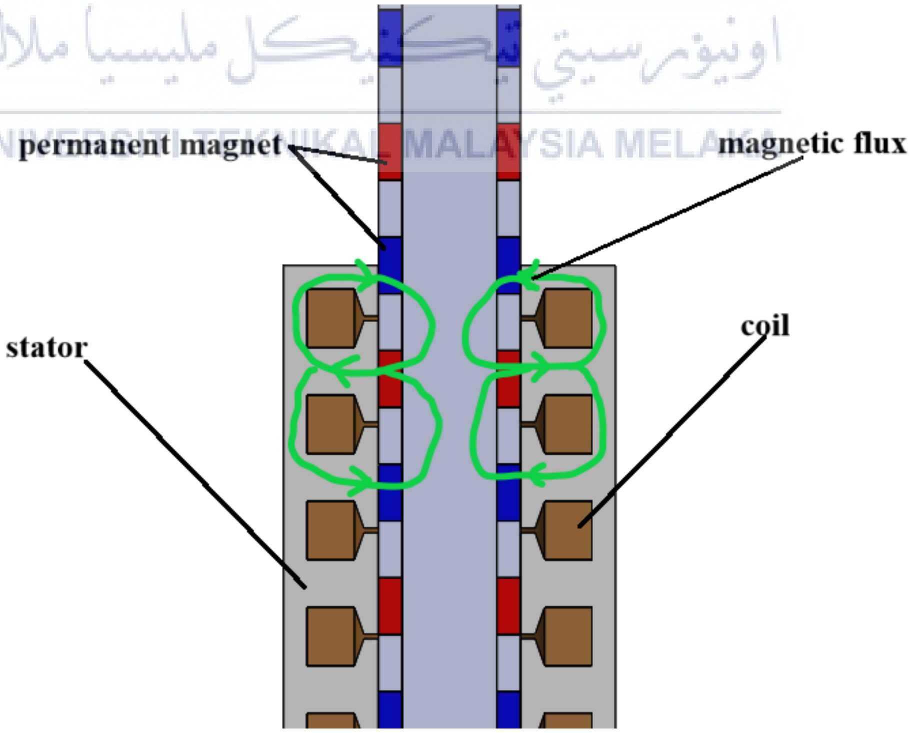


Figure 2.6: Magnetic field of permanent magnet

The red permanent magnet will produce outward magnetic flux and go to stator direction perpendicular to the movement of stator. As the blue magnet is inward direction of magnetic flux, the flux will form a cycle path around the coil. If the mover move down, in instant the position of the red magnet will replace by blue and same goes to position blue magnet will replace by red. This movement will create back and forth of the circular path of magnetic flux and thus induced electromagnetic forces inside the coil winding. This EMF will generate the induce current in the coil and electricity. All the parameter of stator, permanent magnet, and distance of air gap is take into consideration to produce high density power output. EMF can be induced in a coil if the magnetic flux through the coil is changed. It also makes a difference how fast the changes is; a quick changes with time induces more EMF than a gradual change. This is summarized in Faraday's law of induction in equation 2.1 and 2.2 below. The induced EMF in a coil of N loops produced by a change in flux.

Faraday's law can be written:

$$E = \frac{-N\Delta\varphi}{\Delta t} \tag{2.1}$$

$$E = \frac{-N\Delta(BAcos\theta)}{\Delta t} \tag{2.2}$$

Where E is induced voltage, N is number of turn, φ is magnetic flux, and θ is angle in degree.

The negative sign in Faraday's law comes from the fact that the EMF induced in the coil acts to oppose any change in the magnetic flux[7]. This is summarized in Lenz's law. Len's law state that the induced EMF generates a current that sets up a magnetic field which acts to oppose the change in magnetic flux.

2.4 Magnetic material

A wide range of materials and substances groups some sort of attractive properties which are recorded further down in this article. In any case, ordinarily "attractive materials" is utilized just for ferromagnetic materials (depiction underneath), notwithstanding, materials can be arranged into following classes in light of the attractive properties appeared by them.

2.4.1 Non ferromagnetic material:

Non ferromagnetic material consist of paramagnetic material and diamagnetic material. Paramagnetic material is the materials which are not unequivocally pulled in to a magnet are known as paramagnetic material. For instance: aluminium, tin magnesium and so on. Their relative penetrability is little however positive. Whereas diamagnetic material is the materials which are repulsed by a magnet, for example, zinc. Mercury, lead, sulphur, copper, silver, bismuth, wood and etc. There known as diamagnetic materials. Their porousness is marginally short of what one. They are marginally charged when set in an exceptionally string attractive field and act toward the path inverse to that of connected attractive field. In diamagnetic materials, the two relatively weak magnetic fields caused due to the orbital revolution and axial rotation of electrons around nucleus are in opposite directions and cancel each other. Diamagnetic materials have very little to no applications in electrical engineering because permanent magnetic dipoles are absent in them. Figure 2.7 and 2.8 show the magnetic characteristic of paramagnetic and diamagnetic material.

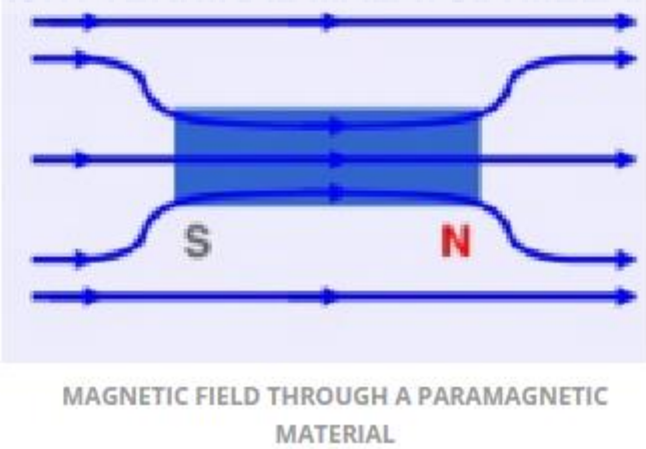


Figure 2.7: Paramagnetic characteristic

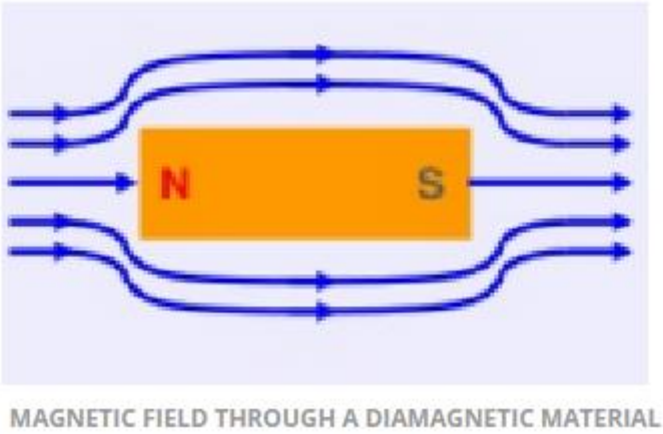


Figure 2.8: Diamagnetic characteristic

2.4.2 Ferromagnetic material

Ferromagnetic material are material that are strongly attracted by a magnetic field for example iron, steel, nickel, cobalt etc. This material have high permeability. In an atom of such a material, the opposite magnetic effects of electron orbital motion and electron spin do not eliminate each other. The establishment of an internal magnetic field is a relatively large contribution from each atom. Ferromagnetic consist of hard ferromagnetic and soft ferromagnetic. Soft ferromagnetic have high relative permeability, low coercive force, easily magnetized and demagnetized and have extremely small hysteresis. Soft ferromagnetic materials are iron and its various alloys with materials like nickel, tungsten and aluminium. Hard ferromagnetic have relatively low permeability, and very high coercive force. These are difficult to magnetize and demagnetize. Typical hard ferromagnetic materials include cobalt steel and various ferromagnetic alloys of cobalt, aluminium and nickel.

The BH curve is represent the graph of magnetic flux density (B) versus magnetic field intensity (H)[8]. Before selecting material for electrical machines, it is important to refer BH curve. BH graph curve show the change in the flux density of a material when the magnetic field intensity is increased. When the magnetic intensity increases the magnetic flux density will increase gradually. If the magnetic field intensity increase even further, the graph line will become almost flat. This indicate the magnetization is done, so any increment in field intensity won't increase the magnetic flux density. This point is called maximum positive saturation, b in the curve.

If the magnetic field intensity is reduced to zero in section b-c, it is show that the magnetic flux density do not decrease to zero. This is mean the material can retain it magnetization characteristic. This has been known as residual magnetism. By decreasing the magnetic field intensity even further, this can lean to zero reading of magnetic flux density in section c-d. Magnetic field intensity that needed to decrease the magnetic flux density to the zero is called coercive strength of the magnetic field. The magnetic flux density will increase negatively until it reach negative saturation, point e when the magnetic field intensity decrease further more. The material still possesses magnetism in opposite direction, if the magnetic field intensity brought back to zero and this is known as negative residual magnetic strength which is in point f. the magnetic flux density will return in zero again if the magnetic field intensity increase in positive direction. Figure 2.9 represent the BH curve graph.

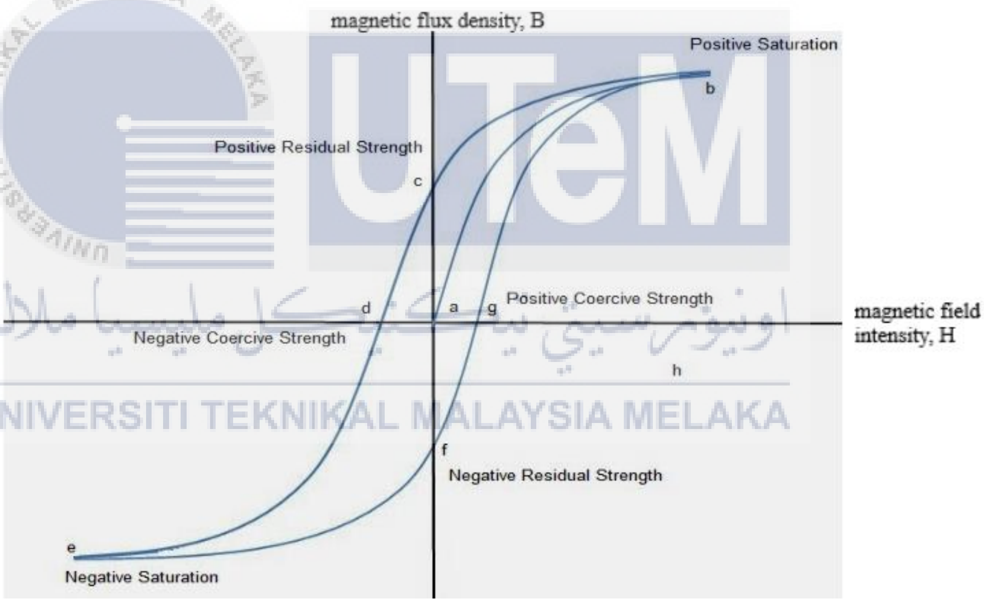


Figure 2.9: BH curve

2.4.3 Permanent magnet

A decent permanent magnet should deliver a high attractive field with a low mass, and ought to be steady against the impacts which would demagnetize it. The remanence, coercivity and temperature coefficient of the magnet materials are typically state term to determine the desirable properties of such permanent magnets. Permanent magnet usually made from ferromagnetic material. Coercivity is the strength of ferromagnetic material to resist to become demagnetized. Whereas remanence is the residue of magnetism that left behind after the magnetic field has been remove from the material. In this thesis the permanent magnet used is Neodymium Iron Boron (NdFeB) due to high strength of coercivity, remanence and temperature coefficient. Not only that, NdFeB is one of the cheapest permanent with high strength of coercivity, remanence and temperature coefficient. Table 2.2 show the properties of permanent magnet.

