MODELLING OF LINEAR GENERATOR FOR INTELLIGENT BUMPING SYSTEM

By

KOO SHUK YEE

DISSERTATION REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

MODELLING OF LINEAR GENERATOR FOR INTELLIGENT BUMPING SYSTEM

by

Koo Shuk Yee

Dissertation submitted to the
Electrical & Electronics Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

Approved by,

____

Dr. Taib Bin Ibrahim
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

MAY 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

Koo Shuk Yee

ABSTRACT

This report presents the designs of linear generators which can be applied into the road bump of UTP. Universiti Teknologi PETRONAS consists of more than 1000 cars and it should be able to apply a force on the linear generator while car crossing the bump. The linear generator is able to produce electricity when a force is applied to it. In the report, literature review of the linear machine topology is included. Four types of linear machine are discussed in the report and two designs of suitable linear generator are proposed. The designs are set based on few criteria which are simplicity, performance and suitability to be used in the road bump. The parameters of the proposed designs are included and it is set according to the standard size of a road bump so that it is able to be fitted perfectly into the road bump. Finite Element Analysis method is applied to simulate and analyze the result by using ANSYS software. The results of both designs are included whereby comparisons have been made in terms of air gap flux density that is taken in air gap of the machine and also the induced EMF. Besides, optimization work has been carried out in order to obtain the maximum magnetic flux and also optimized design whereby maximum EMF can be induced. Three areas have been optimized where maximum magnetic flux can be obtained, balanced between electrical loading and magnetic loading and also balanced between copper loss and iron loss. The results of both designs about the magnetic flux in the stator and air gap flux are discussed. Furthermore, a comparison on both designs is included as well. The air gap flux induced in the linear generator is discussed and graphs are included. In conclusion, a decision has been made to decide which design should be chosen and applied in the road bump in order to increase the performance of the road bump application to generate electricity.

ACKNOWLEDGEMENT

First and foremost, I would like to show my heartiest gratitude to my Final Year Project supervisor, Dr. Taib Bin Ibrahim who has guided me throughout the project by giving me suggestions and opinions until the completion of the project. His professionalism and expertise has been helping me to reach the current milestone of my project.

Besides, I would like to thank Dr. Nursyarizal Bin Mohd Nor and Dr Mohd Shiraz Bin Aris who has guided me throughout the project by giving and teaching me lots of knowledge in ANSYS software whereby I am able to use the software to analyze my designs.

Last but not least, another heartfelt gratitude to my friends and family. Without their support and consideration, I will not be able to complete the project with this good result. THANK YOU.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Introduction

This chapter involves the background study and main problem that leads to the idea of designing and modeling of linear generators that is to be applied into the road bump. The idea is to be focused on the area of Universiti Teknologi PETRONAS whereby road bumps in UTP is the research and design target.

1.2 Background of Study

Universiti Teknologi PETRONAS is a university where it contains of more than 4000 students and 650 staffs in year 2011. The normal activities and daily operations need a lot of electricity until UTP needs to pay at least RM 1.3 million for the electricity bill. The data is obtained from the Management Department of UTP. To name a few, lecture hall needs electricity to turn on the light, air-conditioner and projector for a normal lecture class, students stay in hostel and electricity is needed to turn on the light and fan. Thus, the consumption of electricity to maintain a daily operation of a university is huge. A constant huge sum of supply of electricity is needed to provide to the UTP in order for them to consume the electricity without any worries. The supply of the electricity comes from three ways. One is by using non-renewable energy like petroleum, coal and natural gases to generate electricity where it is normally used in many countries includes Malaysia. Another way is generating electricity by using renewable energy like solar, hydro and wind and of course, lastly there should be a way for the user to generate electricity by using generator and apply it into the facilities that is around us. For instances, user can apply generator into the road bump and while car crosses the bump, the force that is applied onto the generator will be able to generate electricity. The rotating fan can be used as a generator to supply electricity to the other electrical appliances while the fan is being turned on. For the current issue of global warming, a better way to provide users the electricity is by using renewable energy or using the facility around the users thus the users are no longer needed to consume the electricity by using non- renewable energy and in another hand, UTP is able to help the earth from going into deeper global warming issue which it does bring a lot of troubles to the human.

