COMPARISON DIFFERENT TYPE OF MATERIAL FOR 15 SLOT 14 POLE PERMANENT MAGNET LINEAR GENERATOR

MUHAMMAD FIKRI BIN ROZUKI

BACHELOR OF ELECTRICAL ENGINEERING WITH HONORS
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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MUHAMMAD FIKRI BIN ROZUKI

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in partial fulfillment of the requirements for the degree of
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DECLARATION

I declare that this thesis entitled "COMPARISON DIFFERENT TYPE OF MATERIAL FOR 15 SLOT 14 POLE PERMANENT MAGNET LINEAR GENERATOR is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

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Name	:	MUHAMMAD FIKRI BIN ROZUKI
Date	:	

APPROVAL

I hereby declare that I have checked this report entitled "Comparison Different Type Of Material For 15 Slot 14 Pole Permanent Magnet Linear Generator" and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Mechatronics Engineering with Honours

Signature : ....

Supervisor Name : ....

Date : ....

DEDICATIONS

To my beloved mother and father

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ABSTRACT

This project about the analysis and comparison the performance of generator at different structure setting under three phase. The project consist of two main component which is permanent magnet as mover made up of NdFeB magnet, SmCo magnet, Alnico magnet and Ceramic magnet by using Halbach array configuration for the setting of direction of magnet that work on the permanent magnet surface and the stator consist 15 slot to place the coil inside. The objective of this project are model and simulate 15 slot 14 pole of permanent magnet linear generator using Ansoft Maxwell software and analyze the permanent magnet linear generator performance with different type of permanent magnet apply on it. In order to achieve the objective, the model of 15 slot 14 pole of PMLG has to construct in Solidwork software. For the simulation result, the model is need to transfer into the Ansoft Maxwell software in 2D to get the analysis result. The speed of the mover moving in 0.5 m / s with the step time 2 ms and stop time 0.1 s in analysis setup of Ansoft Maxwell software. However, the speed of the mover is changed from 0.5 m/s to 1.5 m/s. The focus of this project, to observe the magnetic flux density, flux linkage, cogging force and induce voltage. By the same model, the experiment will be extend by vary the speed mover and the induced voltage is observed.

ABSTRAK

Projek ini mengenai analisis dan perbandingan prestasi penjana pada penetapan struktur yang berbeza di bawah tiga fasa. Projek ini terdiri daripada dua komponen utama iaitu magnet kekal sebagai penggerak terdiri daripada magnet NdFeB, magnet SmCo, magnet Alnico dan magnet seramik dengan menggunakan konfigurasi array Halbach untuk penetapan arah magnet yang berfungsi pada permukaan magnet kekal dan stator terdiri 15 slot untuk meletakkan gegelung di dalamnya. Objektif projek ini adalah model dan mensimulasikan 15 slot 14 kutub penjana linier magnet kekal menggunakan perisian Ansoft Maxwell dan menganalisis prestasi penjana linear magnet kekal dengan jenis magnet yang berlainan yang digunakan di atasnya. Untuk mencapai matlamat, model 15 slot 14 tiang PMLG perlu dibina dalam perisian Solidwork. Untuk hasil simulasi, model ini perlu dipindahkan ke dalam perisian Ansoft Maxwell dalam 2D untuk mendapatkan hasil analisis. Kelajuan penggerak bergerak dalam 0.5 m / s dengan masa langkah 2 ms dan masa berhenti 0.1 s dalam analisis analisis perisian Ansoft Maxwell. Walau bagaimanapun, kelajuan penggerak berubah daripada 0.5 m / s kepada 1.5 m / s. Fokus projek ini, untuk memerhatikan ketumpatan fluks magnet, hubungan fluks, daya cogging dan mendorong voltan. Dengan model yang sama, eksperimen akan diperluas dengan mengubah penggerak kelajuan dan voltan yang diinduksi diperhatikan.

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LIST OF SYMBOLS AND ABBREVIATIONS

WEC	-	Wave energy converter
FEA	-	Finite Element Analysis
PMLG	-	Permanent magnet linear generator
PM	-	Permanent magnet
NdFeB	-	Neodymium iron boron
Alnico	-	Aluminum nickel cobalt
SmCo	-	Samarium cobalt
N	-	Number of turn
H_{c}	-	Coil height
W_{c}	-	Coil width
H_{m}	-	Magnet height
W_{m}	-	Width magnet
ϕ_c	-	Coil diameter
R	-	Resistor
$\boldsymbol{\theta}_{\mathbf{N}}$	-	Coil sequence

CHAPTER 1

INTRODUCTION

1.1 Project Background

After the ’70’s oil crisis, many research program were started in that period focusing on renewable energies emerged as a possible long term solution and amongst them the wind and solar energy. Different region has their own way to yield electrical energy based on their renewable source [1]. For region with ocean coasts were focused on ocean energy as their renewable energy. Refer to wave energy converter (WEC), the most recognized are offered in the following traces, along with the operating principle.

Linear generator is considered to have higher efficiency and higher performance in comparison to rotary generator due to the fact they do no longer require any transmission tool [2]. The advantage of the PMLG are better power density, better dynamic overall performance, easy shape and the sensitivity degree of working air gap is small. The gain of fractional slot winding motor is brief quit winding, low copper intake detent force, high energy density and easy to region the winding [3]. Instead of advantage there also some disadvantage represent as a drawback from PMLG such as existence cogging force, excitation is fixed and output voltage varies with load.

In permanent magnet linear generator, there are many type of magnetization array such Radial array, Axial array and Halbach array. Each type of magnetization has their own structure and application. In radial one, magnet display a magnetic area oriented orthogonally to the longitudinal measurement of the device and depending if the device has shifting magnets or transferring armature, they may be positioned internal or outside of the stator. For the axial array, the magnet magnetized separated with the aid of iron core. The flux traces here are directed by way of the iron pole pieces, which are positioned by using two magnets with contrary magnetization direction. Then, the most recommended magnetization configuration which is Halbach array. The magnet configuration can be visible because the superposition of the radial and axial magnetization. A Halbach magnet array is an exciting arrangement of everlasting magnet to increase the magnetic discipline on one facet of the array even as canceling it on the opposite side [4].

This project will analyze and compare the performance of 15 slot 14 pole of PMLG by changing the type of permanent magnet. Linear generator has recently been used in different application, such as wave power conversion. A lot of research is carried out in the field of WEC when wave energy is adequately available and considered to be renewable [5]. This research uses Ansys Maxwell software with the concept of finite element analysis because of the complexity of the model. By using Ansys Maxwell software the results of flux density quantum, induce voltage, flux path, cogging phase and flux density can be reach from the simulation. The PMLG is set to generate Thee phase output power.

1.2 Problem Statement

Generally, the linear generator has higher efficiency and better performance compared to rotary generators, because they do not require any transmission device. Some application which has linear motion mechanism such as wave energy conversion and energy harvesting widely use linear generator. However, a conventional linear generator to rotational generator system has drawback of setting, lubrication, alignment and introduce operation limitation. One encouraging way to convert wave energy into electrical through direct drive is by using a linear, synchronous longitudinal flux permanent magnet generator where the rotor piston is driven by, for example a point absorber. Refer to wave motion, the motion moving up and down linearly.

Among the various type of PMLG, have interesting features those tubular permanent magnet that represent high efficiency, high force density and zero attraction force between stator and mover. The PMLG are classified in longitudinal flux machine and transverse flux machine that depend on the path followed by magnetic flux line. From previous experiment, there are many example of NdFeB magnet linear generator with high cost. So, this research focused if the other material of permanent magnet can have interesting performance. Basically, NdFeB magnet is important for two reasons. First, these alloy produce energy BH 4-5 times higher than older technologies so that give an affect reduce the size and cost. Secondly, these alloys do not contain cobalt, therefore the alloy much cheaper.

The PMLG has advantage in term of efficient electromagnetic performance but has a drawback which is cogging force. At low speed, the machines are much trouble from such ripple that can cause undesirable acoustic noise and vibration. So the speed gives an impact to the performance of PMLG. Thus, the variety of speed effect the performance of PMLG included in this research.

In term of phase, single phase have many problem and issue compare to multiphase. The problem is single phase has no fault tolerance and higher phase rating. For example, multiphase is very useful for Marine current turbine to maintain the power production even if an electrical fault appears in the power converter. The motor of multiphase can be operated normally even though one of phase is in fault condition. So it can be conclude that multiphase winding is better than single phase winding. Hence, this linear generator preferred to design in Three Phase winding.

1.3 Project Objective

1. To model and simulate 15 slot 14 pole of permanent magnet linear generator using Ansys Maxwell software.

2. To analyze the permanent magnet linear generator performance with different material of permanent magnet by varies the speed of mover.

1.4 Scope and Limitation

To achieve the objective of the project, there are several guidelines that have to follow which are improve the modeling of 15 slot 14 pole PMLG using Solid works and the analysis using Ansys Maxwell software and in term of three phase winding. All the parameter including the number of turn, the material of object, magnet sequence and phase angle of coil were identified by using formula that has been calculated and discussed. Then, analyze the performance and result between both. Make a comparison between different types of permanent magnet based on result obtained on 15 slot 14 pole of PMLG respectively, Neodymium Iron Boron magnet

(NdFeB), Aluminum nickel cobalt iron alloys magnet (Alnico), Samarium Cobalt magnet (SmCo) and Ceramic magnet. The range of speed of moving shaft 0.5 m/s until 1.5 m/s with zero current injected in coil winding. The result need to observe such as induced voltage, magnetic flux line, magnetic flux density, flux linkage and cogging force on different mover speed. The best performance of permanent magnet represents highest value of induced voltage proportional to the speed will be selected.

1.5 Thesis Outline

The thesis consists of five chapters: introduction, literature review, methodology, outcome, analysis and discussion, and finally conclusion and recommendation.

Chapter 1 discussed a brief project introduction that includes the statement of problems, objective, scope and limitation. In addition, this chapter describes the general information concerning the permanent magnet.

Chapter 2 will discuss the review of this research's literature. This will include an explanation of the introduction of PMLG and the basic structure of PMLG. The theory of magnetic materials and the slot pole combination of PMLG will also be described in this chapter.

Chapter 3 deals with project methodology. The project activity describes the entire project flow as set out in the project flow chart. The entire method used to carry out this project is explained. The important thing to know is to calculate the sequence of the coil and the number of turns.

Chapter 4 deals with analysis and discussion of results. This chapter will show the overall results of the Ansys software simulation. The discussion of the results for this proposed topic is set out in Chapter 4.