Table 2.2: Properties of permanent magnet

	PM material				
	AlNiCo	Ba-Ferrite	SmCo(1:5)	SmCo(2:17	NdFeB
Remanence Br/(T)	1.4	0.44	1.05	1.14	1.52
Coercive force Hc/(kA/m)	155	318	796	844	1115
Maximum magnetic energy product (BH)max/(kJ/m^3)	88	36	207	255	446
Temperature coefficient of remanence a/(%/°C)	-0.03	-0.19	-0.05	-0.03	-0.01
Intrinsic coercive force temperature coefficient β/(%/°C)	N/A	0.60	-0.35	-0.05	-0.6

2.5 Summary

In this chapter, it can summarize the PMLG is made up from the translator or mover, permanent magnet, stator, and coil. The translator is made from PM which is neodymium iron boron (NdFeB). The PM use the Halbach arrangement configuration which make it more efficient.

CHAPTER 3

INTRODUCTION

In this chapter, it will discuss more about the procedure and method use to design and analysis the PMLG. First of all, the model of the PMLG was modelled using the SolidWork software. The SolidWork is a tool to modelling the PMLG. During the modelling, it is require to gather all the information regarding structure parameter. After gathered all the information and done the modelling, the 3D modelling will be save in the format of ASIC (*.sat) before transfer to the FEM software. The FEM will simulate the modelling and produce the result and analysis such as flux linkage and output voltage produce.

3.1 Design of the PMLG

The PMLG will be modelled using SolidWork software before transfer to the FEM software to undergo simulation. At the SolidWork software, the PMLG will be draw by a separated component before assemble to become complete PMLG modelled.

3.1.1 SolidWork

All modelling of the PMLG in this project has been draw in the SolidWork software. SolidWorks is a solid modelling computer-aided design (CAD) and computer-aided engineering (CAE) computer program that runs on Microsoft Windows [9]. First of all, PMLG is draw into the 2D model. Next, 2D model will be convert to 3D modelling. The component of the PMLG is converted to the 3D modelling. For example the PMLG consist of shaft, PM, coil and stator; all the component will be convert to 3D part by part. After that, all the component such as stator, coil, PM and shaft will be assemble into become one model which is PMLG. This finished modelling will be convert into compatible file for JMAG-Designer, ACIS (*.sat). Refer figure 3.1 and 3.2 for the PMLG component in the SolidWork. Figure 3.1 consist of 3D components of PMLG: shaft, coil, PM and stator. Figure 3.2 show complete model of PMLG after been assemble.

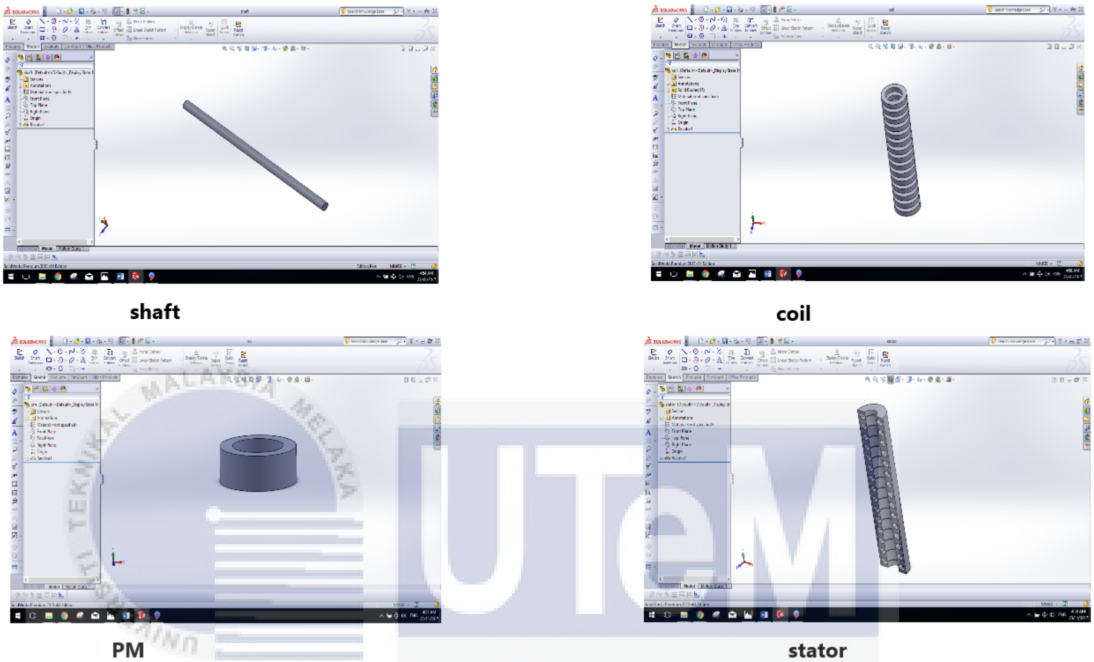


Figure 3.1: PMLG component

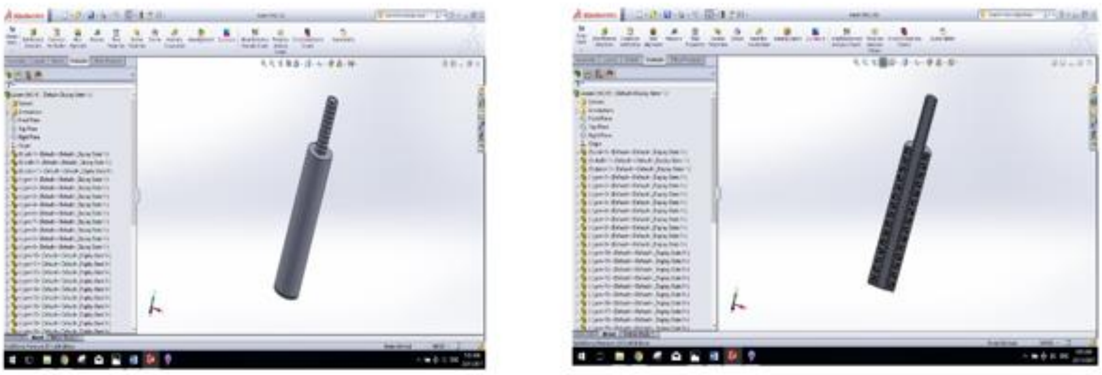


Figure 3.2: Assembled PMLG

3.1.2 FEM software

After done the modelling, the compatible file will transfer to the FEM software to continue next process. Firstly, FEM is simulation software for the development and design of electrical devices. It also a tool to support design for devices such as motors, actuators, circuit components, and antennas. FEM incorporates simulation technology to accurately analyse a wide range of physical phenomenon that includes complicated geometry, various material properties, and the heat and structure at the centre of electromagnetic fields [10]. In this first step, material of the model should be set by a component for example stator, coil, shaft and PM. Next, proceed to the circuit analysis which circuit will be constructed for PMLG coil winding. All the resistance and number of coil will be set by the manually specific calculation. After that, proceed to the condition setting which are stator, translation and Finite element method (FEM) coil. Before FEM coil setting, the coil sequence need to be determine using equation manually. After setting the condition, proceed to mesh. Last but not least, run the simulation by study the material and select the parametric parameter to get the desire analysis. All procedure has been simplified in flow chart as shown in figure 3.3.

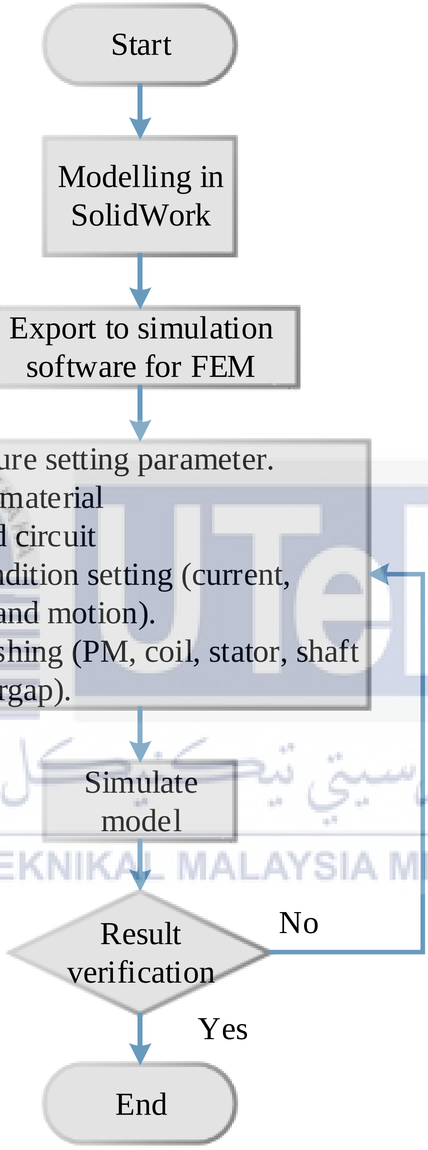


Figure 3.3: Flow chart of the methodology

3.2 Design parameter of PMLG

The PMLG will be modelled according to specific parameter setting before undergo simulation. This simulation output will reflect on model of parameter setting. Example of parameter setting are, slot opening size, coil sequence, number turn of coil and resistance of the coil.

3.2.1 Slot opening of PMLG

In this thesis, the main variable is the slot opening which will effecting the performance of generator. Slot opening is located in stator where the generator is design base on different value of slot opening height, *ht* and slot opening length, *lt* of the stator. The dimension of permanent magnet is constant throughout the project. Figure 3.4 show the slot opening of stator that will be variable in this project and this parameter variable will be test to the 15 slot 14 pole of PMLG. As show in figure, the value of slot opening height, *ht* and slot opening length, *lt* will determine the slot opening size of the stator. The value slot opening height, *ht* will be set between 0mm until 1mm whereas, slot opening length, *lt* will be set 1mm until 12mm. Overall model of this project is 24 model. The permanent magnet setting will be constant throughout this project which is Halbach arrangement method.

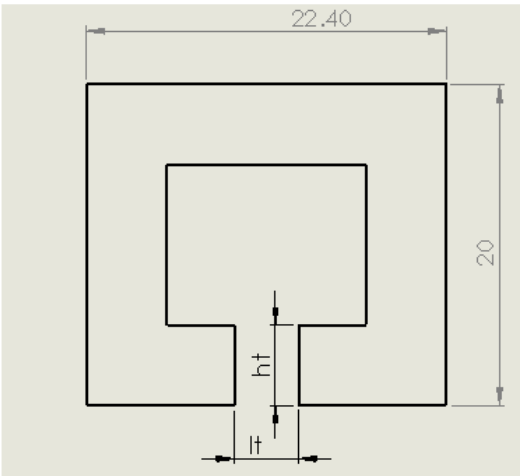


Figure 3.4: Slot opening of PMLG

3.2.2 Coil sequence

Before the model will be analyst, the coil sequence should be determine because the coil polarity will be set in the FEM software. To set the polarity, the coil sequence will be calculate manually. The PMLG will generate five phase and three phase for this project. The coil sequence will be different for three phase and five phase. The equation to calculate the coil sequence is shown below in equation (3.1). Table 3.1 show the coil sequence phase winding for 15 slot 14 pole. The winding Figure 3.5 show the angle in degree for coil winding based on equation (3.1). The degree angle in coil winding in figure 3.5 need to divide by three and five group because the generator consist of three and five phase system. The coil winding angle will be group by the nearest phase from them. For example, coil 15 angle is nearest to the red phase after been reflected thus, coil 15 belong to the red phase (refer figure 3.6 and 3.7). The coil winding angle after grouping into three and five phase can be shown in figure 3.6 and 3.7 respectively, which will determine the phase of the each coil winding inside PMLG. Negative and positive value of the coil will be used to set the condition of the FEM coil setting inside the FEM software.

$$\theta_N = \left[\left(\frac{360/N_{slot}}{360/N_{pole}} \right) \times 180 \right] + \theta_{N-1} \qquad (3.1)$$

Where θ_N is coil winding angle, θ_{N-1} is previous coil winding angle, N_{pole} is number of pole and N_{slot} is number of slot.