1.3 Problem Statement

The global warming issue is a topic that everyone should take up the responsibility to fix it as it brings a lot of disasters like flood, a sudden change of climate and tsunami to the human. The problem happened is mainly due to the excessive use of non- renewable energy to produce electricity and other purposes. Thus, it is now the time to think of a better way likes using renewable energy to generate electricity. The vehicles that cross the bump along the roadside are able to produce a linear motion, while the car cross the bump, the bump will go down as it will act as a spring where it is pressed and it will move back to the original shape. The same concept is applied to the bumping system where a linear generator will be put into the bump and while the cars cross the bump, the motion of going down and up will act to the linear generator and a certain amount of electricity will be produced. Moreover, there are a lot of road bump in the compound of UTP that are not fully utilized. The road bump in UTP can be used as the background to generate electricity by using inserted a linear generator into the road bump.

By using linear generator under the road bumping system to generate electricity is another good way to produce electricity by saving on the usage of non- renewable energy. There are estimated 3700 vehicles include the cars and motorcycles of the staffs, students and vendors in UTP in year 2010. The crossing of the bump of all those cars is able to generate a huge sum amount of electricity if a linear generator is applied into the bump. It is a way to generate electricity by not using the non- renewable energy. In another word, it is a way of harvesting the energy and produces it into a useful way.

1.4 Objective and Scope of Study

1.4.1 To fully utilize linear generator into the bumping system on the road of UTP

It is be able to fully utilize the linear generator into the bumping system on the road of UTP and so some force and energy that are produced by the cars while crossing the bump can be changed into electrical energy and that electricity can be used by UTP itself. From that point of view, this project helps UTP on saving a lot of electricity and the usage of non- renewable energy to generate electricity can be reduce.

1.4.2 To carry out literature review on linear machine topology

The concept of linear machine can be fully understood by studying on literature review of linear machine topology. There are a few types of machine available. Each has different characteristic and performance. A suitable type of machine can be determined in order to apply into the new design machine.

1.4.3 To propose new designs of linear generator to improve the performance

The concept of applying linear generator into the road bump will be used thus the performance of the generator is importantly influencing the electricity that can be generated. A few designs are designed and researched by other scientists and researchers, the linear generator that is going to apply into the road bump should have better design and performance in order to suit into the road bump concept and be able to generate electricity at low speed. Hence, a linear generator is studied and designed in order to come out with a linear generator that is equivalently good at all specifications.

1.4.4 To analyze the suitable linear machine for bumping system

The simulation and analysis of the new design should be carried out in order to make sure the new design meets the required performance and of course, the new design should be able to fit into the road bump which it can perform efficiently.

1.4.5 To optimize the design parameters

The new design should be verified and optimize in order to make sure the design is working at its best performance. It can increase the credibility and reliability of the design.

1.5 Conclusion

Due to the excessive usage of non- renewable energy that leads to global warming issues arise, a green technology is to be used to generate electricity by using road bumps with linear generator inserted under it. In UTP, there are more than 20 road bumps and it should be fully utilized to generate electricity. In order to make bring out this brilliant idea, a few methodologies that need to be executed for instances, study on various topologies of linear machines that is suitable to be applied into the road bump, to design and improve from the initial design in order to generate higher electricity, to optimize the designs in order to obtain the optimum number of flux and size of linear machine.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter involves the literature review on the various topologies of the linear machine for instances linear synchronous machine, linear induction machine, linear dc machine and linear permanent magnet machine. A suitable linear machine will be chosen to be applied into the road bump. Two new designs of chosen linear machine will be proposed in order to improve from its initial performance.

2.2 Basic Theory of Linear Generator

A linear generator is an alternative solution in providing an electrical power supply with high efficiency. Without any rotary part in the engine, the machine will be light weight and compact. The electricity can be generated by the linear motion of the rotor. The rotor will moves up and down or left to right instead of rotary motion. Magnet of the motor is being put in flat way and electricity will be generated from the linear motion of the rotor and it can be referred to Figure 1. By using linear generator, the motor of translator is converted to electrical energy and used for quite a number of purposes. For example, it can be used in hybrid, electric vehicles, magnetic levitation train and bumping system where the linear generator is applied in the bump [1].