Chapter 5 is the final chapter, which summarizes all the themes of the previous chapter. At the end of this chapter, some recommendations were written for better improvement in the future.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

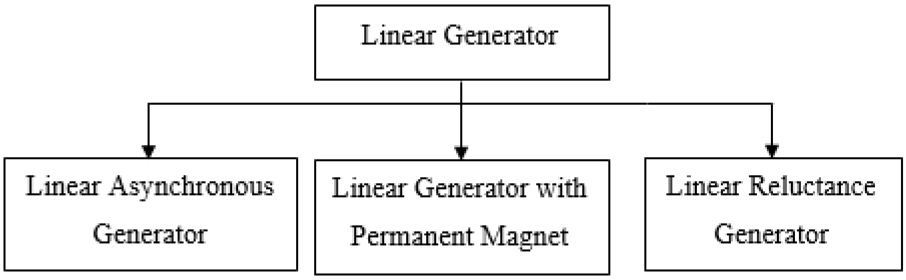
In Chapter 2, all related PMLG theories and literature reviews such as the introduction of PMLG and the basic structure of PMLG are described. This chapter also deals with the magnetic material and the PMLG slot pole combination.

2.2 Introduction Of Linear Generator

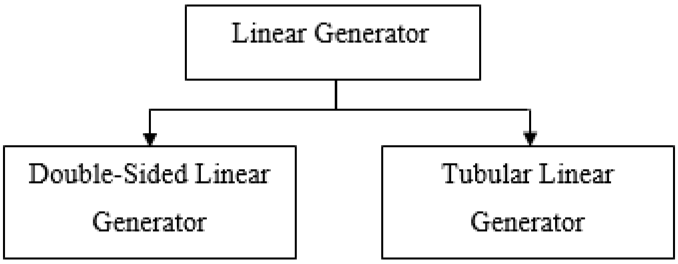
In the evolution structure, the linear generator can be regarded as a rotary generator. It can be seen as a rotor generator in a straight line along the open radial cut and the generator circumference. The stator is a cylindrical dimension with several circular grooves that held the winding of the stator. The moving part of a linear generator which is translator consist of magnetic yokes and permanent magnets. The magnetic yoke is the magnetic path between the magnetic pole. In order to maximize the amount of power at relative low speed, the design concept involving tubular linear generator is the best choice.

The linear generator can be applied and suitable in various type of application and it has been used in industry widely. Linear generator has advantages than any other generator, that are gearbox less, simple structure, high efficiency, high flux density and it could convert energy on the calm wave. However, it still has disadvantages that will give and impact to industry. For example, it has high investment cost, large size dimension for large power generation, has varying voltage and frequency and material required that resist to corrosive materials [6].

There are several types of linear generator that have different in terms of their magnetic and geometric structure [7][8]. In part of magnetic configuration, the linear generator is distinguishing into three types which are linear asynchronous generator, linear generator with permanent magnet that commonly used in many application and linear reluctance. Meanwhile, for the geometric configuration, the linear generator is divided into two types, double-sided linear generator and tubular linear generator. **Figure 2.1** shows the type of linear generator. **Table 2.1** shows the comparison of linear generator with briefly explanation for each criteria such as performance, construction, difficulties, robustness and system cost.



(a) Type of linear generator for magnetic configuration.



(b) Type of linear generator for geometric configuration.

Figure 2.1: The type of linear generator

Table 2.1: Table of comparison for linear generator

Feature	**Linear induction generator**	**Permanent magnet linear generator**	**Switch reluctance linear generator**
Performance	Find little space in the application as wave generator.	-Exhibit high value of residual induction -High BH product allowed to build highly efficient. -Yield high energy density	Constantly changing magnetic field is non-linear, the torque ripple is high at low speed and position sensor complicate the design.
Construction	Manufacture in single-sided, double	Manufactured in single-sided, double	Analogous to the switched

	sided and tubular structure.	sided and tubular structure.	reluctance rotating generator.
Difficulties	-High air gap causing a reduced efficiency. -Complicated control structure.	Present forces perpendicular to the direction of motion that cause mechanical and electrical system complicated.	Complicated control loop and to the magnetization requirement.
Robustness	Rotor made of copper or diamagnetic material cause absence of parasitic force.	Coatings the magnets to slower the oxidation.	High fault tolerance and high reliability.
System cost	Made by sturdy element that have excellent characteristic in longevity.	Short longevity due t to replacement of permanent magnet thus needed for maintenance action.	Linear generator is cheap specially cage generator are maintenance free.

2.3 Basic Principle Of PMLG

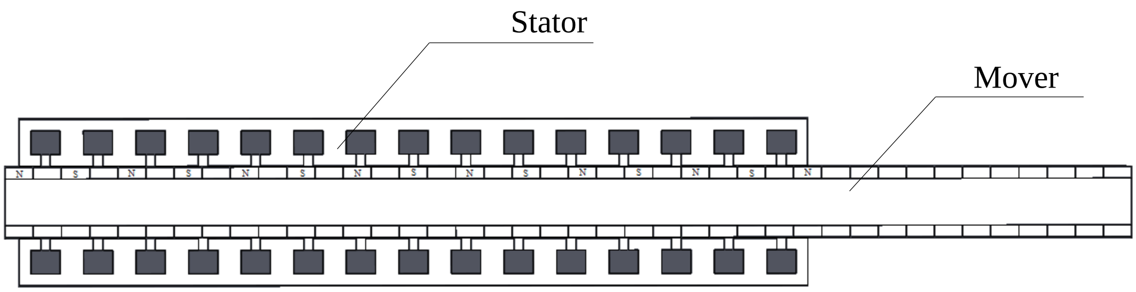


Figure 2.2: Basic principle of PMLG

Figure 2.2 shows the basic principle of PMLG. The PMLG consists of a permanent magnet as the mover and the coil winding stator. The movement of the mover between the stator generates magnetic flux that produces induction voltage on the basis of the law of Faraday. The magnetic flux can be reach higher near the permanent magnet edges, the air gap between stator and translator can be closer to get the value of flux leakage is low.

Faraday’s Law formula:

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

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

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 is a fact that exist to oppose any change in magnetic flux acted from the induce EMF.

2.4 Basic Structure Of PMLG

The PMLG structure consists essentially of permanent of magnet represent as a mover and the coil is set as a stationary part. It consists of 15 coils in one stator that means 1 coil represent 1 slot, so the total of slot is 15 slots. Meanwhile to determine the pole, it can be identifying by the polarity of magnet from north to south polarity. The number of pole can be evaluate when the polarity of magnet is begin from north to south valued as 1 pole. Each combination of structures is set to winding in three phases. The **figures 2.3** show the different number of pole in PMLG.

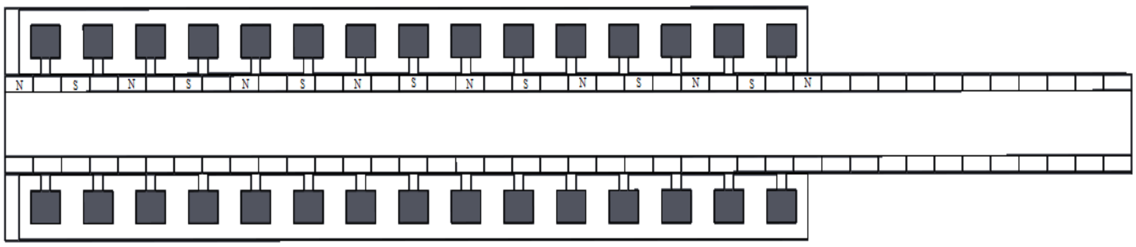


Figure 2.3: Structure of 15 slot 14 pole of PMLG

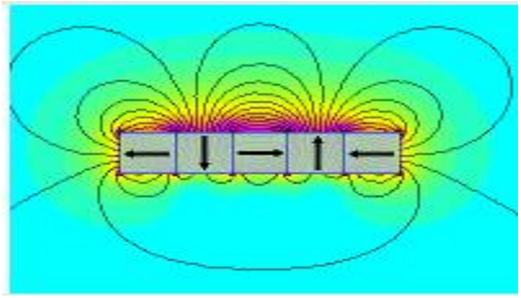


Figure 2.4: Halbach array configuration

Figure 2.4 shows the Halbach array configuration. The linear generator of the Halbach array consists of a permanent magnet in axial and radial direction. It has a much stronger field for a given PM material size and weight than the alternating polarity magnet array. The Halbach array's magnetic field can be concentrated without the use of back iron and the removal of back iron on the stator reduces the overall weight of the generator and eliminates iron-related hysteresis and eddy losses.

A mover magnetic field is generated in the generator either by designing the mover as a PM or by applying a DC current to a mover winding to create an electromagnetic source. The generator mover is then moved by a primary mover, which produces a rotary magnetic field inside the machine. This magnetic field induces a set of three phases of voltages within the coil setting of the generator's stator winding. **Table 2.2** shows the parameter setting which is the most commonly used for setting parameter of PMLG at previous project.

Table 2.2: Parameter setting for PMLG 15 slot 14 pole and 15 slot 16 pole

STRUCTURE PART	PARAMETER	14 POLE	16 POLE
	NUMBER OF COIL	15	15
STATOR	NUMBER OF TURN	158	201
	RESISTANCE	1.81	2.3
	TYPE OF MAGNET	NdFeB	NdFeB
MOVER	SHAFT	SUS304	SUS304
	MAGNET ARRANGEMENT	HALBACH	HALBACH

2.5 Working Principle of PMLG

The dynamic magnetic pole in the direction of the permanent magnet flow is perpendicular to the PMLG axis. The magnetic field line path can be obtained if all the blue magnetic flux is axis direction device, then all red magnetic flux direction is to the axis direction. After the magnetic rotor yokes back to the blue magnetic pole, it forms a loop, the magnetic field line is outwards from the blue magnetic pole through the air gap into the stator core and bypasses the winding through the air gap to the red magnetic pole in the stator core. When the rotor moves a slot to the left, the magnetic field line through the air gap still out of the blue magnetic pole bypasses the winding in the core of the stator through the air gap to the red magnetic pole, when the rotor move continuously. **Figure 2.5** shows magnetic flux direction of the PMLG.

The linear generator has two parts translator and stator. When the translator (mover) moving, the mover induces magnetic flux to stator winding. The coil at stator producing magnetic flux then the mover and stator emf clashed each other and they are produce charged magnetic flux. So, this mechanism is called electromagnetic induction which produce voltage from generator.