Table 3.1: Coil sequence phase winding for 15 slot 14 pole

Coil number, N	$\theta_N(°)$
1	0
2	168
3	336
4	144
5	312
6	120

7	288
8	96
9	264
10	72
11	240
12	48
13	216
14	24
15	192

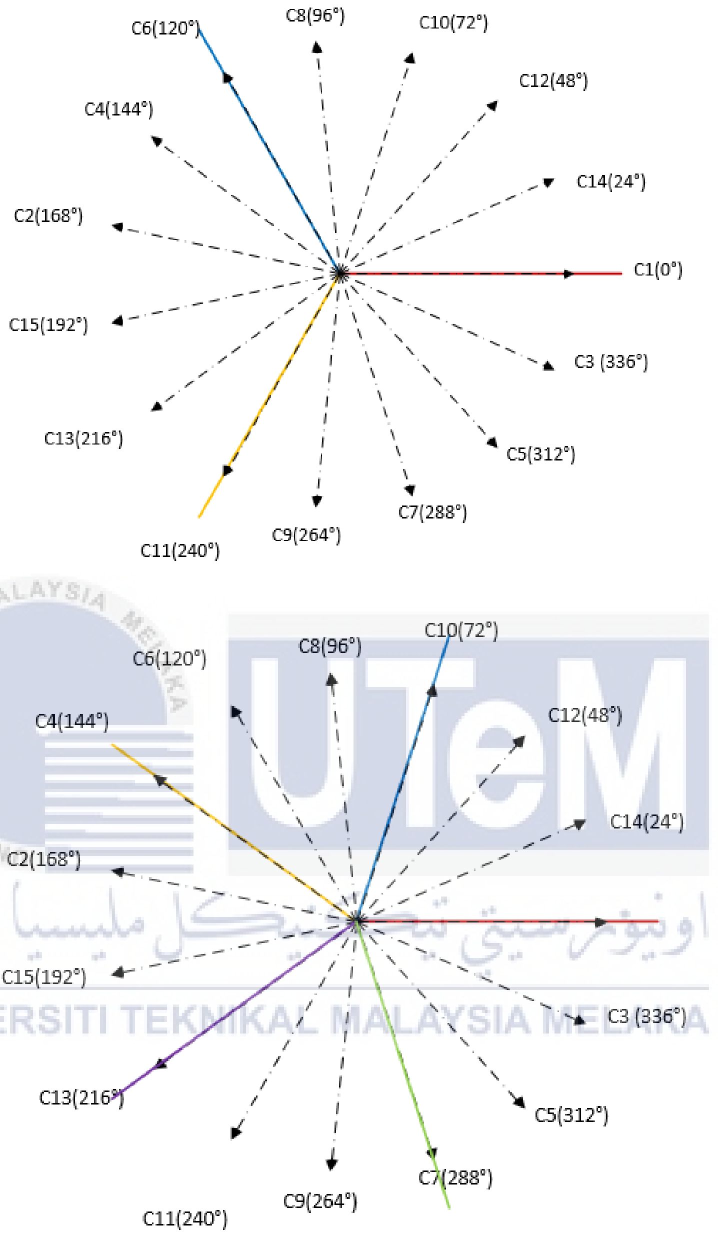


Figure 3.5: coil sequence angle of three and five phase

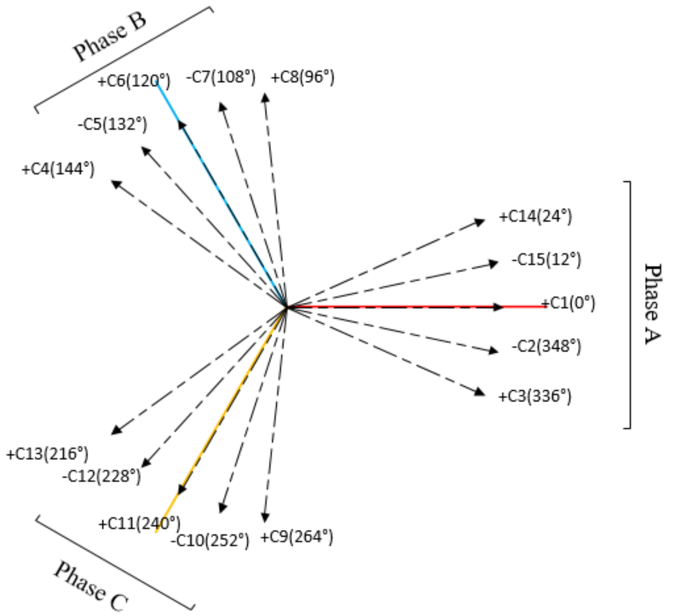


Figure 3.6: 3 phase coil sequence angle after grouping

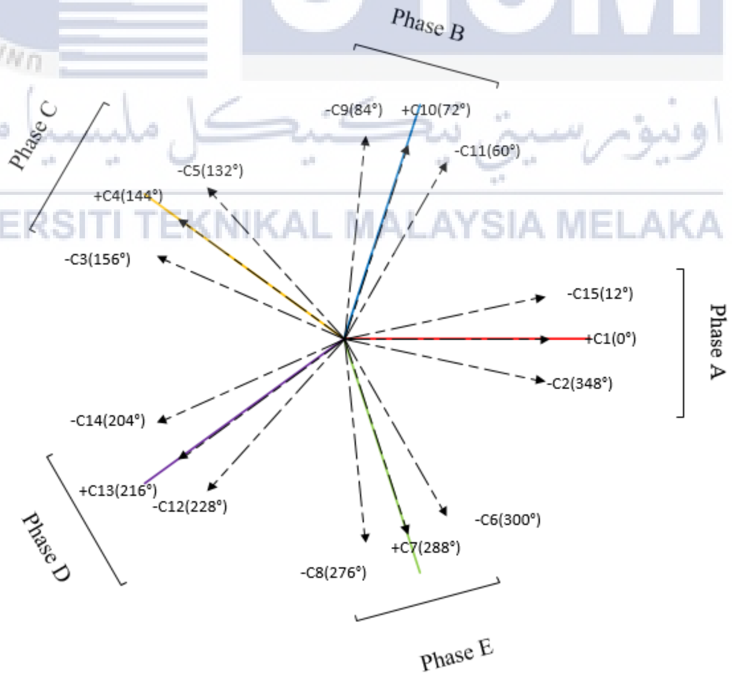


Figure 3.7: 5 phase coil sequence angle after grouping

3.2.3 Number of turn and resistance of coil winding

Every generator have its own specification of coil winding. Same goes to PMLG, it have its own number of turn and resistance. This number of turn and resistance of coil need to be set inside the FEM setting under the circuit setting. Besides, the circuit need to be draw during the setting of resistance inside the FEM software. The value of the resistance and number of turn are calculate manually using the equation (3.2) until (3.5). Table 3.2 show the value resistance and number of turn of three phase and five phase coil winding for 15 slot 14 pole. After determine the value of the resistance, the circuit need to be draw and set under circuit analysis inside the FEM software. Figure 3.9 and 3.10 show the winding circuit for three and five phase 15 slot 14 pole of PMLG respectively.

$$N = \frac{w_c - 2}{\phi_c} \times \frac{h_c - 1}{\phi_c} \times \xi \quad (3.2)$$

$$\ell_{ave} = 2\pi r_{pm} + \delta + t_{y2} + \frac{h_c}{2} \quad (3.3)$$

$$\ell_{total} = \ell_{ave} \times N \quad (3.4)$$

$$R = \frac{\rho \times \ell_{total}}{a} \quad (3.5)$$

Where ϕ_c is copper diameter, ξ is space factor, r_{pm} is radius of PM, δ is air gap, t_{y2} is yoke thickness, w_c is coil width and h_c is coil height. All the unit used in mm. The value of parameter are $\phi_c = 0.852mm, \xi = 0.6,\ r_{pm} = 15mm,\ \delta = 0.1mm, t_{y2} = 5mm, w_c = 12.40mm$ and $h_c = 10mm$. All of these parameter show in figure 3.8 below.