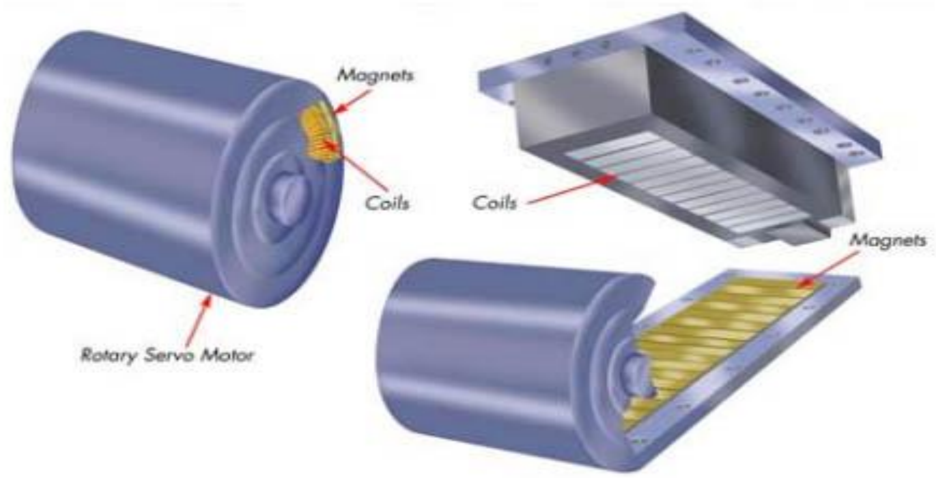

Figure 1: Development of linear machine from rotary motor [1]

2.3 Linear Machine Topologies

Various types of linear generators are available and each type of the linear machines will have its own characteristic and suitability to be used in order to generate electricity. Four types of linear machines will be discussed and they are as following:

i. Linear Induction Generator

ii. Linear DC Machine

iii. Linear Synchronous Generator

iv. Linear Permanent Magnet Generator

2.3.1 Linear Induction Generator

A linear induction generator is basically an electric motor with its stator unrolled and laid out in a line. Opposite of achieving torque by rotation, it causes a linear force along the length of the stator. There are two design categories of linear induction generator, low and high acceleration. The low acceleration linear generators are of linear synchronous design. This means the stator has a winding movement on one side of an air gap and a range of alternate pole magnets on the other side. The energy is caused by a moving electromagnetic field applied on conductors. The eddy currents of any conductor appearing on the field will be induced. It is a synchronous machine. The other design category is the high acceleration linear induction generator. This means that the stator has an active three phase winding on one side of the air gap and a passive conductor plate on the other side. It is hard to design and will need a huge amount to manufacture it [2].

Advantage of using Linear Induction Generator [6]:

i. Apply in heavy industry for instance transportation and conveyor system

ii. Size is huge

Disadvantage of using Linear Induction Generator [6]:

i. Motor has poor performance at low speed

ii. Normally used for three phase system

The application of linear induction machine is limited to heavy duty performance machine and it is not recommended to be used under road bump and generate electricity as this type of linear machine cannot provide a performance at low speed.

2.3.2 Linear DC Machine

A DC motor is designed to run on DC electric power. By far, the most common two types of DC motor are the brushed and brushless types which use internal and external commutation respectively to create an oscillating AC current from the DC source.

Advantage of using Linear DC Machine [6]:

i. DC linear motor is easy and accurate to control of force and position

ii. Suitable to be used for long stroke applications

iii. Suitable to applied in robotics and positioning tables

Disadvantage of using Linear Induction Generator [6]:

i. Motor has poor performance at low speed

ii. Expensive to manufacture

iii. Suffer from brush wear

iv. High maintenance

v. Noisy during operation

For the application of low speed in road bump in order to generate electricity, linear DC generator is not recommended to be used as it has poor performance at low speed and it is expensive to manufacture and the maintenance cost is proportionally higher.

2.3.3 Linear Synchronous Generator

It generates propulsive force by running current through a stator, which creates an electro-magnetic field. This electro-magnetic field interacts with a set of permanent magnets on a vehicle to create thrust. The permanent magnets serve as the motor secondary, equivalent to a rotor in conventional motors enabling linear motion. The vehicle is propelled by the moving electro-magnetic field, travelling along as electric current is applied to the stator beneath the vehicle. The vehicle’s movement is regulated by a sophisticated control system incorporating state-of-the-art position sensing technology [7].