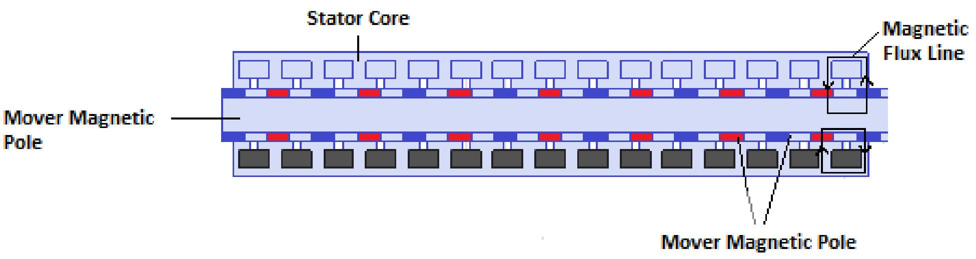


Figure 2.5: Magnetic flux direction of PMLG

2.6 Slot and Pole Combination

The fractional slot concentrated winding PMLG, the slot pole combination, whose pole number increases, the flux linkage decrease due to the leakage flux increment and flux decrement per pole. For the same number of slot, the larger the pole number, the smaller the widths of the inner and outer stator teeth and the slot area become larger when the number of turn per slot is larger. In addition, the larger number of pole give an impact for the iron losses become worse cause by the larger flux densities in the translator.

By using the slot pole combination, whose pole number is greater than its slot number, the thrust and thrust density performance will be reduced, but its detent force and thrust ripple will be much less. **Table 2.3** shows the slot-pole combination [9]. So, this project, we focused on 15 slot 14 pole as a good choice for this project due to high output torque, low torque ripple and low leakage flux.

Table 2.3: Table of slot-pole combination

Number of slot	Number of pole
12	10
	14
15	14
	16
21	20
	22
24	22
	26
27	26
	28

2.7 Magnetic Material

The magnetic material classification based on the magnetic sensitivity of the bulk, which indicates whether the material is attracted or repelled from the magnetic field. The magnetic material performance can be measured on the basis of temperature stability, permeability, coercive strength, resistance to corrosion and mechanical strength. Magnetic material can be classified as ferromagnetic, non-ferromagnetic and permanent magnet in three classes.

2.7.1 Ferromagnetic Material

Ferromagnetic is characterized by its attraction to metals like iron and steel. Ferromagnetic materials may either be soft-ferromagnetic or hard-ferromagnetic depending on their coactivity. These materials usually have ferromagnetic properties under curie temperature. This magnetic sensitivity depends heavily on the intensity of the external magnetic field and the ambient temperature [10]. Besides, the electric machine experiences more flux with iron than air when using ferro-magnetic materials for a given magnetic force.

Low coactivity typically it lower than 1000 A/m and high permeability are classified as soft magnetic material, due that it easy to magnetize and demagnetize. Instead of hard magnetic materials, high coactivity normally exceeds 10,000 A/m and low permeability is classified, so it hard to magnetize and demagnetize. There are many examples of soft magnetic materials such as soft iron core, soft ferrites, iron-silicon and nickel-iron alloys. Properties such as permeability, magnetization of saturation, resistance and coactivity are taken into account when selecting a soft material with a higher magnetization of saturation and a higher permeability for flux containment and concentration. Soft materials that are normally used in many devices, such as transformers, inductors, relays and engines.

The ferromagnetic material flux can be observed through the saturation curve shown in **figure 2.6** below [11]. B is magnetic density while H is magnetic field intensity.

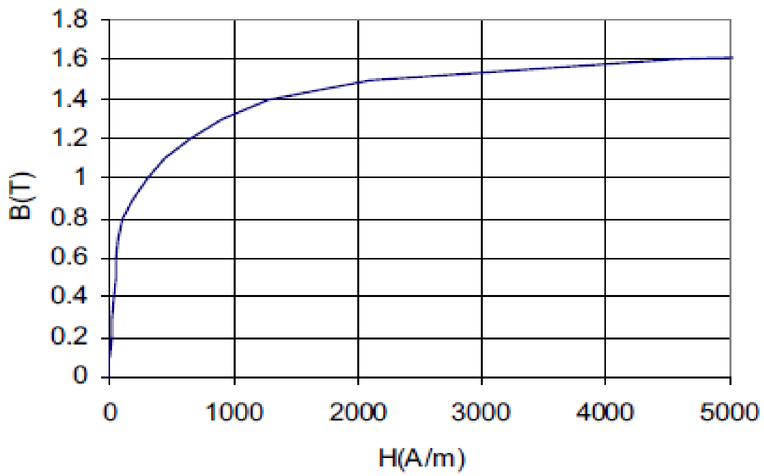


Figure 2.6: The characteristic of ferromagnetic material

Table 2.4: The properties of permanent magnet material

	Alnico	Ba-Ferrite	SmCo(1:5)	SmCo(2:17)	NdFeB
Remanence Br/T	0.8-1.4	0.2-0.44	0.85-1.05	1-1.14	1.1-1.52
Coercive Force Hc/(kA/m)	38-155	143-318	637-796	717-844	796-1115
Intrinsic coercive force (Hcj/kA/m)	40-159	159- 358	1194-2388	1194-2388	955-2388
Maximum Magnetic Energy product (BH)max/kJ^3)	8-88	8-36	127-207	175-255	239-446
Temperature coefficient of remanence a/(%/˚c)	-(0.02-0.03)	-(1.18-0.19)	-(0.04-0.05)	-0.03	-0.01
Intrinsic coercive force Temperature Coefficient β/(%/˚c)	N/A	0.20-0.60	-(0.30-0.35)	-(0.03-0.05)	-(0.45-0.6)
Recoil permeability μ_{rec}	1.3-5.2	1.05-1.10	1.02-1.10	1.05-1.10	1.05-1.10
Curie point T_c/(˚c)	800-860	465	750	800-850	312-420

2.8 Summary

In this chapter it can be summarized that the PMLG used the NdFeB magnet as the material for the PM, because it shows the best performance of all other magnetic materials. The types of directions used for magnetization are Halbach magnetization. The Halbach array has a much stronger field than the magnet array with alternating polarity for a given size and weight of permanent magnet material. The Halbach array magnetic field can be concentrated without the use of back iron and the removal of back iron on the stator reduces the overall weight of the generator and eliminates iron-related hysteresis and eddy current losses. Power density and efficiency of energy conversion can also be improved.

CHAPTER 3

METHODOLOGY

3.1 Introduction

Chapter 3 discusses the procedures and methods and the entire process used in simulation computing software such as Solidworks and Ansys. First, information about PMLG and its topologies is collected and studied to avoid from misunderstanding and opposite meaning about the information. It is the way to help generate an idea about this project. After providing sufficient information on the proposed title, then overview some literature on the previous research and identify the parameters to be considered in the design of the part. Ansys software will then apply to the design and analysis of the performance of PMLG. The problem solving part provides a space to verify the simulation. All data, results and discussion that were analyzed are collected and will be inserting in the report. The flow of the project progress can be expressed using the research methodology flow chart.

3.1.1 Research Methodology

In this project, the focus is given on the performance of linear generator based on different type of magnet applied on it. The different material characteristic of the magnet will determine the performance of PMLG. A flowchart for overall process of methodology is shown in **Figure 3.1**. Firstly, modeling the linear generator based on specification that has been studied. Each part designed part by part before combined to be one complete design of PMLG. After that, the model of PMLG will export to Ansys Maxwell software for simulation. The purpose of using Ansys Maxwell software is to analyze and select the best performance of PMLG by using simulation. In order to choose the best PMLG, it takes to measure the design PMLG by using different type of magnet. Based on the result, the best performance of linear generator is proposed and selected.

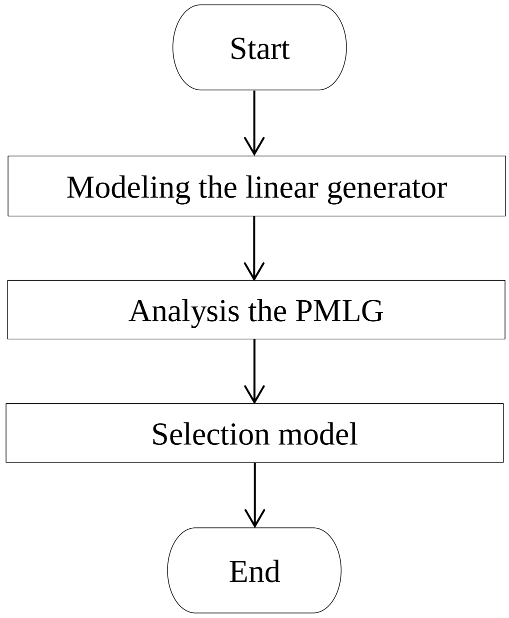


Figure 3.1: Overall research methodology

3.2 Modeling Using Solidwork

The model of the PMLG has been design in the Solidwork software part by part. The drawing of model PMLG consists of shaft, permanent magnet, stator and coil. The drawing began by sketch 2D sketching of modeling permanent magnet linear generator. In this software, the unit that has been used in millimeter (mm) so that easy to design the model in small ratio value instead of large ratio value that applied for the real prototype of permanent magnet linear generator so it can give huge number of power with more efficiency. **Figure 3.2** shows the structure of PMLG in 2D design with position to state the distance of mover move fluctuate up and down.

Table 3.1 shows the design of PMLG parameter used in this project. After complete sketching the model in 2D design, the drawing then will convert into 3D design and assemble all the part to be one complete design of PMLG. Then, the model will transfer to Ansys software for the simulation. The PMLG with 3 phase and long translator. The stator is made of the steel contains 15 coils and 15 slots which the coil is made of copper material. The translator made of permanent magnet that contains 14 poles with quasi-Halbach magnetized magnets. Quasi-Halbach magnetization provides higher air gap magnetic field distribution. The PMLG is carried out with the four different magnet materials.

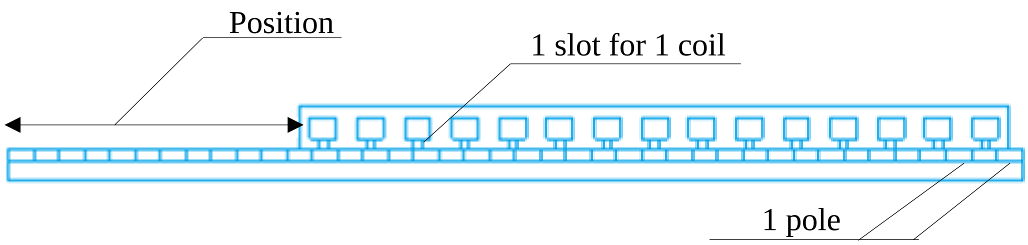


Figure 3.2: Structure of PMLG in 2D design

Table 3.1: Design parameter of PMLG

Parameter	**Value**
Translator length, $l_{translator}$	480 mm
Number of magnet rings	40 mm
Number of iron rings	15 mm
Coil width, W_c	12.5 mm
Coil height, H_c	11 mm
Magnet width, W_m	5 mm
Magnet height, H_m	12 mm
Air gap	0.5 mm

3.3 Modeling Using Ansys Maxwell Software

The next step after complete design the permanent magnet linear generator in solidwork software, the model is transferred to the Ansys Maxwell software to simulate the model. By using Ansys Maxwell, the best performance of linear generator is determined. The steps in order to used Ansys Maxwell software is shown in flowchart **Figure 3.3**. Firstly, convert the model from 3-Dimension into 2-Dimension and set the selection in 'XY' plane along Z axis. Justify the type of material that will be used before assign the material for each model. **Table 3.2** shows the material used for the simulation. The coordinate system of the magnet is determined the polarity either it is North Pole or South Pole.