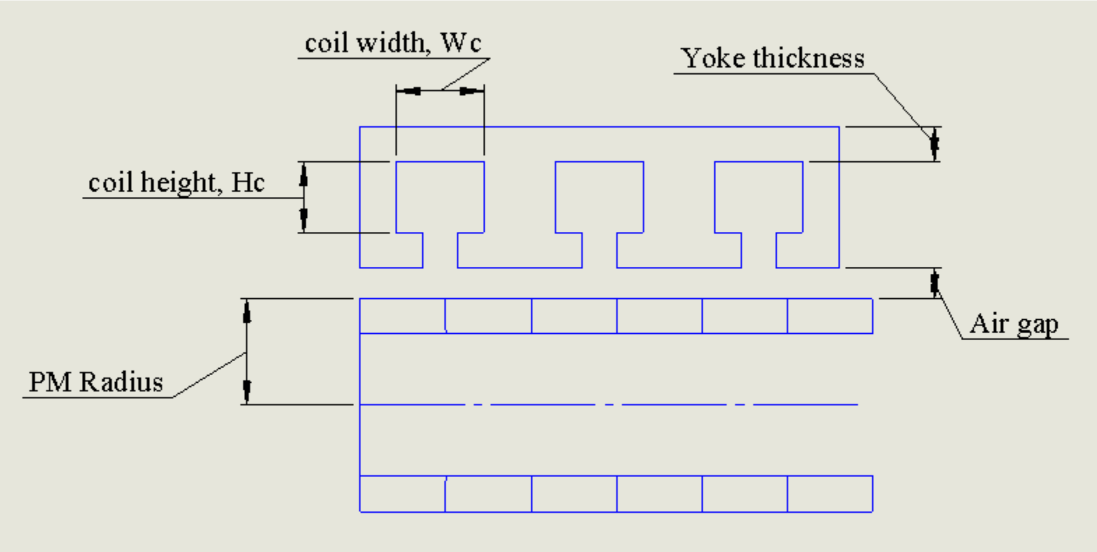


Figure 3.8: Structure parameter of PMLG

Table 3.2: Number of turn and resistance of the coil winding

	Number turn of coil, N	Resistance value, R(ohm)
15 slot 14 pole	77	0.427

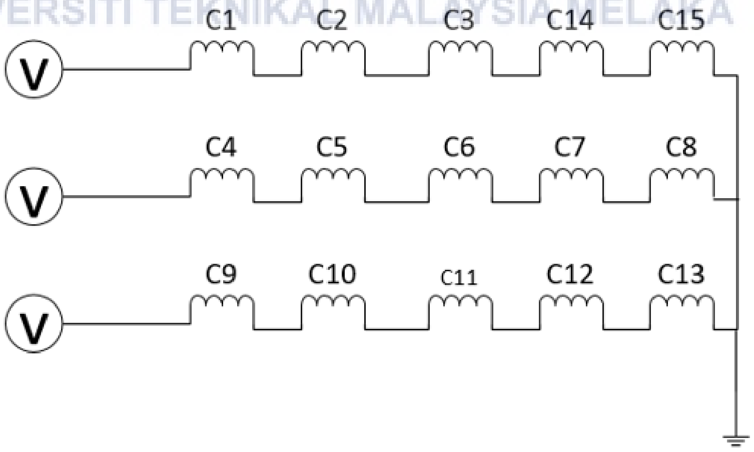


Figure 3.9: Circuit coil winding of three phase

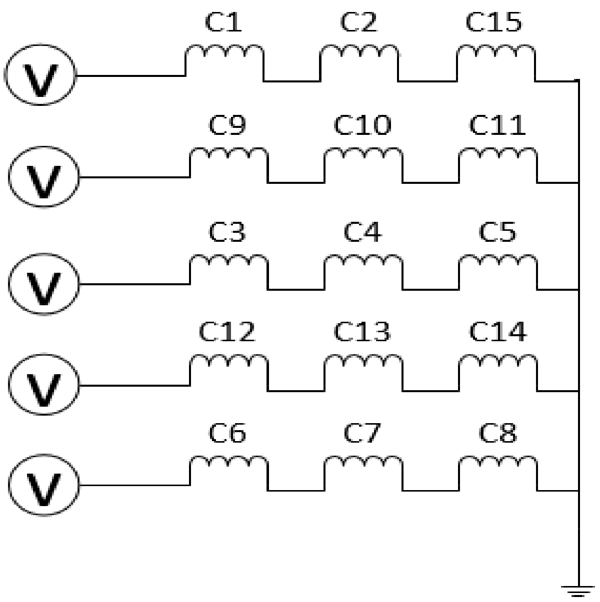


Figure 3.10: Circuit coil winding of five phase

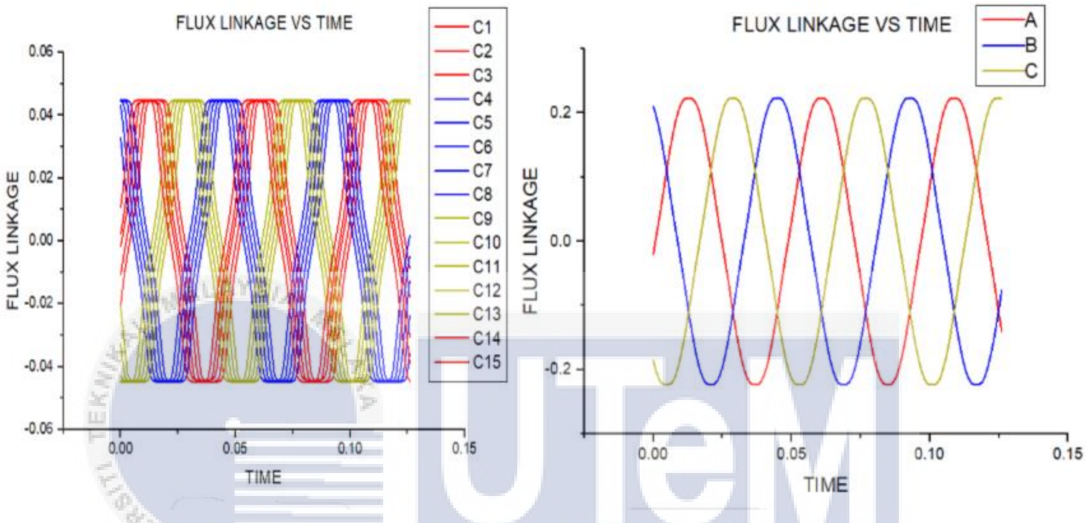
After the resistance has been set, each component of the PMLG need to undergo meshing. Meshing is process of dividing the component into small part so that the element in each component can be easily to be study during the simulation process. For 15 slot 14 pole PMLG the meshing been set are, air gap = 0.5mm, PM = 2mm, coil = 1.5mm, stator = 3mm and shaft = 5mm. The simulation has been run under no load condition with speed from 0.5m/s to 2m/s. All model of PMLG has undergo same meshing process.

Lastly, the simulation has been run under no load condition and the result are show in next chapter which is chapter 4 in aspect of magnetic flux linkage, voltage output and cogging forces.

3.3 Magnetic flux linkage

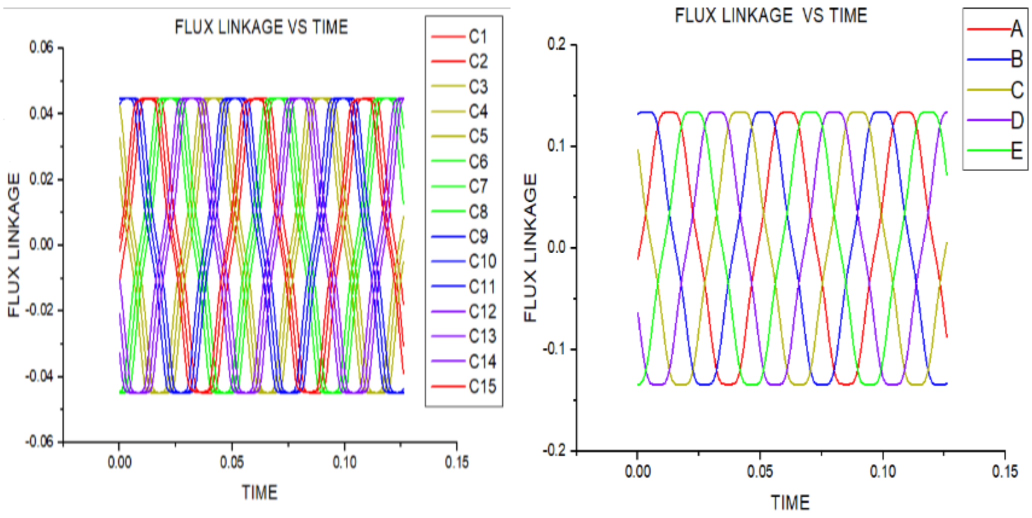
Based on figure 3.11 (a) and 3.12 (a), the figures show the graph of overall coil flux linkage which are coil 1 until coil 15 in three phase and five phase system. This figure is to prove the vector in figure 3.6 and 3.7 related with the flux linkage in figure 3.11 (a) and 3.12 (a) respectively. If refer to the figure 3.6 and 3.7, it show that each coil has their own phase shift angle. But when we arrange the coil as figure 3.9 and

3.10, the magnetic flux linkage will produce a balance three phase and five phase output as shown in figure 3.11 (b) and 3.12 (b). A balance three and five phase system in figure 3.11 (b) and 3.12 (b) is produce by adding all the flux linkage in their specific phase. For example for 3 phase system, flux linkage coil 1, 2,3,14 and 15 are add together to form specific single phase which is phase A based on figure 3.11 (b). Both of figure 3.11 and 3.12 is from simulation speed of 1.0m/s.



a) Overall coil flux linkage b) Total flux linkage

Figure 3.11: 3 phase flux linkage at speed 1.0m/s



a) Overall coil flux linkage b) Total flux linkage

Figure 3.12: 5 phase flux linkage at speed 1.0m/s

3.4 Summary

This chapter is about the procedure how to run the simulation using FEM software. But before run the simulation, the model need to be design using SolidWork software and then transfer to the FEM software. After that, the model need to be set inside the FEM software under specific setting which are material setting, circuit analysis setting, condition setting and meshing.

CHAPTER 4

INTRODUCTION

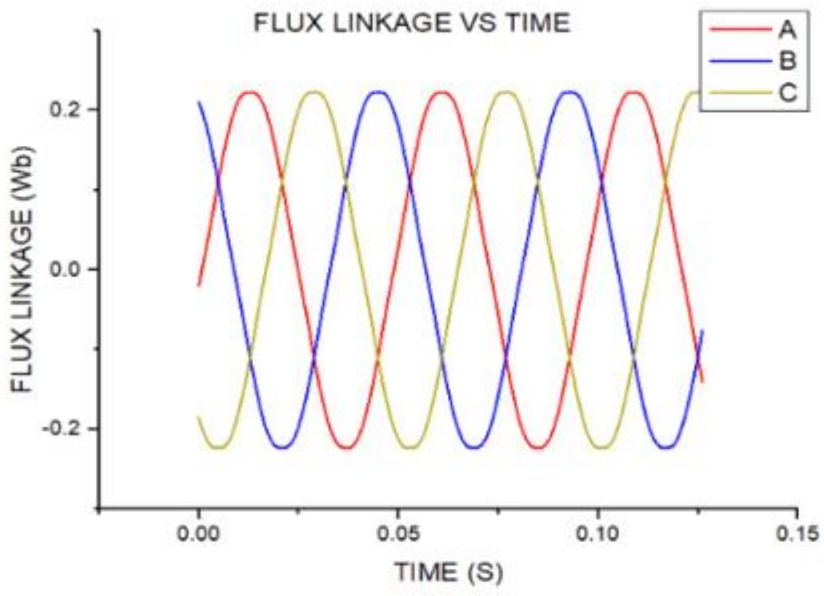
In this chapter, the result will be show based on the slot opening size which are height and length of slot opening of the PMLG. The result are based on three phase and five phase topology. The PMLG analysis will be focus on cogging force, Vrms and total harmonic distortion, THD by the different slot opening size.

4.1 Flux linkage characteristic

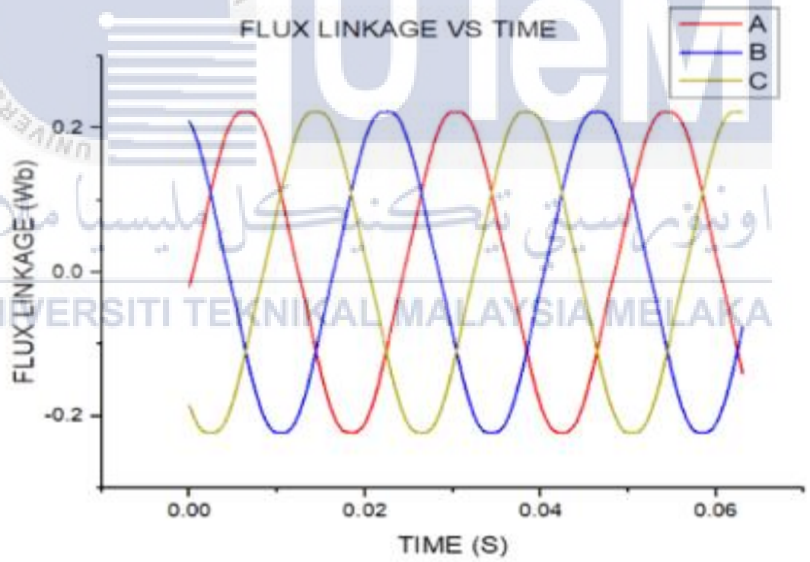
Figure 4.1 a) and 4.1 b) show the flux linkage of three phase produce by the same slot opening of PMLG with different speed condition. Figure 4.1 a) show the flux linkage at speed of 1.0m/s meanwhile, figure 4.1 b) show flux linkage at speed 2.0m/s. PMLG show same reading of flux linkage although the PMLG is simulate at different speed condition. Both speed condition show flux linkage reading of 0.22Wb.

Figure 4.2 a) and 4.2 b) show the flux linkage of five phase by the same slot opening of PMLG with different speed condition. It show same characteristic as three phase PMLG which both flux linkage show a reading of 0.13Wb. Even though the reading of three and five phase flux linkage do not show the same reading but it have some similarity which are PMLG produce same reading of flux at different speed condition with the same slot opening of PMLG. This both phase system also show the five phase PMLG produce smaller flux linkage compare to the three phase system.

As the conclusion, PMLG produced different flux linkage at different phase system but show same reading of flux linkage at different speed condition.