Advantages of using Linear Synchronous Machine [7]:

i. Increase reliability
ii. Improve performance on speed and efficiency
iii. Negotiate steep grades without depending on friction
iv. Eliminate the need to have propulsion power and control on the vehicle
v. Ability to control multiple vehicles on complex trajectories

Disadvantages of using Linear Synchronous Machine [7]:

i. Poor performance at low speed
ii. Application is limited due to relative complexity of stator winding
iii. Require power supply

For the application of using linear synchronous generator into the road bump, it is not suitable to be used as the application is limited to the complexity of the stator winding configuration and the need for a multi- phase power supply makes the conventional topology of linear synchronous machine un-suitable for low power reciprocating applications.

2.3.4 Linear Permanent Magnet Generator

Linear permanent magnet generator can be classified into three categories which are moving- coil machine, moving- iron machine and moving- magnet machine. They provide magnetic field for the machine coils. The permanent magnet is used as the magnetic field source for the machine. It gives a high flux density in the air gap compared to the other type. The designs of the axial and radial permanent magnets had been used. In the axial permanent magnet machine, a high cogging force is produced due to the interaction between permanent magnet and stator teeth. Since it is a serious problem, radial permanent magnet has been applied to reduce the cogging force problem. As a result, a quasi Halbach permanent magnet is used [1]. The efficiency and performance of the permanent magnet will be different if the magnet is arranged in different way. According to the research, Neodymium magnet is considered because it has higher remanence compare to other magnet [3].

Disadvantages of moving coil [6]:

i. Difficulty in dissipating heat from coils

ii. Fragility of the connections and flying leads

iii. Limited access to moving coil

Disadvantages of moving iron [6]:

i. Heavy moving mass that can reduce the dynamic capability of the motor

ii. A relatively low force capability due to low air- gap flux density

Advantages of moving magnet [6]:

i. Higher force capability

ii. Higher efficiency

A number of studies shown that linear permanent magnet machine is able to perform well at low speed and it is very suitable to used for low power reciprocating applications. Besides that, moving magnet linear machines can offer higher efficiencies than moving coil linear machines [13]. Further, a comparison between moving coil and moving magnet linear machine has dedicated that the volume of magnet required for a moving coil is greater than for a moving magnet linear machines of the same power. In addition, the absence of flying leads to the armature makes moving magnet linear machines more reliable and rugged, making them more suitable for higher duty operation [9]. Thus, linear permanent magnet with category of moving magnet machine is to be used for low power reciprocating application.

2.4 Previous Technology / Topology

Linear machine has been applied into a few areas. Piezoelectric is one of the examples which it has the piezoelectric effect that it is understood as the linear electromechanical interaction between the mechanical and the electrical state in crystalline materials with no inversion symmetry [8].

Applications piezoelectric:

i. Electric cigarette lighter:

   By pressing the button causes a spring-loaded hammer to hit a piezoelectric crystal, producing a sufficiently high voltage electric current that flows across a small spark gap, thus heating and igniting the gas.

ii. A piezoelectric transformer:

   An input voltage is applied across a short length of a bar of piezoceramic material, creating an alternating stress in the bar by the inverse piezoelectric effect and causing the whole bar to vibrate.

Piezoelectric is not been used to for road bump application as it generates low current compared to linear permanent magnet machine. Thus linear permanent magnet machine is preferred in the application of road bump.

2.5 Proposed Designs

After the studied on the various types of linear machine, linear permanent magnet machine is considered as the most suitable linear machine to be applied into the road bump due to its characteristic and thus, further designs will be proposed in order to improve its performance in terms of air gap flux density.