Next, all the linear generator parameter will be assigned and the excitation of the coil is determined. The excitation of the coil is divided into 3 winding represent Phase A, Phase B and Phase C. Then, the mesh operation is determined. After all the setting is done, the model can be analyzed and all the result will be plotted. If the result appeared is wrong, the parameter setting will be change until the desired result is comes out. Then, validate the desired result with the article related that has been proven through the experiment. If the result still not satisfied such as the phase shift of waveform for three phase still not fulfill the requirement which is 120^{o}, the setting parameter is changed and the process is repeated until the result is satisfied with specification needed.

The flux path and flux density are also can be determined by using Ansys Maxwell software. The mesh of the linear generator can be viewed as shown in **Figure 3.4(a)**. It is important to justify the shape missing on the linear generator structure.

After the shape of mesh is matching for the linear generator, the flux path is appeared shown in **Figure 3.4(b)**. Flux path is the lines are flow from North Pole to the South Pole. Since the stator is assign as steel, the maximum flux density is 1.5 T shown in **Figure 3.4(c)**.

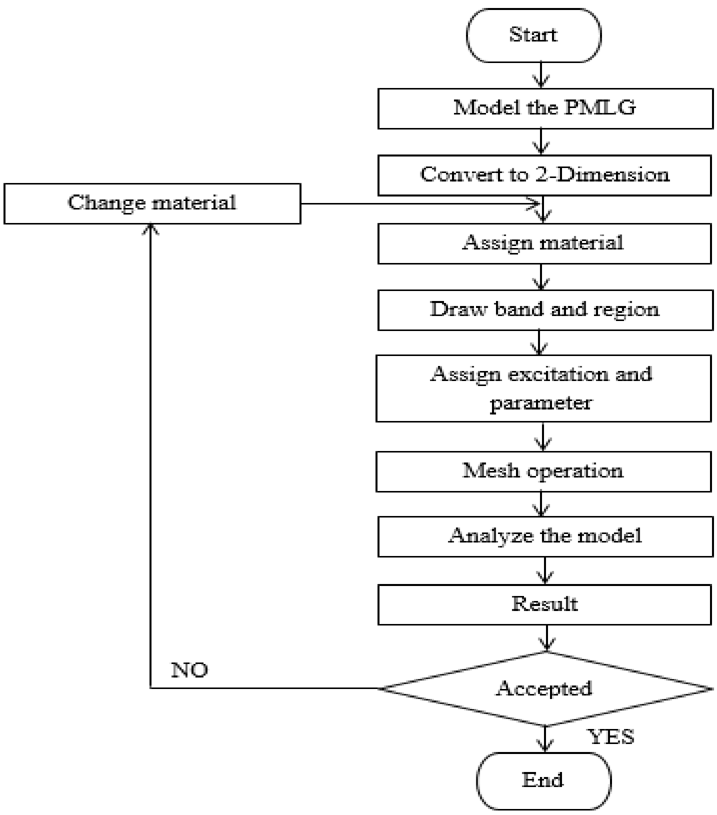
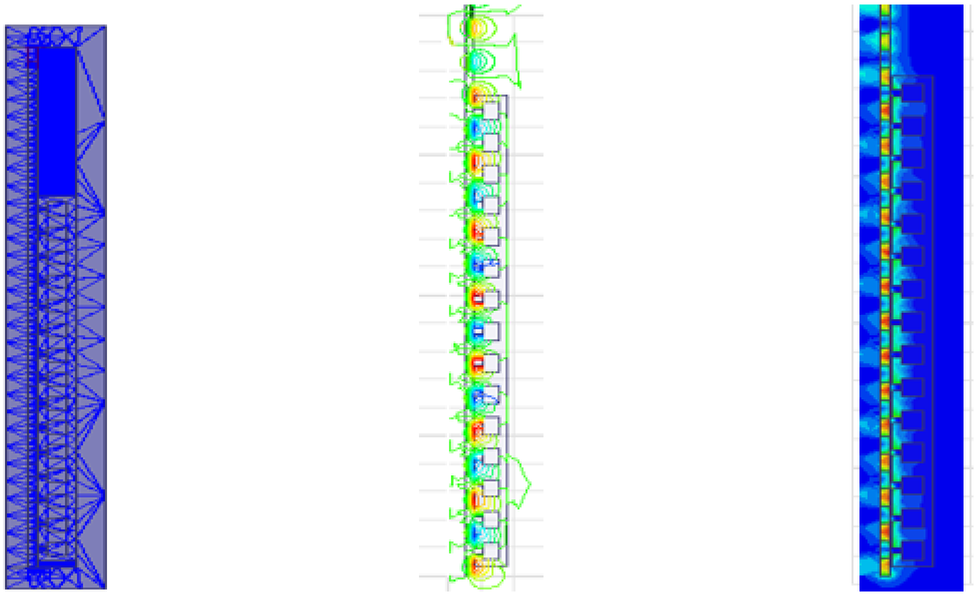


Figure 3.3:Modeling flowchart using Ansys Maxwell software

Table 3.2: Material use in Ansys Maxwell software

Parts	Material
stator	Steel 1008
coil	copper
mover	Shaft: vacuum PM : NdFeB material



(a) Mesh operation (b) Flux line (c) Flux density

Figure 3.4: The characteristic of magnetic flux

3.3.1 Number Of Turn Calculation

In order to find the number of coil and the value of resistance, there is some equation that has been used. The number of coil turn should be calculated to know the exact value of wire length used to turn on the coil. The value of resistance exists when the wire is used because each wire has own resistance to control the amount of current in the circuit. **Figure 3.5** shows the partial structure 15 slot 14 pole of PMLG.

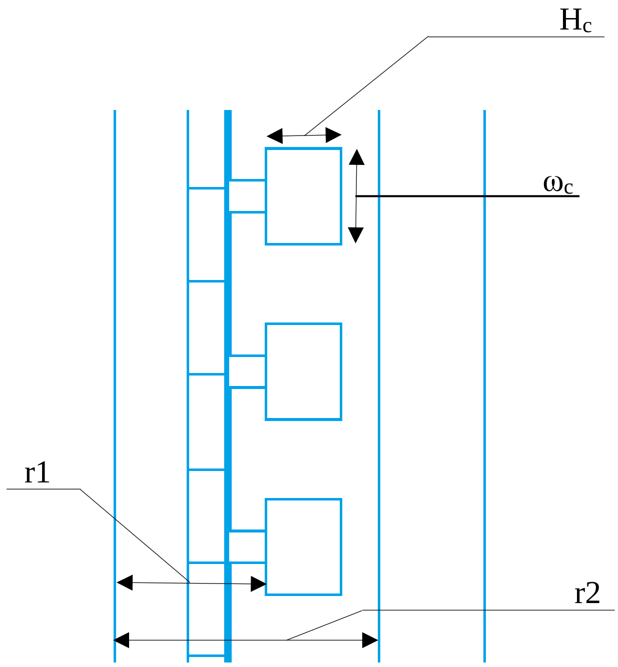


Figure 3.5: The partial structure of 15 slot 14 pole of PMLG

Table 3.3: Parameter model for calculation

Parameter	**Size**
Coil length, W_c	12.5 mm
Coil height, H_c	11 mm
Coil diameter, ϕ_c	0.852 mm
r1	20.5 mm
r2	35.5 mm

The coil number and the resistance number per phase can be calculated as follows:

$$N = \frac{\omega_c}{\phi_c} \times \frac{h_c}{\phi_c} \times \varepsilon \quad (3.1)$$

$$l_{ave} = 2\pi \left(r_1 + \frac{r_2 - r_1}{2}\right) \quad [m] \quad (3.2)$$

$$l_{total} = l_{ave} \times N \quad [m] \quad (3.3)$$

$$R = \frac{\rho l_{total}}{a} \quad [\Omega] \quad (3.4)$$

Where N is the coil turn, ω_c is the coil width, h_c is the coil height, ε is epsilon, $\emptyset_c$ is diameter of coil, R is the coil resistance measured in ohm, l_{total} is the copper wire length in mm and 'a' copper wire cross sectional area in mm^2 unit.

Calculation of the number of coil turns 15 slots 14 pole by using equation 3.1. For some PMLG parameter dimensions in equation such as coil width, ω_c, coil height, h_c , r_1 and r_2 , the PMLG 2D model can be obtained by calculation before put the model inside Ansys software for simulation. After calculating the number of coil turns for 15 slot 14 pole, the next step for 15 slot 14 pole is calculated the number of resistance per phase using formula 3.2 till 3.4. The number of coil turn and value of resistance in unit ohm for 15 slot 14 pole per phase can be observed in the **table 3.4** below.

Table 3.4: Result drom calculation coil turn and resistance

Parameter	**Value**
Resistance	1.81 Ω
Coil turn	158
Copper wire diameter	0.852 mm

3.3.2 Coil Sequence, θ_N

Based on the design specification and a certain fixed parameter, the coil sequence for 15 slot 14 pole was calculated in the three-phase setting. The coil sequence for 15 slot 14 pole can be calculated by using equation :

$$\theta_N = [(\frac{360^o / N_{slot}}{360^o / N_{pole}})\ x\ 180^o\ ] + \theta_{N-1} \tag{3.5}$$

Where θ_N is coil winding angle, θ_{N-1} is previous coil winding angle, N_{slot} is number of slot and N_{pole} is number of pole. The coil winding angle for 15 slot 14 pole can be determined by using the equation 3.5 above. For the coil 1, the value of coil winding angle is zero because the starting angle is zero. Then, the next coil winding angle value for coil 2 and the next coil can be determine by insert the N_{slot} with value of 15. Then insert value of 14 represent number of pole in N_{pole}. The value of θ_{N-1} will start from zero angle as a beginning for previous coil winding angle to find the next value of coil winding angle for the next coil number. **Table 3.5** shows the coil sequence phase winding for 15 slot 14 pole of PMLG.

Table 3.5: Coil sequence phase winding for 15 slot 14 pole

Coil number, N	θ_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

Determining which one coil for grouping by flip and recalculated coil angle in phase A, phase B and phase C. For three phase winding, each phase has five coils. The polarity at the coil angle changes from positive polarity to negative polarity when the coil angle is flipped. Flip mean the angle of the coil take from the nearest value after the value is compare with 120°, 240° and 360°. **Figure 3.6** shows the coil sequence of 15 slot 14 pole in three phase winding before flip coil angle.

