Faculty of Electrical Engineering

EFFECT OF SLOT OPENING TO PERMANENT MAGNET LINEAR GENERATOR PERFORMANCE

Eivan anak Kelvin

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.

Signature :…….....
Supervisor Name : Dr. Fairul Azhar Bin Abdul Shukor
Date :……..

EFFECT OF SLOT OPENING TO PERMANENT MAGNET LINEAR GENERATOR PERFORMANCE

EIVAN ANAK KELVIN

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

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

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.

ACKNOWLEDGEMENTS

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.

TABLE OF CONTENTS

LIST OF FIGURE

LIST OF TABLE

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.

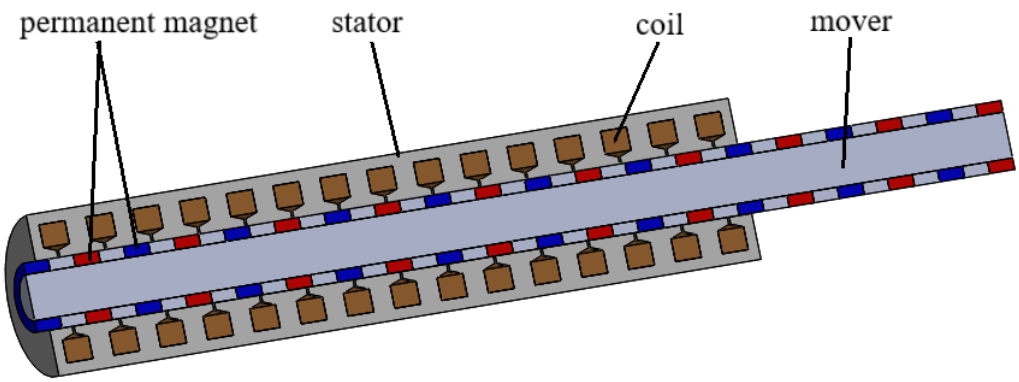

Figure 2.1: Structure of PMLG

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.

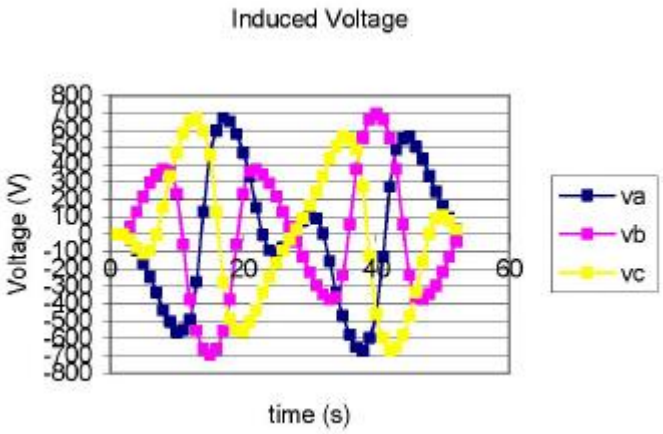

Figure 2.2: Three phase induced voltage produced by the linear generator

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.

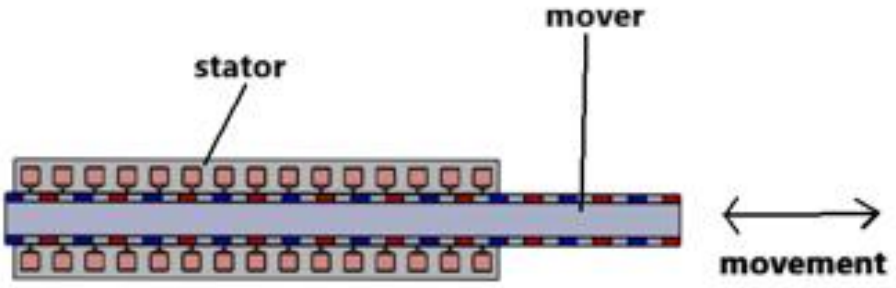

Figure 2.3: Basic principle of PMLG

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.

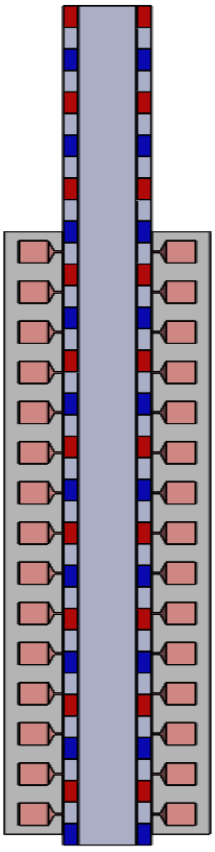

Figure 2.4: 15 slot 14 pole PMLG

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.

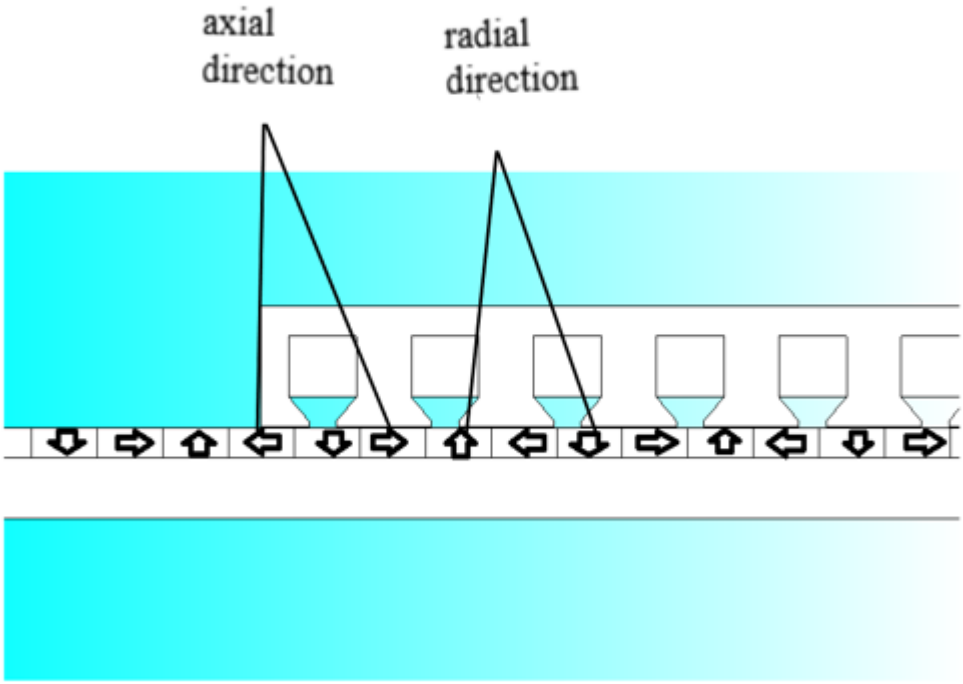

Figure 2.5: Halbach permanent magnet configuration

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.