2.5.1 Rectangular arrangement of permanent magnet

There are a lot of choices to design for a good linear generator. However, to make a perfect in efficiency, manufacturing cost and weight of the linear generator, it can be said as very difficult to achieve. The research and design that can be executed is only to optimize the existence design of linear generator and make improvement in the configuration of the whole linear generator. Thus, 2 designs and new configurations of quasi- Halbach permanent magnet are selected for further analysis. The first proposed design is the design of the linear generator with the rectangular arrangement of quasi-Halbach permanent magnet as can be seen in Figure 2 and in Figure 3, it shows the 3D design of the rectangular arrangement of linear permanent magnet machine. It will only allow a certain amount of magnetic flux to pass through the tube. Thus, it leads to lower flux density and lower thrust force capability. Besides, slotted design is to be employed as it can increases the force capability of the machine. The advantage of using rectangular arrangement of permanent magnet is able to have lower iron loss. The efficiency of the rectangular shape of permanent magnet will be compared with the second proposed design which is trapezoidal shape of permanent magnet since the arrangement of magnet is different.

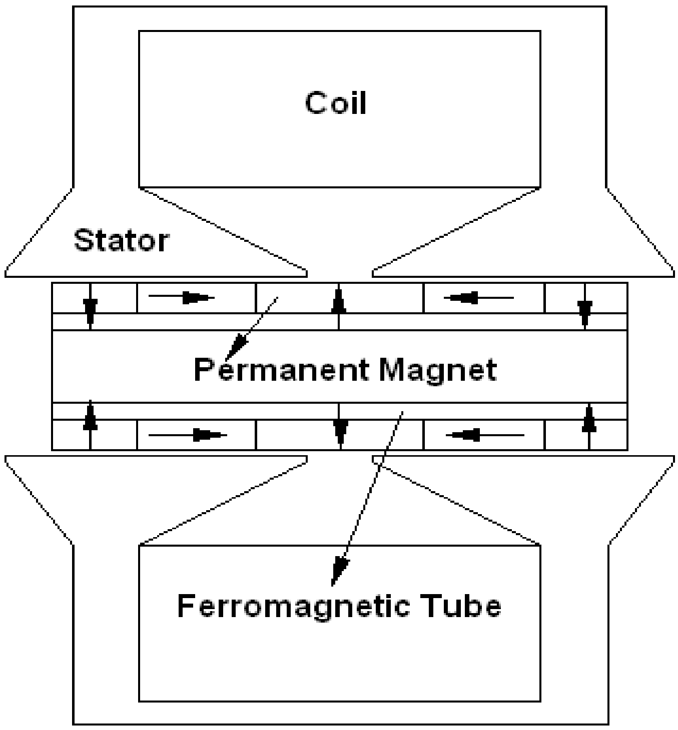

Figure 2: Rectangle arrangement of permanent magnet

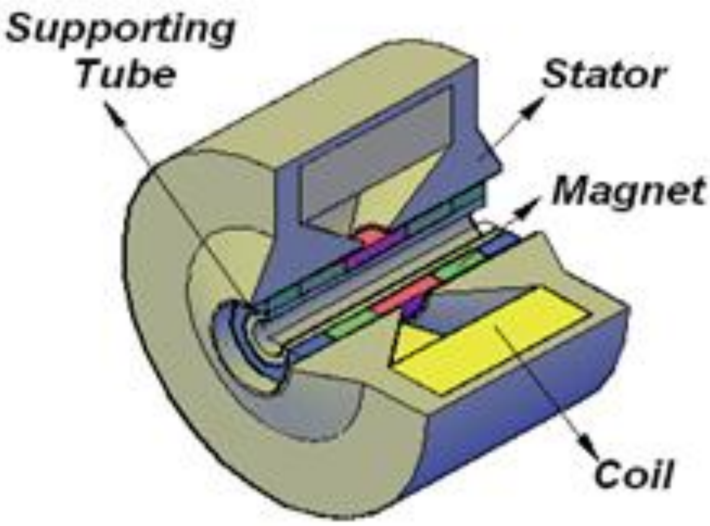

Figure 3: 3D view of rectangular arrangement of permanent magnet linear machine

2.5.2 Trapezoidal arrangement of permanent magnet

Another proposed design is trapezoidal arrangement of permanent magnet linear machine whereby the arrangement of trapezoidal magnet is focused on the middle main magnet only since it is the focus to pass magnetic flux through the coil. It is able to generate more magnetic flux. It can be referred to Figure 4 where trapezoidal arrangement of permanent magnet can be seen in the rotor part and Figure 5 shows the 3D view of trapezoidal arrangement of linear permanent magnet machine. The number of magnetic flux increases, thus, it leads to have better force capability of the linear machine. Besides, this design is able to have higher voltage induced since it has higher magnetic flux. However, the manufacturing cost of the permanent magnet may be slightly higher than the rectangular arrangement permanent magnet since the shape of permanent magnet needs to be custom made.