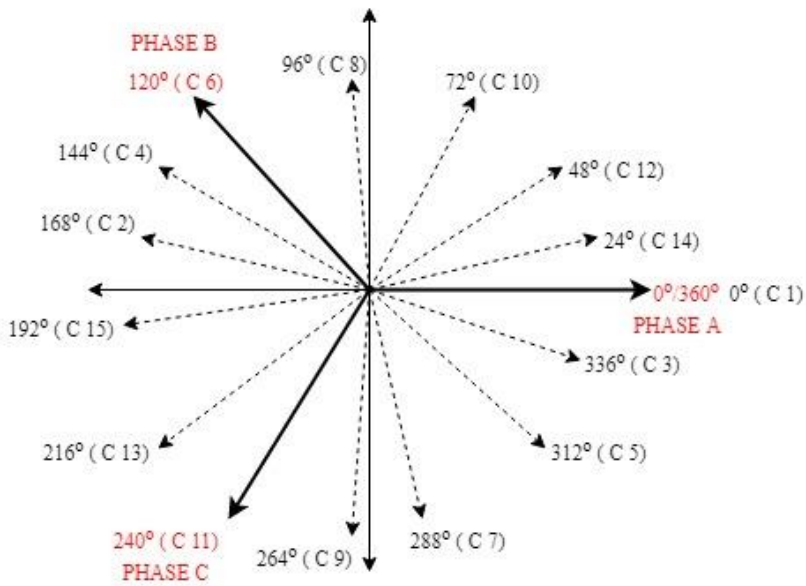


Figure 3.6: Coil sequence three phaase winding

Figure 3.7 show the three phase winding for 15 slot 14 pole after flip. The positive polarity for phase A is coil 1, coil 3 and coil 14 instead coil 2 and coil 15 is negative polarity. The positive polarity for phase B is coil 4, coil 6, coil 8 instead the coil which have negative polarity coil 5 and coil 7. While phase C, the positive polarity is coil 9, coil 11 and coil 13 instead coil 10 and coil 12 which is negative polarity. After calculate the coil sequence, Ansys Maxwell software sets the value for the calculation of number turns, resistance and coil sequence. The different phase angle for three phase is 120°. The number of coil will be manipulating for grouping whether in phase A, phase B and phase C for three phase by flip and the value of coil angle recalculated. When coil angle are flip, the polarity at the coil angle change from positive to negative polarity.

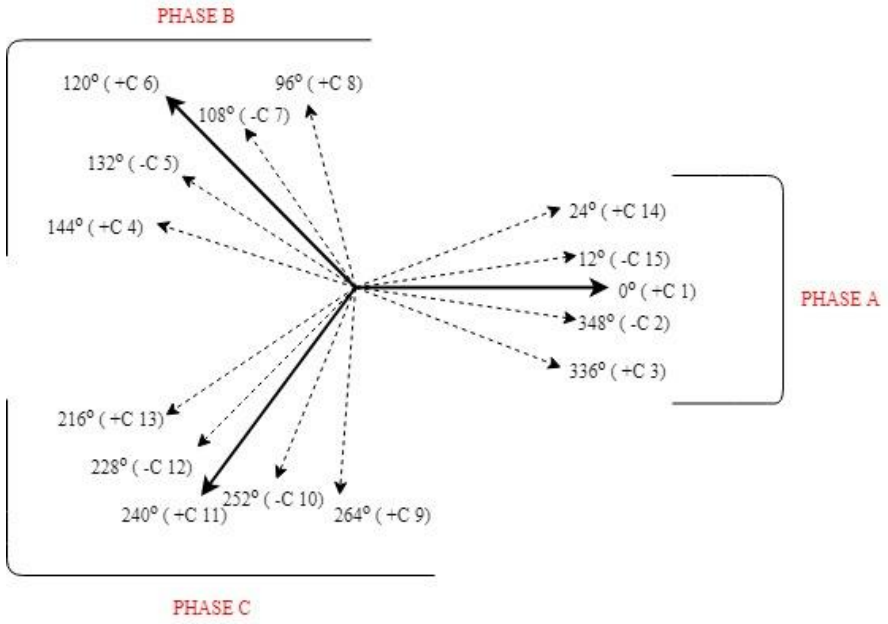


Figure 3.7: Three phase winding 15 slot 14 pole after flip

3.3.3 Operating Setup

The operational setting with unloaded condition for 15 slot 14 pole with three phases winding before the simulation begins. Refer to unloaded conditions, the equivalent circuit has no load resistance and then the value velocity for the setup motion on the mover is set to 0.5 m / s. The analysis were setup with the value that has been calculated which are the stop time is 0.1 s and the step time is 0.2 ms. It take about 100 cycle to get complete cycle for the result. The circuit has been set under no load condition so that it can be used for the whole simulation in this experiment. The unloaded condition circuit will undergo two main case of experiment. First, the equivalent circuit was setup to undergo the simulation of different material of magnet such as NdFeB magnet, SmCo magnet, Alnico magnet and ceramic magnet. After all the simulation for the first case is done, the other simulation for the second case has been run under no load condition with speed from 0.5 m/s up to 1.5 m/s. **Figure 3.8** shows the equivalent circuit with no load in three phase winding.

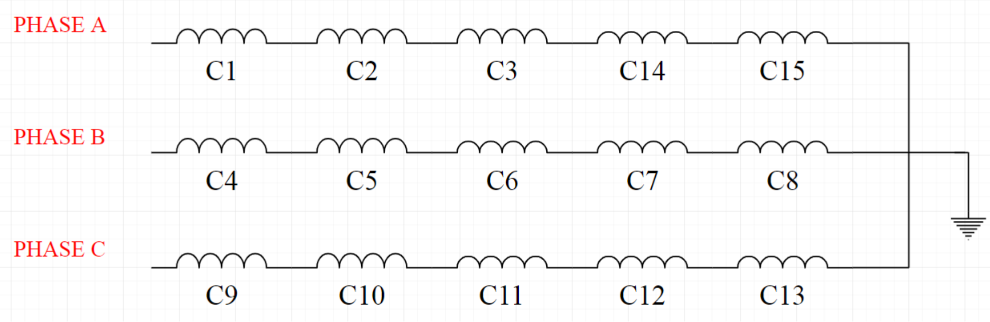


Figure 3.8: The equivalent circuit of coil winding in three phase

Finally, all the simulation that has been set with different type of permanent magnet followed by second case which is the speed mover has been set from 0.5 m/s to 1.5 m/s. The result of simulation is shown in next chapter which is chapter 4.

3.4 Analysis Parameter

This project begins with the design of a 3D model of 15 slot 14 pole PMLG using the software of Solidworks. The model was fixed in Solidworks based on the parameter. The diameter of the magnet for PMLG is 30 mm and the height is 12 mm. All parameters such as the size of magnet, number of turn, resistance and the size of mover and stator are fixed. In order to maintain the air gap 0.5mm, the size of mover has been fixed meanwhile the stator maintained with the size 384mm. The material of magnet is changed regularly. Each type of magnet has different characteristic that will determine the result at the end of the experiment. The flowchart shows the process of parameter change shown in **Figure 3.9**.

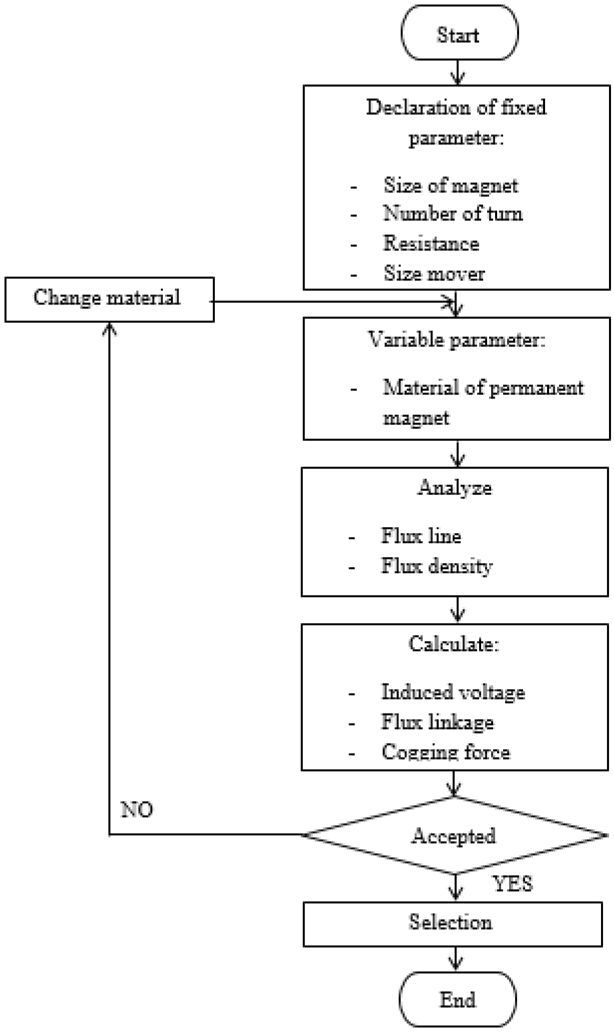


Figure 3.9: Flowchart of analysis parameter

After the variable parameter which is material of magnet is changed, the linear generator will analyze. Thus the result of voltage output can be determined. The design of PMLG is selected when the linear generator yields the highest voltage output. Repeat the step by remain the same all parameters but change the material magnet within NdFeB magnet, SmCo magnet, Alnico magnet and Ceramic magnet. After the analysis process is done the result will be compared and the best result of the simulation will be selecting to propose for PMLG.

3.4.1 Parameter Analysis For No-Load Voltage

In this analysis, all the parameter structure including stator, mover and the air gap is fixed as the structure of PMLG proposed except, the material of magnet which are NdFeb magnet, SmCo magnet, Alnico magnet and Ceramic magnet. For this analysis, there is no current inject into the coil so that the cogging force exist that will be discuss in the next sub topic. The coil is set in 3 phase winding which is phase A, phase B and phase C will turn on. So, the voltage induced result will have 3 lines with different colour to indicate the phase line. In order to find which design is better to produce higher induced voltage, the different materials of magnet are used to observe the performance.

3.4.2 Parameter Analysis For Flux Linkage Characteristic

In this analysis, all the parameter structure is fixed except, the material of magnet is changed. This analysis will operate in 3 phase and there is no current inject in the coil. For this analysis all the step is same with previous subchapter but the analysis is focus on flux linkage. The result of analysis at different material of magnet will be observed and the higher value of flux linkage will be chosen due to the high saturation of magnetic field.