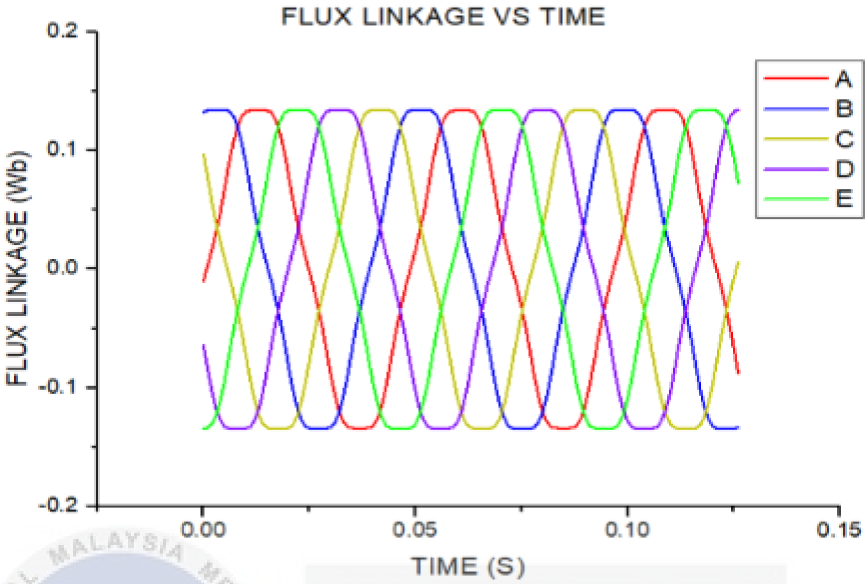


a) Speed 1.0 m/s

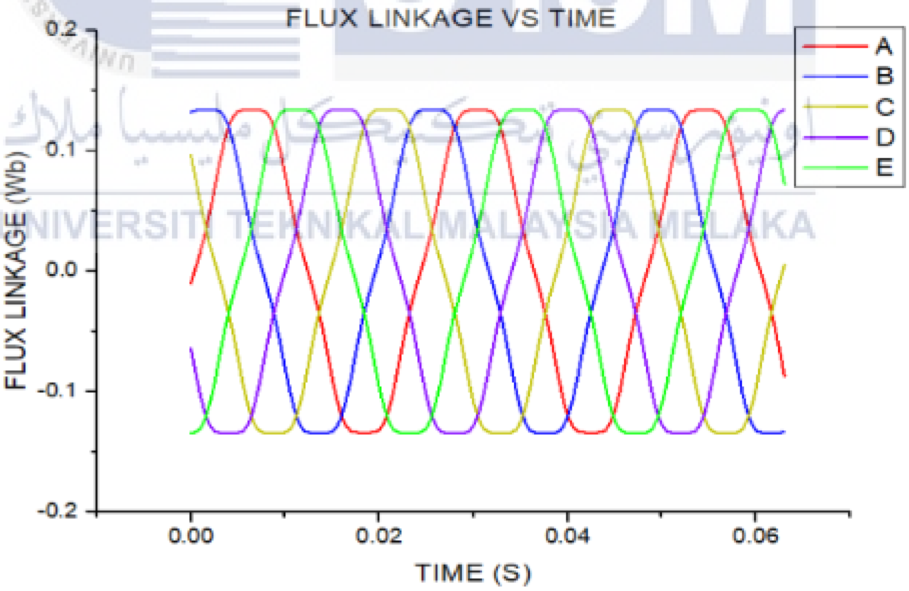


b) Speed 2.0 m/s

Figure 4.1: Three phase flux linkage of PMLG at speed 1.0 m/s and 2.0m/s



a) Speed 1.0 m/s

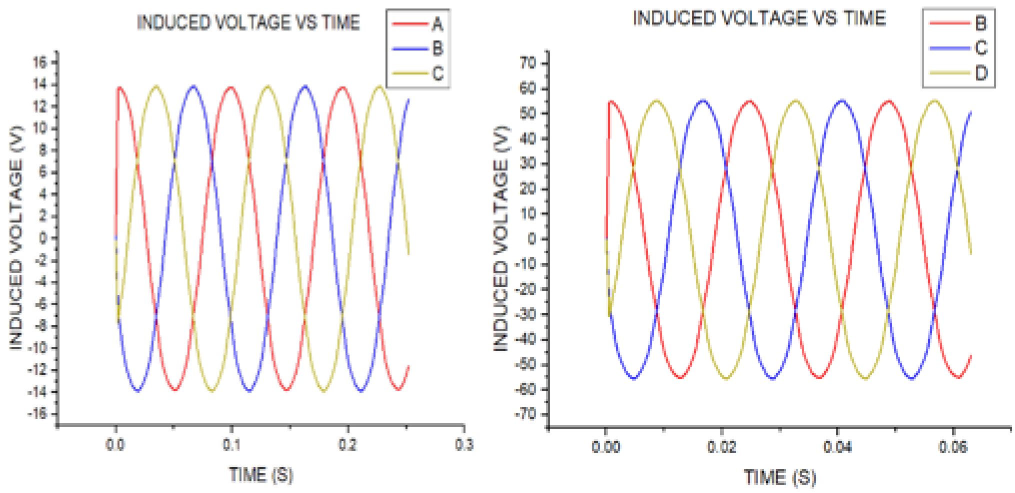


b) Speed 2.0 m/s

Figure 4.2: Five phase flux linkage of PMLG at speed 1.0 m/s and 2.0m/s

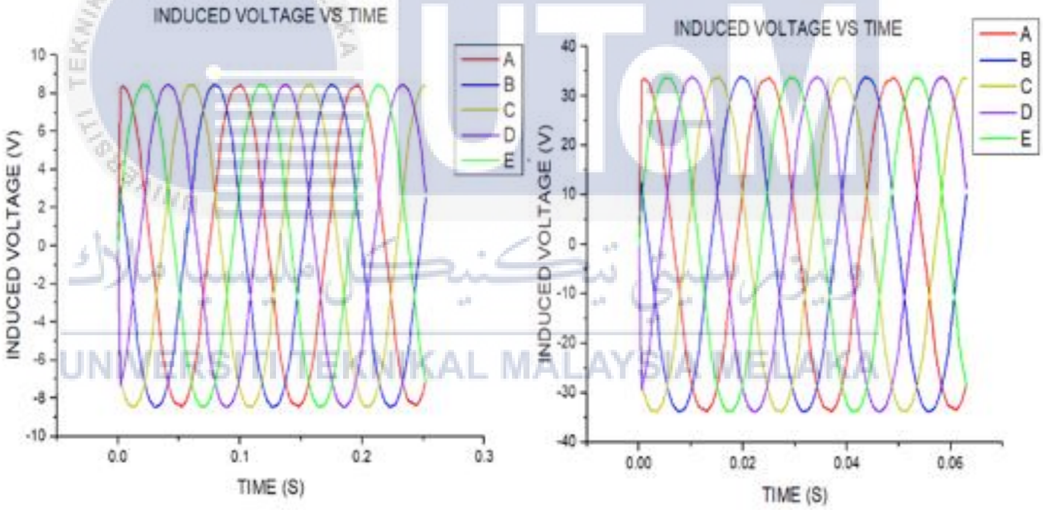
4.2 No-load voltage characteristic

Figure 4.3 and 4.4 show the induced voltage of three phase and five phase PMLG based on the simulation. It has been show that the voltage induced by the three phase PMLG have higher value compare to five phase PMLG. The figure 4.3 and 4.4 is produced form figure 3.11 and 3.12 b) based on the formula (2.1) which is Lenz's law in chapter 2. The three phase and five phase PMLG have been simulate under different speed condition. At speed of 0.5 m/s, three phase and five phase PMLG induced maximum voltage of 13.8V and 8.43V respectively. Whereas when the speed increase to 2.0 m/s, the maximum induced voltage of three phase and five phase PMLG increase to 55.3V and 33.85V respectively. Based on this observation, induced voltage increase as the speed of PMLG increase. Decreasing value of induced voltage from three phase to five phase PMLG is due to arrangement of coil in figure 3.9 and 3.10 in chapter 3. Based on figure 3.9, the three phase PMLG consist more number of coil in each phase thus the resistance of each phase getting higher. If referring to Ohm's law, the higher the resistance, the higher the voltage produced. Meanwhile in the five phase PMLG, number of coil is less compare to the three phase PMLG thus, the resistance in each phase is lower. To recap everything up, the induced voltage will decrease as the phase of the PMLG increase whereas, the induced voltage can be increased by increasing the speed of the PMLG.



a) Speed 0.5 m/s b) Speed 2.0 m/s

Figure 4.3: Three phase induced voltage of PMLG

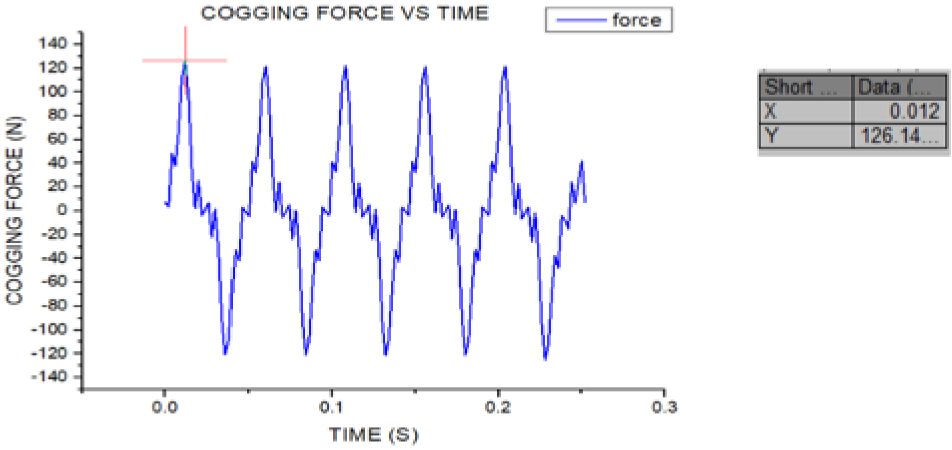


a) Speed 0.5 m/s b) Speed 2.0 m/s

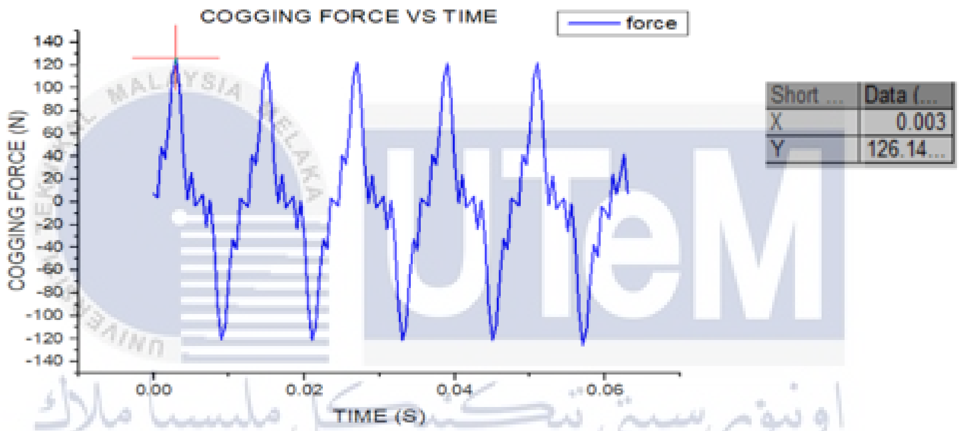
Figure 4.4: Five phase induced voltage of PMLG

4.3 Cogging force characteristic

Figure 4.5 show the result of cogging force at different speed condition whereas, figure 4.6 show the result of cogging force at different phase of the PMLG. The graph of different speed and different phase show almost similar reading of cogging force which is 126.13N until 126.14 N. But cogging force of PMLG will be varies if the slot opening of the PMLG change. This can be proved in figure 4.7. Figure 4.7 show the maximum cogging force that been produce by the PMLG if the slot opening is change from 1mm to 12mm. Blue line in figure 4.7 represent slot opening height of 0mm whereas red line represent slot opening height of 1mm. Slot opening height of 1mm produce higher cogging force compare to slot opening height of 0mm. Maximum value of cogging force produced by the PMLG is at slot opening height of 1mm, which is at reading of 170.41N. The figure 4.7 also show the cogging force of the PMLG produced is inconsistence and hard to predict if the slot opening of the PMLG is change. This cogging force is due to interaction between the permanent magnet of the mover and the stator slot of coil winding of the PMLG. Thus as the opening slot is varies, it will change the structure of the stator of the PMLG and this will effecting cogging force that been produced by the PMLG.