Besides, ferromagnetic tube will be used in the quasi- Halbach magnetized shaft with rectangular and trapezoidal magnets since this results in a stronger air-gap and therefore, a better force capability. Further, slotted design is to be employed as it can increases the force capability of the machine.

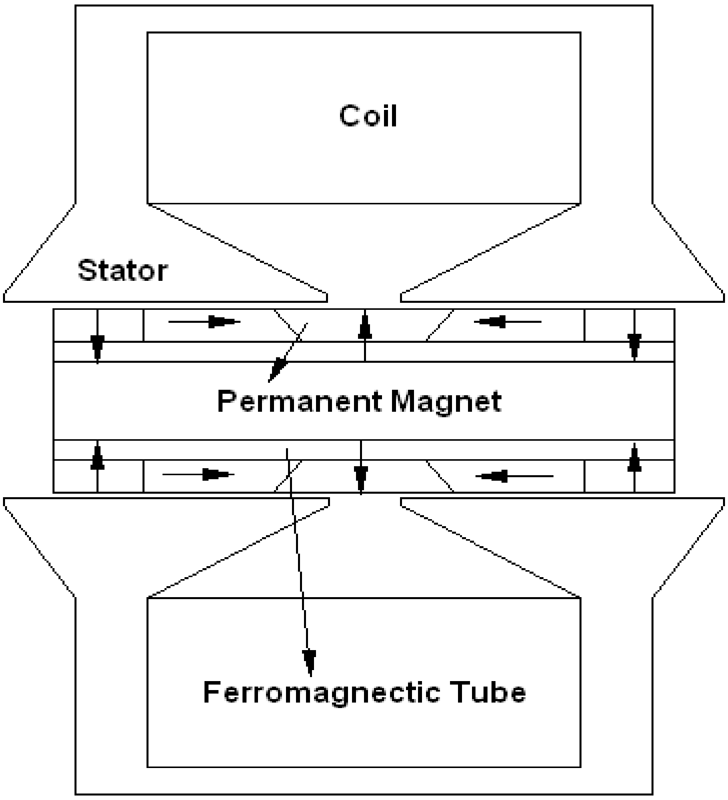

Figure 4: Trapezoidal arrangement of permanent magnet

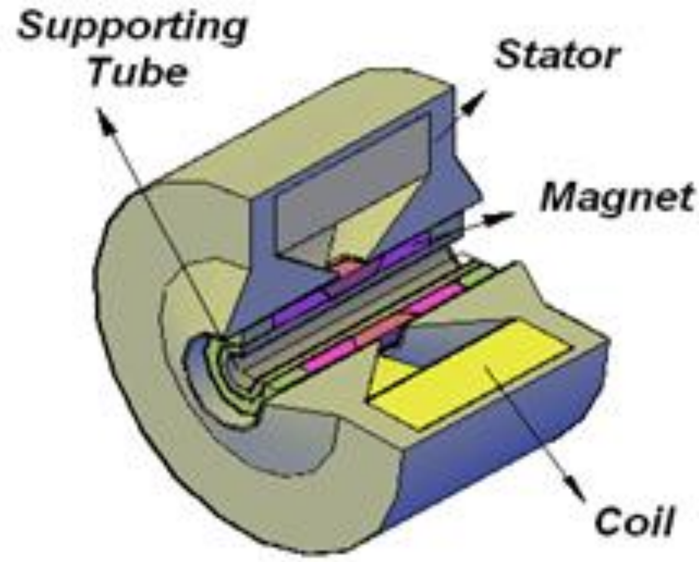

Figure 5: 3D view of trapezoidal arrangement of permanent magnet linear machine

2.6 Conclusion

Various types of linear machine have been studied and discussed in this chapter such as linear DC machine, linear synchronous machine, linear induction machine and linear permanent magnet machine. Linear permanent magnet machine has been chosen to be applied into the road bump due to its characteristic that has great performance at low speed, high force capability and also high efficiency. Besides, moving magnet of linear permanent magnet has been used since it is able to have high force capability and reliable to be used for heavy duty operation. Two designs have been proposed which are rectangular arrangement of permanent magnet and trapezoidal arrangement permanent magnet. Both designs have their own advantages that need to be further analyzed and compared.