3.4.3 Parameter Analysis For Cogging Force Characteristic

In this analysis, all the parameter is kept same as been discussed in the previous subchapter. The analysis result will be shown that there is only 1 line to represent the result of cogging force even the coil is set in 3 phase winding. The value of cogging force will take base on the peak value of the graph. The lower the cogging force could be better in the performance of PMLG. The speed of mover is set in 0.5 m/s same with the previous analysis subchapter.

3.4.4 Parameter Analysis For Induce Voltage vs Speed

In this analysis, the parameter of the structure is fixed but there are two comparisons that need to observe. First, the analysis is focus on the induce voltage produced at different material of magnet combined with second analysis which varies speed of mover. This analysis will show for 1 phase only because the other phase produces the same result. It means only 1 phase will select to represent the line for NdFeB magnet, SmCo magnet, Alnico magnet and Ceramic magnet. Then each graph indicates for each material of magnet will combine in one graph against velocity. The speed of mover is varying from 0.5 m/s, 1.0 m/s and 1.5 m/s to observe the best result of induce voltage when the speed is changed.

3.5 Parameter Analysis For Best Model selection

At the end of simulation process, the best performance of PMLG is selected based on characteristic that have been identified due to simulation result. The PMLG is select refer to the characteristic which produce higher induce voltage with higher flux linkage output and low value of cogging force. Another characteristic to select witch one is better performance for PMLG when the speed of mover is changed. The main target of this project want to choose the best performance of PMLG in term of voltage induced characteristic, flux linkage characteristic and cogging force characteristic directly proportional with the speed of mover consistently. The higher the speed of mover the higher the voltage induced show the best performance for PMLG proposed.

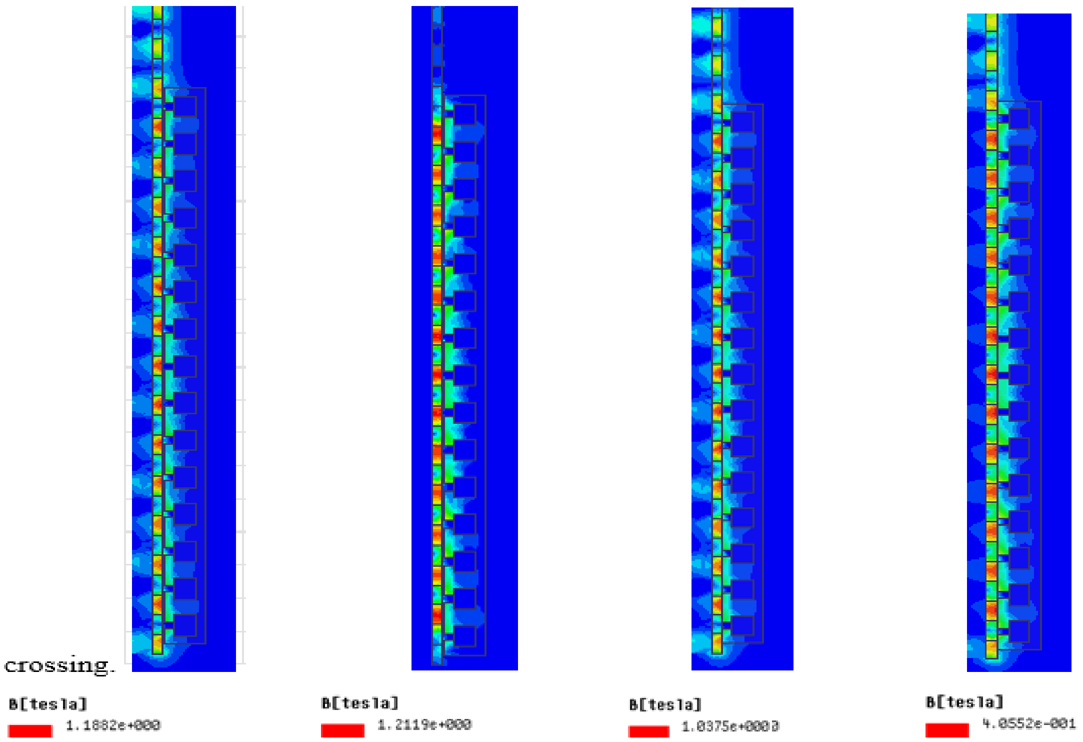
CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

In this chapter, all the result obtained from the analysis will be discuss. The discussion is about the effect of different type of permanent magnet and the different setting of speed at the mover. There are four types of permanent magnet which is NdFeB magnet, SmCo magnet, Alnico magnet and Ceramic magnet that applied to the 15 slot 14 pole of PMLG by fix the setting parameter of the linear generator. By using the same model, the experiment will be extend by changing the speed of mover from 0.5 m/s to 1.5 m/s. In order to choose the best performance among four type of permanent magnet, the result from analysis will proven which one is the best.

4.2 Magnetic Flux Density



(a)NdFeb magnet (b)Alnico magnet (c)SmCo magnet (d)Ceramic magnet

Figure 4.1: The characteristic of magnetic flux density of PMLG

Magnetic flux density known as the total number of magnetic field lines that passing through at certain area. **Figure 4.1 (a)**, shows the diagram of magnetic flux density of PMLG for the type of NdFeB magnet. The maximum saturation of flux density located at the magnet area which is 1.1882 T. From the result, it is show that NdFeB magnet produces much higher flux density compare to SmCo magnet show in **figure 4.1 (c)** and Ceramic magnet which is 1.0375 T in **figure 4.1 (d)** and 0.40552 T. Based on the **figure 4.1 (b)**, the Alnico has the highest magnetic flux density which is 1.2119 T, but the transversal magnetization of the NdFeB magnets causes a major dispersion of the magnetic flux density. Furthermore, the highest flux density is located in the area of magnet while in the circuits and yoke the field intensity is lower due to the gap crossing.

4.3 The Analysis of No-Load Voltage

Figure 4.2 shows the characteristic of induced voltage of PMLG in three phase system based on the simulation. The graph of voltage is produced under the simulation at speed 0.5 m/s in three phase system. The main target the results is shown to compare the induced voltage yeilds at different type of permanent magnet at the same time the speed of mover is maintain. Based on **figure 4.2 (a)** and **figure 4.2 (b)**, it is shown that NdFeB magnet induced maximum voltage of 15.49 V where as for the SmCo magnet yeilds maximum voltage of 13.47 V. Meanwhile the graph of induced voltage represented for Alnico magnet shown in **figure 4.2 (c)**, the maximum induced voltage produced 22.68 V and for the type of Ceramic magnet the result of maximum induced voltage is 6.89 V as shown in **figure 4.2 (d)**. Among of these four type of permanent magnet, the Alnico magnet has the highest value of induced voltage.

Based on the result analysis, it can be conclude that the strenght of magnetic field can effect the induced voltage. The stronger the magnetic field the higher the voltage induced. Refer to the **figure 4.1** which is show the magnetic flux density, the highest concentration of flux density goes to Alnico magnet which is 1.2119 T followed by NdFeB magnet, SmCo magnet and Ceramic magnet as 1.882 T, 1.0375 T and 0.40552 T. It is prove that the higher value of magnetic field the higher the induced voltage yeilds.

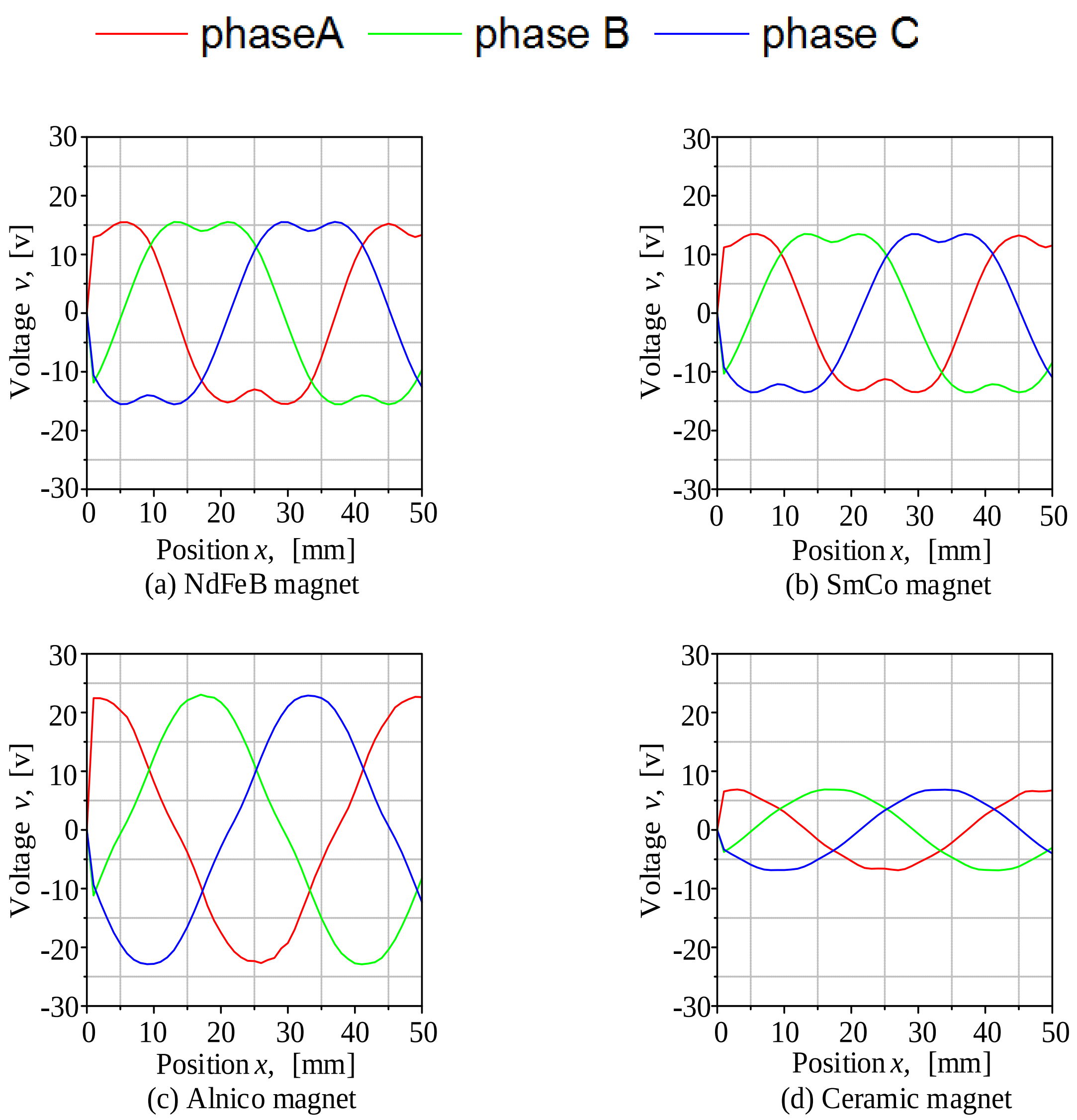


Figure 4.2: The characteristic of induced voltage of PMLG

4.4 The Analysis Of Flux Linkage Characteristic

Figure 4.3 show the graph of flux linkage in four different type of magnet for 15 slot 14 pole of PMLG in three phase winding at at the same speed of mover which is 0.5 m/s. The reading show in the **figure 4.3 (a)** and **figure 4.3 (b)** that the maximum value of flux linkage is 0.2802 wb and 0.2434 wb. Refer to the graph, both of the graph need the position of 13 mm to reach the maximum value of flux linkage. While for **figure 4.3 (c)**, the flux linkage reach the maximum value at position 13 mm. The maximum value of flux linkage for Alnico magnet is 0.3392 wb which has the highest flux linkage among the permanent magnet. **Figure 4.3 (d)** show that the value of flux linkage reach the maximum value which is 0.1070 wb at position 13 mm. All the maximum value of flux linkage is refered to the graph for phase A.