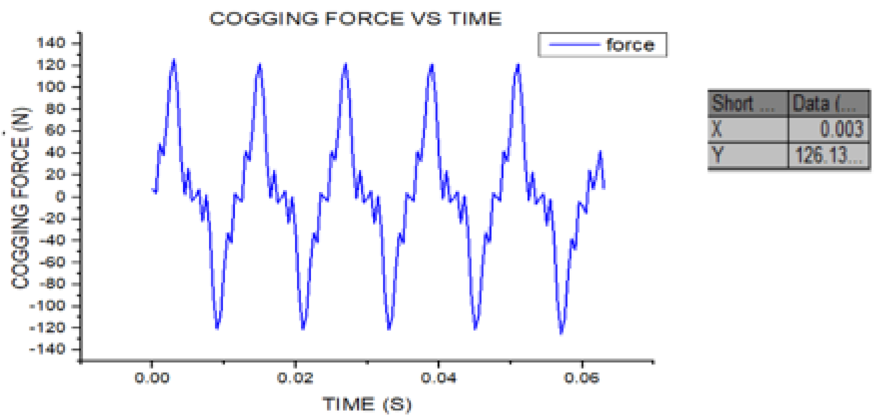


a) Speed 0.5 m/s

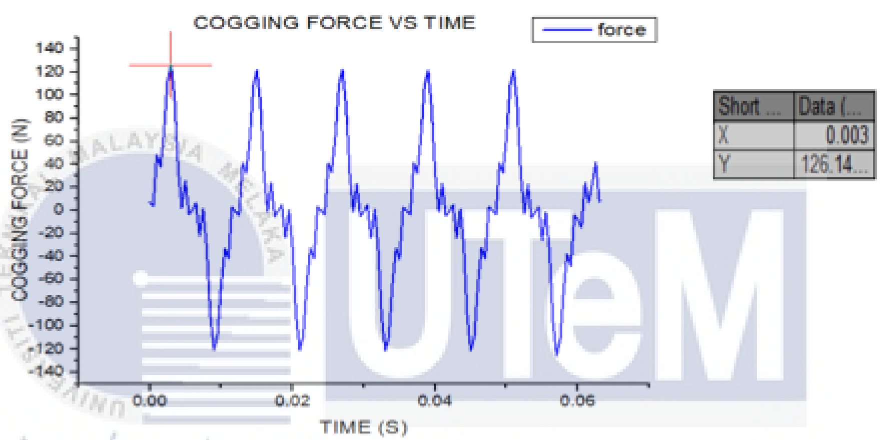


b) Speed 2.0 m/s

Figure 4.5: Cogging force with vary speed condition



a) Three phase PMLG



b) Five phase PMLG

Figure 4.6: Cogging force with vary phase system

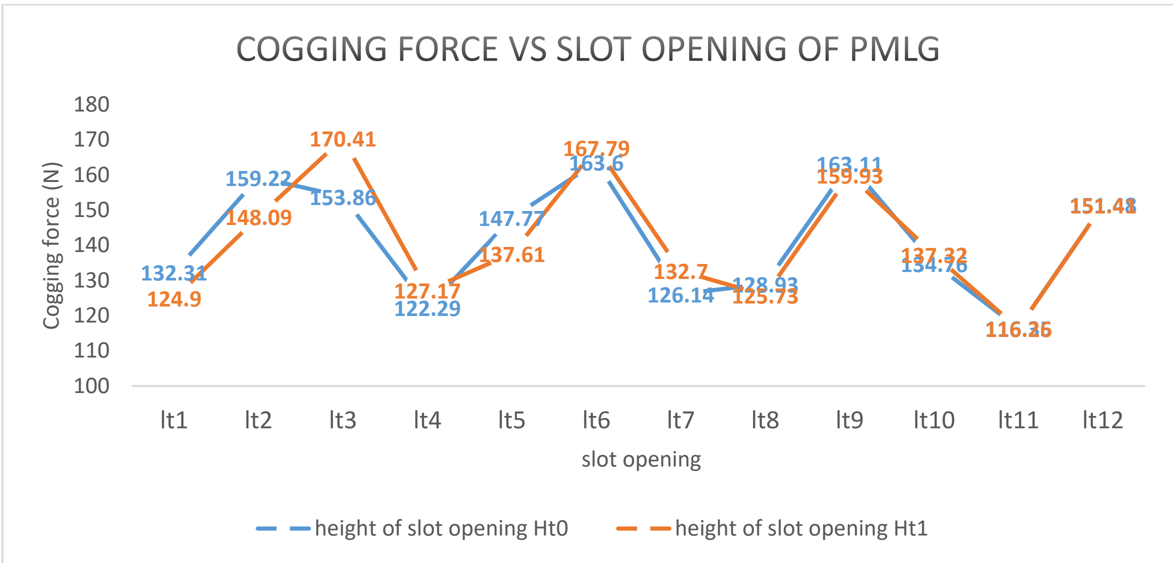


Figure 4.7: Cogging force vs. slot opening (model) of PMLG

4.4 Vrms 15 slot 14 pole of PMLG with no load characteristics

Figure 4.8 until 4.11 show the Vrms value that been produce with no load condition by the different slot opening of PMLG which in three phase and five phase topology. This value is obtain by using equation 4.1 from the output voltage that been discuss in sub-chapter 4.2. To get the Vrms value, first phase of the output voltage of each speed of the PMLG is taken out and put inside OrginPro software. After that, the first phase of the output voltage will been analysis by the OrginPro software under integral method which represent the equation 4.1 below. The Vrms can be obtain manually using equation 4.1 which V^2 is the output voltage of the first phase.

Figure 4.8 and 4.9 show three phase Vrms value of the PMLG which represent of slot opening height of 0mm and 1mm (ht0-ht1) respectively. In each figure 4.8 and 4.9, all the Vrms value of the slot opening length is been show which are from 1mm to 12mm (lt1-lt12). What can be observe from this two graph in this figures is the Vrms that been produce of the PMLG is only small different changes. For example in figure 4.8 which represent slot opening height of 0mm and slot opening length of 1mm (ht0, lt1) show value of 42.52V at speed 2.0m/s whereas, in figure 4.9 with slot opening height of 1mm and slot opening length of 1mm (ht1, lt1) show value of 42.56V at speed 2.0m/s. If compare these two model of PMLG (ht0, lt1 and ht1, lt1), it only show small changes between this two. Thus, increasing the value of the slot opening height of the PMLG will increase slightly the value of the Vrms produced.

In figure 4.8, it show twelve models of PMLG which are from model ht0, lt1 until ht0, lt12. What can be observe base on this graph in this figure, the value of Vrms produce is getting decrease from model ht0, lt1 to ht0, lt12. The model of PMLG ht0, lt1 and ht0, lt12 show the value of 42.52V and 37.36V respectively at speed 2.0m/s.

In figure 4.9, it also show twelve model of the PMLG from model ht1, lt1 until ht1, lt12. It show same characteristic as graph in figure 4.8 which by the value of the Vrms is getting decrease as the slot opening length is increases. Ht1, lt1 and ht1, lt12 show the value of 42.56V and 37.39V respectively at speed 2.0m/s. Thus, the bigger the slot opening length of the PMLG, the smaller the Vrms produced by the PMLG.

$$V_{rms} = \sqrt{\frac{1}{T}\int_0^T V^2\, dt} \qquad (4.1)$$

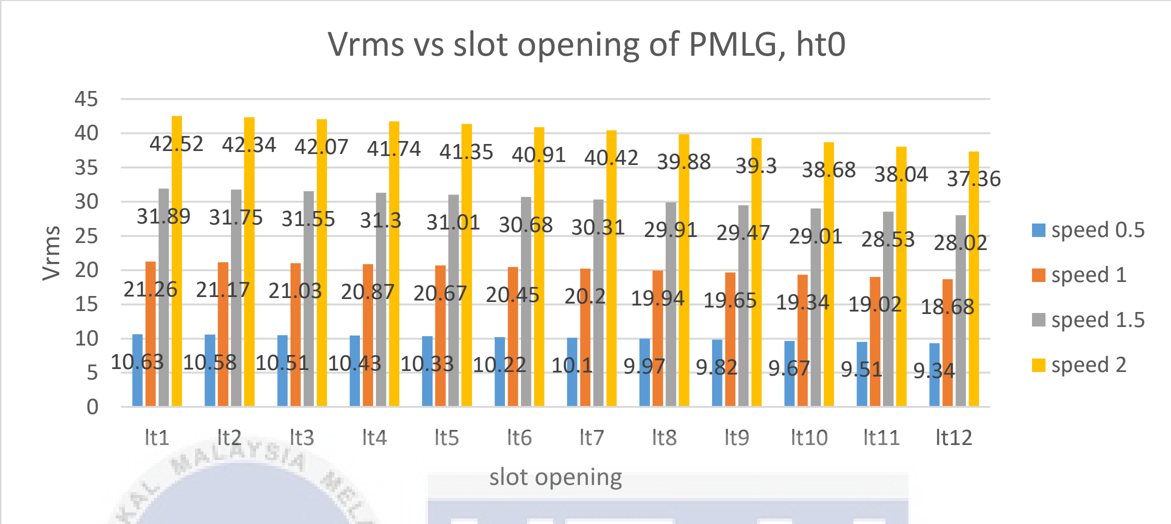


Figure 4.8: Vrms vs. slot opening of three phase PMLG, slot opening 0mm (ht0)

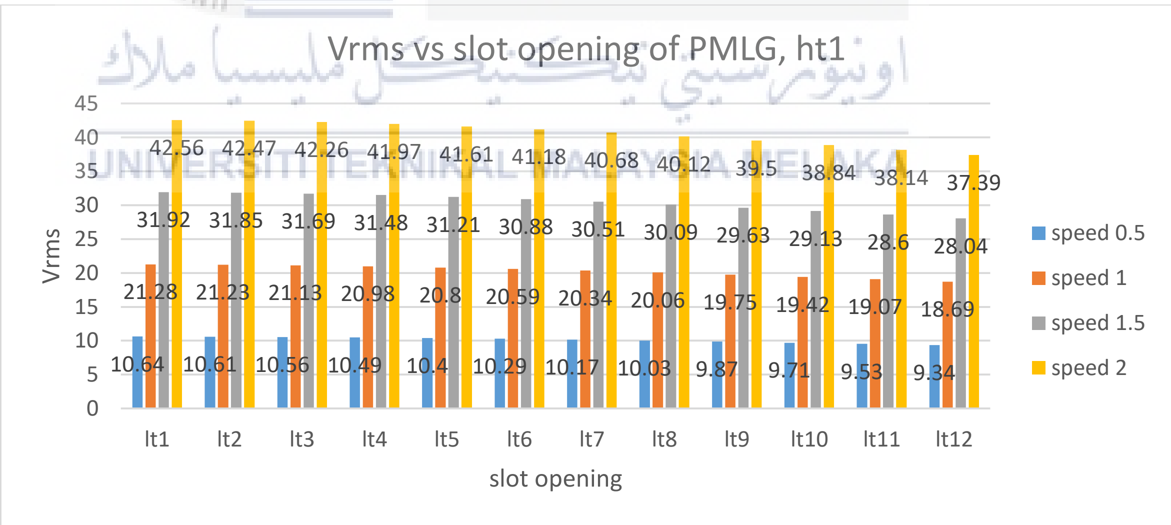


Figure 4.9: Vrms vs. slot opening of three phase PMLG, slot opening 1mm (ht1)

Figure 4.10 and 4.11 show five phase Vrms value of the PMLG which represent of slot opening height of 0mm and 1mm (ht0-ht1) respectively. As in figure 4.10 and 4.11, the value of Vrms increase slightly when the slot opening height increase from

0mm to 1mm. For example in model ht0, lt1 and ht1, lt1of PMLG, the Vrms value produced are 26.97V and 21.17V respectively at speed of 2.0m/s.