From the Faraday's Law, it state that the value of induced voltage directly proportional to the rate of change of flux linkage. Flux linkage produced when the magnetic field pass through the loop of coil at the stator. The relationship between **figure 4.2** and **figure 4.3** is the value of induced voltage increase as the value of flux linkage increase.

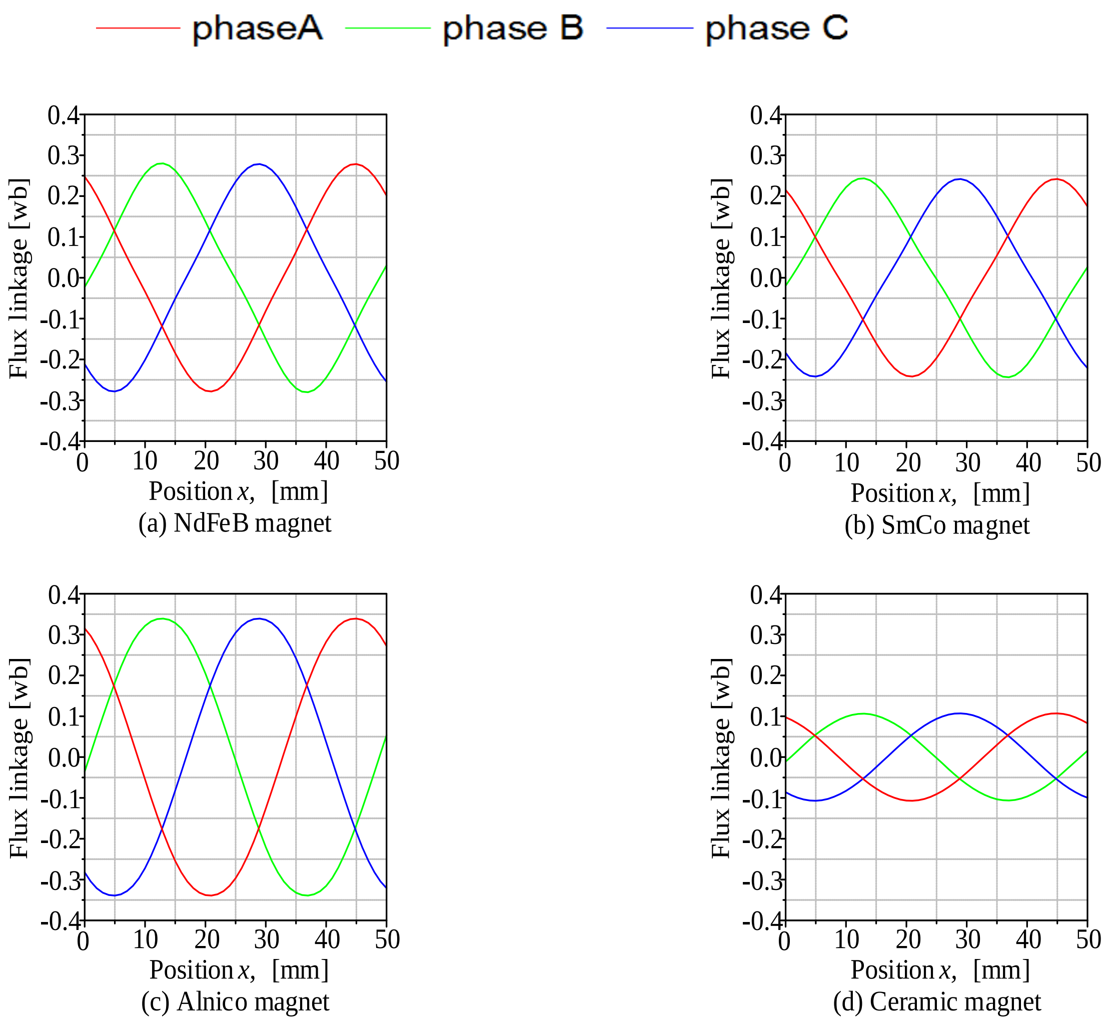


Figure 4.3: The characteristic of flux linkage of PMLG

4.5 The Analysis Of Cogging Force Characteristic

Figure 4.4 show the result of cogging force at different type of permanent magnet with the condition of same speed at the mover. The result obtained in three phase system. The graph for all type of permanent magnet almost similar but the reading sclae of the force are different. There are large different of cogging force between NdFeB magnet with SmCo magnet and Alnico magnet and Ceramic magnet. **Figure 4.4 (a)** show the graph of cogging force for magnet NdFeB type. The maximum cogging force of NdFeB magnet is 49.1 N which is higher than SmCo magnet as 38.2 N as shown in **figure 4.4 (b)**. Meanwhile, the **figure 4.4 (c)** and **figure 4.4 (d)** shows the maximum cogging force of Alnico magnet and Ceramic magnet are 11.99 N and 5.11 N.

Cogging force are form due to the attraction of ferromagnetic core of permanent magnet and zero current in the winding of the stator. These force caused the undesired vibration and acoustic noise that can reduce the performance of linear generator. The cogging force is depend on the strenght of magnetic field in the air gap. In order to reduce the cogging force, the magnetic field in th air gap should be reduce.

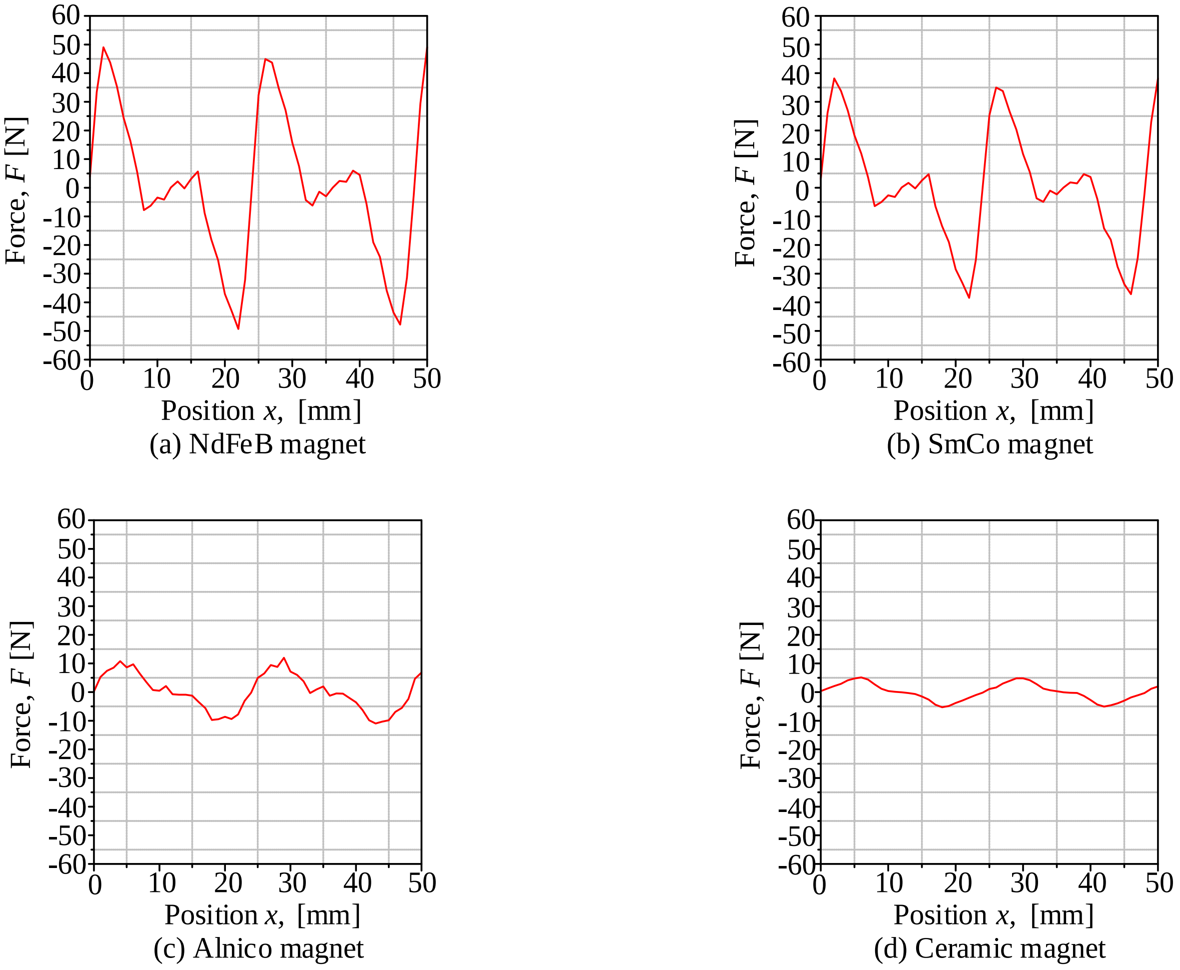
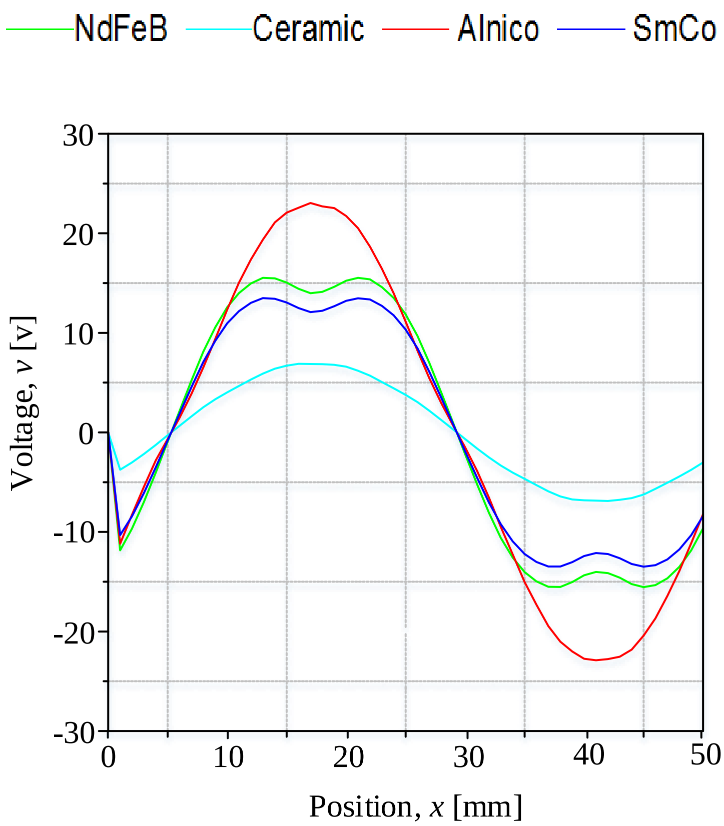


Figure 4.4: The characteristic of cogging force of PMLG

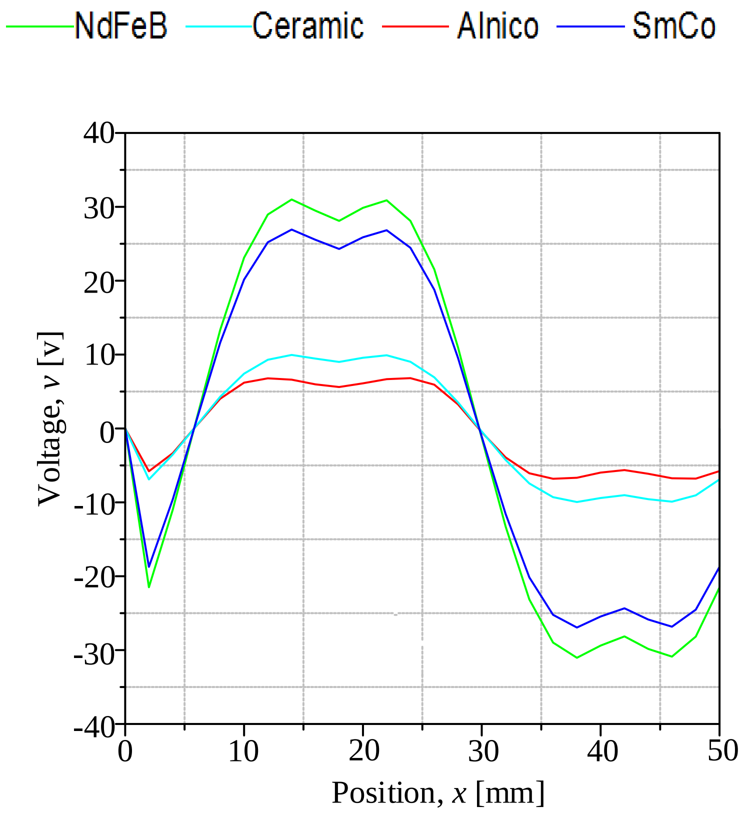
4.6 Comparison Of Induced Voltage At Different Material Of Magnet

Figure 4.5 (a) shows the comparison of induced voltage produced at the velocity of 0.5 m/s and using four different type of permanent magnet for the translator core. The result up and down between the negative and positive value is observed. From the graph, it can be observed that each line represent the data for four different type of permanent magnet, namely NdFeB magnet, SmCo magnet, Alnico magnet and Ceramic magnet respectively are 15.49 V, 13.47 V, 22.67 V and 6.89 V. It can be conclude that in this range of speed of mover Alnico magnet is eligible for the translator core of PMLG.



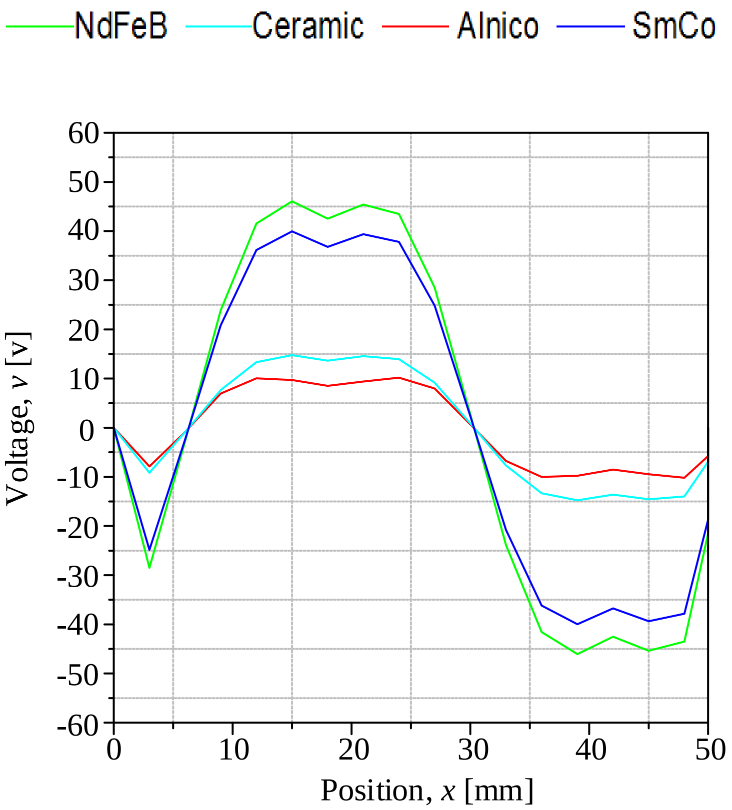
(a) Induce voltage at speed 0.5 m/s

Figure 4.5 (b) shows the comparison of induced voltage produced at the velocity of 1.0 m/s and using four different type of permanent magnet for the translator core. Refer to the graph, the PMLG with the mover used NdFeB magnet has higher induced voltage among the four type of permanent magnet which is 30.96 V. It can made the conclusion that in this range of speed, the NdFeB magnet is selected for the translator core of PMLG.



(b) Induce voltage at speed 1.0 m/s

Figure 4.5 (c) shows the comparison of induced voltage produced at the velocity of 1.5 m/s and using four different type of permanent magnet for the translator core. Based on the result, the PMLG with the translator of NdFeB magnet has highest value of induced voltage which is 45.95 V whereas the other type of permanent magnet as SmCo magnet, Alnico magnet and Ceramic magnet respectively 39.90 V, 10.54 V and 14.75 V. It can be conclude that, the NdFeB magnet is more prefered for the translator of the proposed generator.



(c) Induced voltage at speed 1.5 m/s

Figure 4.5: The characteristic of induced voltage of PMLG at different type of magnet.

4.7 Induced Voltage Against Speed

Figure 4.6 shows the comparison of the induced voltage of the PMLG at various velocity of the translator and four different type of permanent magnet for the translator core. Based on the graph, it is show that the PMLG with NdFeB magnet has the highest value of induced voltage proportional to the velocity of the mover consistently. The PMLG with SmCo magnet has second higher of induced voltage followed by the Ceramic magnet with consistent value as the velocity increases. At last, the PMLG with Alnico magnet has a lowest induced voltage with no consistency result as the velocity increases.

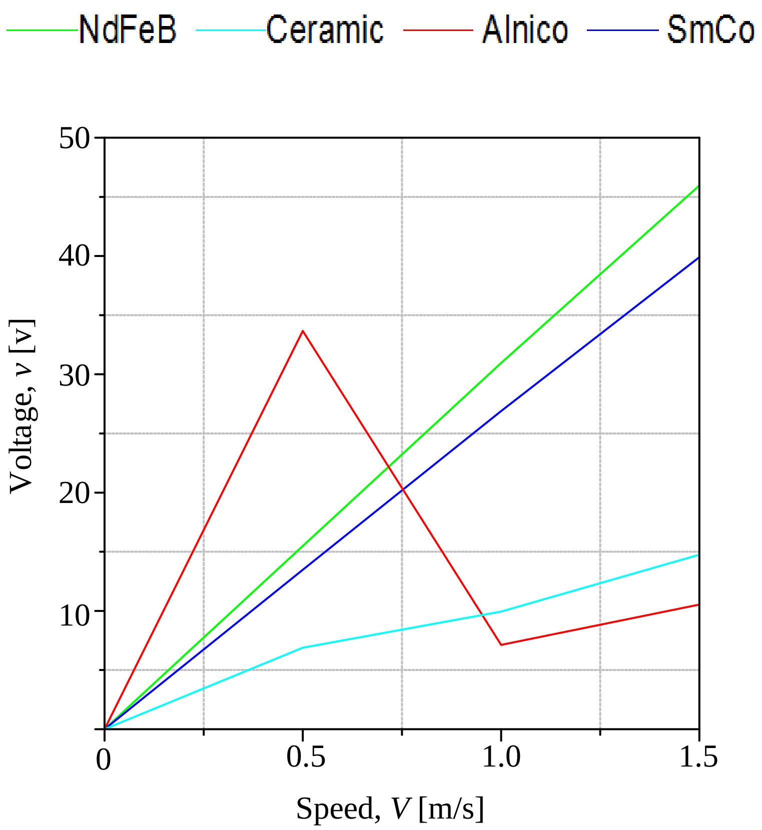


Figure 4.6: Comparison of induced voltage under four different type of permanent magnet and different velocity.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In this project, the focus is on the varies type of permanent magnet that applied to the translator of 15 slot 14 pole of PMLG in three phase winding. The scope is to find out the best performance among four type of permanent magnet by study each characteristic of the permanent magnet that can produce maximum performance for linear generator with high efficiency.

Several type of permanent magnet is analyzed in order to choose the best permanent magnet to apply in the PMLG. Based on the simulation result at speed 0.5 m/s, NdFeB magnet is chosen as the best permanent magnet even though Alnico magnet produces high induced voltage. This is because NdfeB magnet produce high induced voltage with more efficient than Alnico magnet, SmCo magnet and Ceramic magnet.

This project had presented the analysis of induced voltage, magnetic flux density, cogging force and flux linkage based on the mover speed 0.5 m/s, 1.0 m/s and 1.5 m/s at four different type of permanent magnet. It is noted that when the value of induced voltage is high with the low cogging force consistently, the performance is in good condition.

The permanent magnet of NdFeB magnet had been selected from analysis result based on the material requirement. This magnet is suggested as a recommended permanent magnet for the next experiment as it fulfill all the requirement needed.

5.2 Suggestion

Based on the result obtain, there are few suggestion are made in order to improve the permanent magnet linear generator. Firstly, make an analysis by adding the pole of permanent magnet. Secondly, analyze the permanent magnet linear generator in five phase winding at different speed of mover.

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