In figure 4.10, it show twelve models of PMLG which are from model ht0, lt1 until ht0, lt12. What can be observe base on this graph in this figure, the value of Vrms produce is getting decrease from model ht0, lt1 to ht0, lt12. The model of PMLG ht0, lt1 and ht0, lt12 show the value of 26.97V and 23.14V respectively at speed 2.0m/s.

In figure 4.11, it also show twelve model of the PMLG from model ht1, lt1 until ht1, lt12. It show same characteristic as graph in figure 4.10 which by the value of the Vrms is getting decrease as the slot opening length is increases. Ht1, lt1 and ht1, lt12 show the value of 27.14V and 23.16V respectively at speed 2.0m/s.

To recap everything up, both of three phase and five phase PMLG show same characteristic which by the Vrms getting decreases as the slot opening length getting increases meanwhile, the Vrms getting increase slightly as the slot opening height getting increase. But, when the PMLG has been change from three phase to five phase, it show a significant drop of the Vrms produce by the PMLG. For slot opening height of 0mm, three phase and five phase PMLG produced Vrms of 42.52V and 26.97V respectively at speed of 2.0m/s. It show 15.55V drop of Vrms when the PMLG change from three phase to five phase topology.

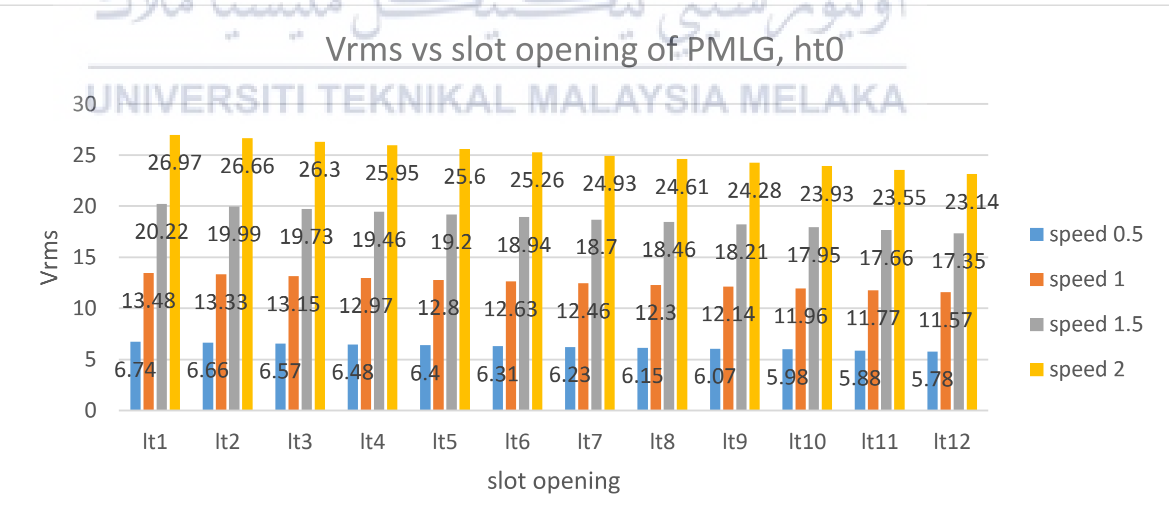


Figure 4.10: Vrms vs. slot opening of five phase PMLG, slot opening height 0mm (ht0)

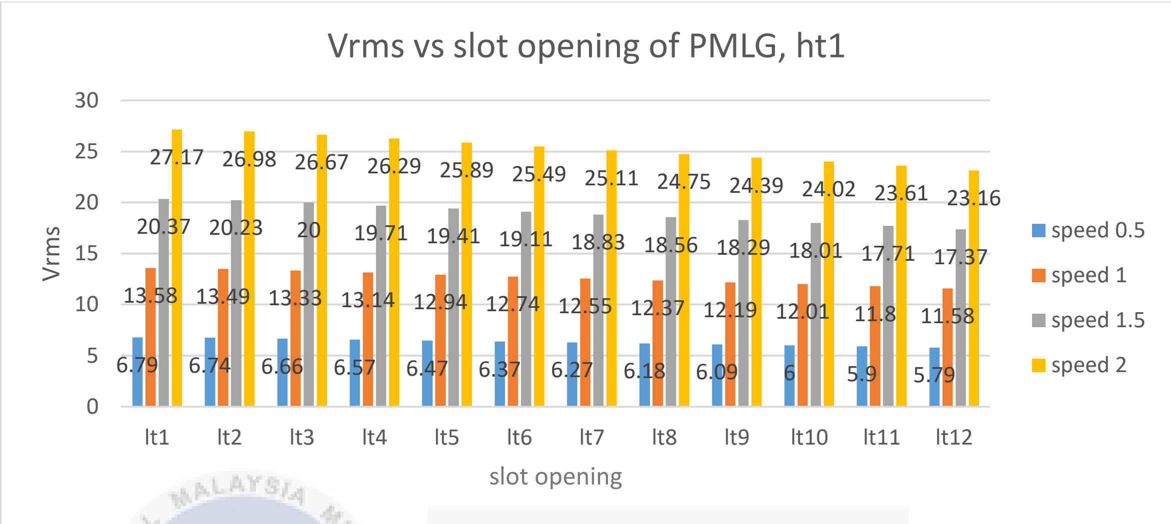


Figure 4.11: Vrms vs. slot opening of five phase PMLG, slot opening height 1mm (ht1)

4.5 THD 15 slot 14 pole of PMLG with no load characteristics

Figure 4.12 until 4.15 show the total harmonic distortion (THD) that been produced with no load condition by the different slot opening of PMLG which in three phase and five phase topology. This value is obtain by using equation 4.2 where, $V_{0,rms}$ is overall RMS voltage, and $V_{1,rms}$ is fundamental RMS voltage of the PMLG. THD is indicate how much the distortion in the voltage due to harmonic inside the signal. Level of THD indicate how well the signal is. The lower the THD the better the performance. In power system, low value of THD means low value of peak current, core losses, emission and heating in generator or motor. THD value also determine sinusoidal shape of the voltage produced. The pure sinusoidal wave of voltage indicate no distortion in the voltage signal. Thus higher THD of voltage will show no shape of sinusoidal wave in the voltage signal.

Figure 4.12 and 4.13 show three phase THD value of the PMLG which represent of slot opening height of 0mm and 1mm (ht0-ht1) respectively. In each figure

4.12 and 4.13, all the THD value of the slot opening length are shown from 1mm to 12mm (lt1-lt12). What can be observe from this two graph in this figures is the THD that been produce by the PMLG shows small different changes. For example, in figure 4.12 which represent slot opening height of 0mm and slot opening length of 1mm (ht0, lt1) show THD value of 66.22% at speed 2.0m/s whereas, in figure 4.13 with slot opening height of 1mm and slot opening length of 1mm (ht1, lt1) show value of 66.48% at speed 2.0m/s. If compare these two model of PMLG (ht0, lt1 and ht1, lt1), it only show small changes between this two. Thus, by increasing the value of the slot opening height of the PMLG from 0mm to 1mm will increase slightly the value of the THD. But when slot opening length reach 7mm (lt7), the pattern of THD between this two (ht0 and ht1) are change. During slot opening length of 7mm until 11mm, the THD of the slot opening height 1mm, ht1 show slightly smaller value compare to slot opening height 0mm, ht0. The THD value eventually become the same at slot opening length of 12mm, ht12 which is 65.7%.

In figure 4.12, the PMLG show maximum value of THD during at slot opening length of 1mm, (ht0, lt1) whereas the lowest THD show at slot opening length of 7mm, (ht0, lt7). The highest value of THD is 66.22% whereas the lowest THD is 65.52%. The THD gradually decrease slightly when the slot opening length increase, but slightly increase when reach slot opening length of 8mm to the 12mm. Besides that, the PMLG show the speed of the PMLG do not effecting the THD. PMLG with same slot opening size show almost the same value when the speed of PMLG increase from 0.5m/s to 2.0m/s.

Meanwhile in figure 4.13, the PMLG show maximum value of THD during at slot opening length of 1mm, (ht1, lt1) whereas the lowest THD show at slot opening length of 7mm, (ht1, lt7). The highest value of THD is 66.48% whereas the lowest THD is 65.51%. The THD gradually decrease slightly when the slot opening length increase, but slightly increase when reach slot opening length of 8mm to the 12mm. Besides that, the PMLG show the speed of the PMLG do not effecting the THD as same as graph in figure 4.12. PMLG with same slot opening size show almost the same value when the speed of PMLG increase from 0.5m/s to 2.0m/s.

$$\mathrm{THD}_v = \frac{\sqrt{\mathrm{V_{0,rms}}^2 - \mathrm{V_{1,rms}}^2}}{\mathrm{V_{1,rms}}} \times 100 \qquad (4.2)$$

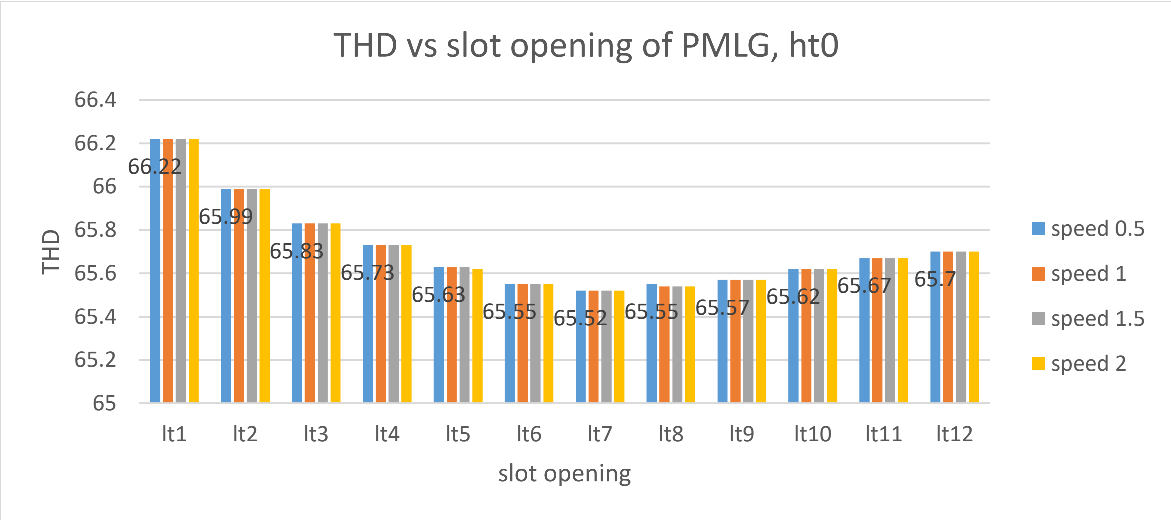


Figure 4.12: THD vs. slot opening of three phase PMLG, slot opening height 0mm (ht0)

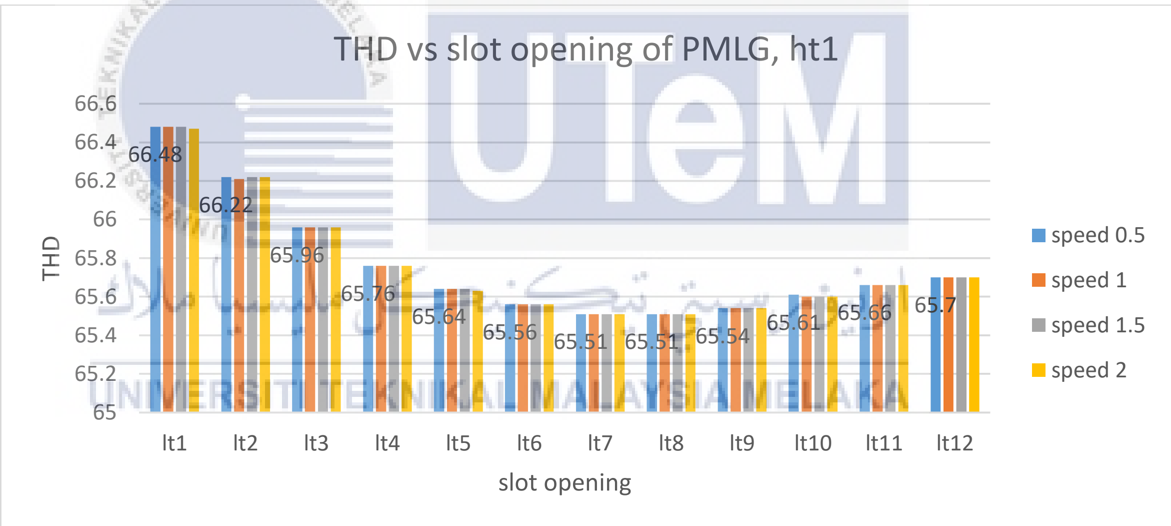


Figure 4.13: THD vs. slot opening of three phase PMLG, slot opening height 1mm (ht1)

In figure 4.14 and 4.15 show five phase THD value of the PMLG which represent of slot opening height of 0mm and 1mm (ht0-ht1) respectively. In each figure 4.14 and 4.15, all the THD value of the slot opening length are shown from 1mm to 12mm (lt1-lt12). What can be observe from this two graph in this figures is the THD that been produce by the PMLG shows small different changes. For example, in figure 4.14 which represent slot opening height of 0mm and slot opening length of 1mm (ht0, lt1) show THD value of 72.34% at speed 2.0m/s whereas, in figure 4.15 with slot opening height of 1mm and slot opening length of 1mm (ht1, lt1) show value of 73.94% at speed 2.0m/s. If compare these two model of PMLG (ht0, lt1 and ht1, lt1), it only show small changes between this two. Thus, by increasing the value of the slot opening height of the PMLG from 0mm to 1mm will increase slightly the value of the THD. But when slot opening length reach 8mm (lt8), the pattern of THD between this two (ht0 and ht1) are change. During slot opening length of 8m until 11mm, the THD of the slot opening height 1mm, ht1 show slightly smaller value compare to slot opening height 0mm, ht0. The THD value eventually become the same at slot opening length of 12mm, ht12 which is 66.39%.

In figure 4.14, the PMLG show maximum value of THD during at slot opening length of 1mm, (ht0, lt1) whereas the lowest THD show at slot opening length of 7mm, (ht0, lt7). The highest value of THD is 72.34% whereas the lowest THD is 65.43%. The THD gradually decrease slightly when the slot opening length increase, but slightly increase when reach slot opening length of 8mm to the 12mm. Besides that, the PMLG show the speed of the PMLG do not effecting the THD. PMLG with same slot opening size show almost the same value when the speed of PMLG increase from 0.5m/s to 2.0m/s.

Meanwhile in figure 4.15, the PMLG show maximum value of THD during at slot opening length of 1mm, (ht1, lt1) whereas the lowest THD show at slot opening length of 8mm, (ht1, lt8). The highest value of THD is 73.94% whereas the lowest THD is 65.4%. The THD gradually decrease slightly when the slot opening length increase, but slightly increase when reach slot opening length of 9mm to the 12mm. Besides that, the PMLG show the speed of the PMLG do not effecting the THD as same as graph in figure 4.12, 4.13 and 4.14. PMLG with same slot opening size show almost the same value when the speed of PMLG increase from 0.5m/s to 2.0m/s.

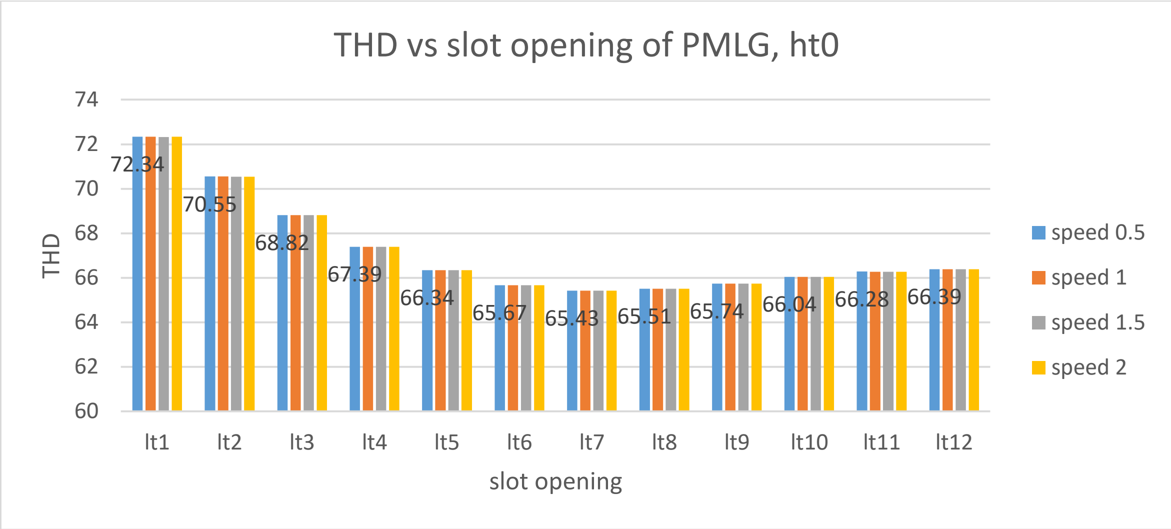


Figure 4.14: THD vs. slot opening of PMLG five phase, ht0

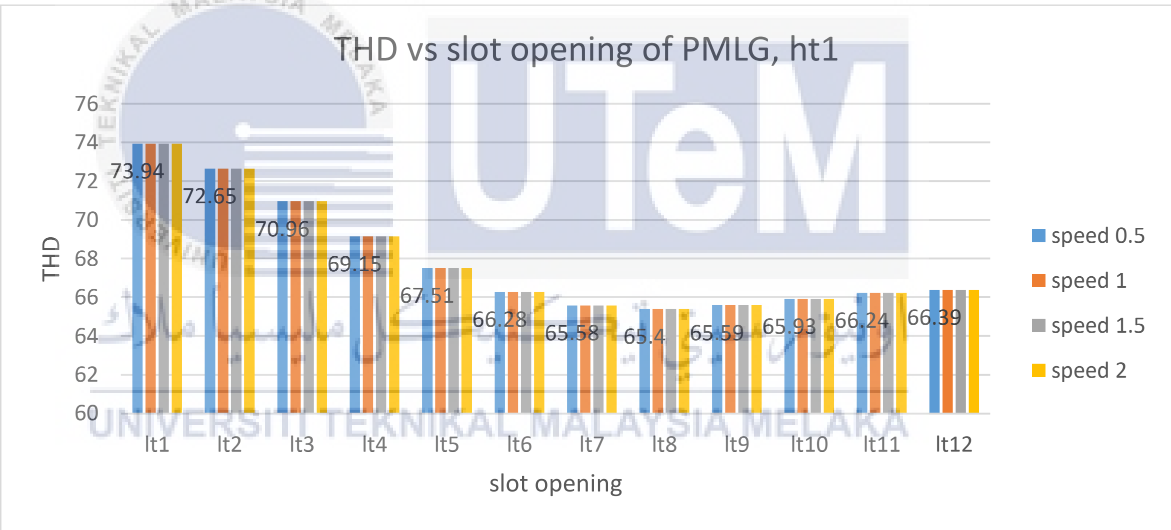


Figure 4.15: THD vs. slot opening of PMLG five phase, ht1

4.6 Optimum PMLG analysis

After go through the analysis on Vrms and THD of the PMLG, they're going to be a pro and cons in order to choose suitable slot opening (model) of the PMLG. Base on this two analysis we can see the performance of the PMLG is influence by the slot opening of the stator.

In three phase analysis, in order to get maximum output voltage, the slot opening length of the PMLG should be small. For example, the maximum voltage that can be reach by PMLG with slot opening height of 0mm and slot opening length of 1mm (ht0, lt1) is 42.52V. This output voltage can be increased slightly to 42.56V when the height of the slot opening is increase to 1mm while the slot opening length still remain the same at 1mm (ht1, lt1). In term of THD analysis, to get lower THD the slot opening length should at 7mm. For example, with slot opening height of 0mm and slot opening length of 7mm (ht0, lt7), the THD produced can be low as 65.52%. But when the slot opening height increase to 1mm while the slot opening length still remain the same (ht1, lt7), the THD can be reduce to 65.51%.

In five phase analysis, in order to get maximum output voltage, the slot opening length of the PMLG should be small. For example, the maximum voltage that can be reach by PMLG with slot opening height of 0mm and slot opening length of 1mm (ht0, lt1) is 26.97V. This output voltage can be increased slightly to 27.17V when the height of the slot opening is increase to 1mm while the slot opening length still remain the same at 1mm (ht1, lt1). In term of THD analysis, to get lower THD the slot opening length should at 7mm and 8mm. For example, with slot opening height of 0mm and slot opening length of 7mm (ht0, lt7), the THD produced can be low as 65.43%. But when the slot opening height increase to 1mm and the slot opening length increase to 8mm (ht1, lt8), the THD can be reduce to 65.4%.

In conclusion, to get maximum output voltage, the THD of the PMLG must be sacrifice while in the other hand, lower THD can be archive by lower down the voltage output of the PMLG.

CHAPTER 5

5.1 Conclusions

The PMLG is among the simples electric machine of energy conversion. It's also one of the basic construction of the free piston linear alternator and wave energy convertor. Thus, by doing this research, it will contribute on development wave energy convertor and free piston linear alternator.

The PMLG consist of stator, coil, permanent magnet and shaft. The electricity is generate by the PMLG through linear motion when the coil of the stator winding cut the flux of permanent magnet. To observe the effect slot opening of the stator, the PMLG need to be modelled using SolidWork software and then transfer to FEM software for simulation. These simulation result will be analyst in certain aspect which are cogging force, output voltage (Vrms) and total harmonic distortion (THD).

The result show, in order to get maximum output voltage (Vrms), the slot opening length of the PMLG should be small. In THD analysis, to get lower value of THD, the slot opening length must in between 7mm to 8mm. Thus, to get maximum output voltage, the THD of the PMLG must be sacrifice while in the other hand, lower THD can be archive by lower down the voltage output of the PMLG.

5.2 Recommendation

For recommendation, there is one suggestion need to be voice out. I recommend to create hardware for this research. I do believe this research will give huge impact in electrical vehicle industry in Malaysia. Thus, by do the research in hardware, this will attract investor to invest in this research and increase the PMLG development in Malaysia. Not only in electrical vehicle industry, this research also can contribute in wave energy converter (WEC), which we can harvest tide energy into electrical energy and lead into renewable energy. Linear generator is simplest compare to rotary generator thus, it is less maintenance and less using gearbox system which lead to lower cost construction.

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