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter involves the design specifications of both proposed designs. The size of the linear machine needs to compare with the size of the road bump in order to make sure the design of linear machine is able to it into the road bump with having any difficulty. The characteristic of different permanent magnet remanence will be discussed in this chapter and thus a decision of which types of permanent magnet to be applied in the machine will be determined. Besides, finite element software, ANSYS that is to be used to analyze the design and generated magnetic flux will be discussed in this chapter as well.

3.2 Procedure Identification

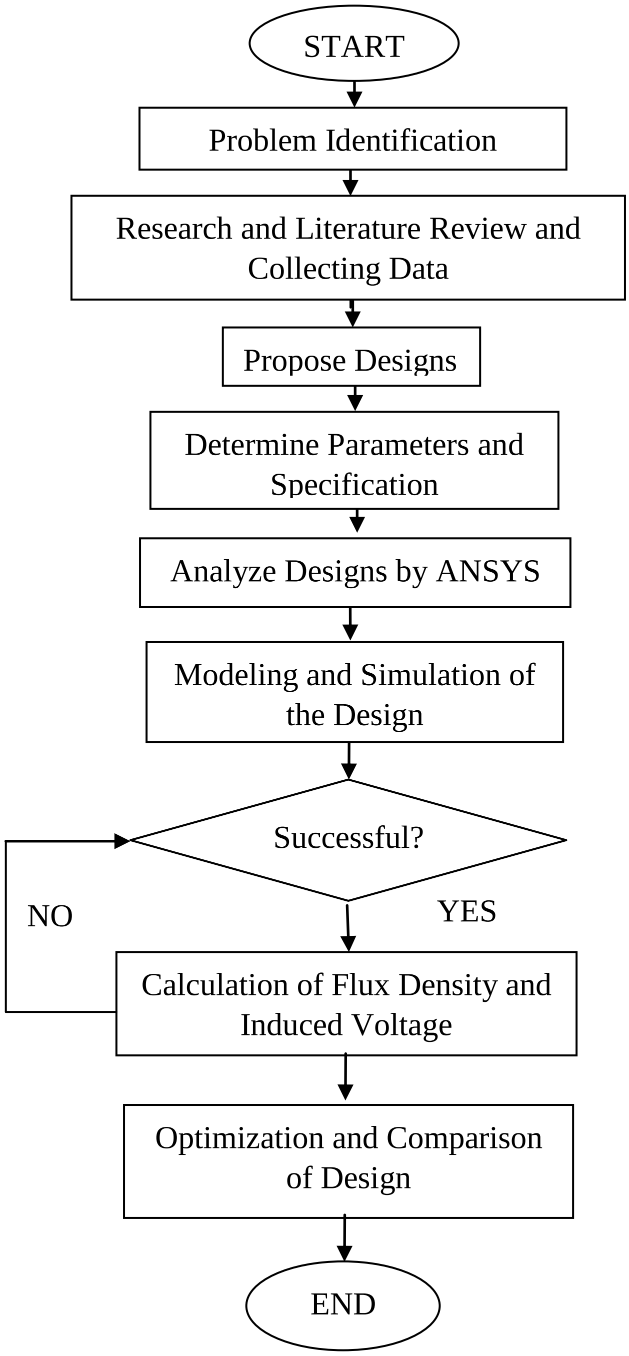

Figure 6: Project flow of designing linear generator

3.3 Design Parameters

The parameters of the design need to be set properly so that the designed linear generator is able to fit into the standard road bump. From the designs, the inner stator is longer than then outer stator, it is because a narrow tooth pitch width is wished to be obtained so the magnetic flux may has high density on the tooth pitch and a better force may can be obtained. Besides, it results in longer length of stator core surface to interact with magnetic flux and it allows more magnetic flux to pass through stator.

Besides, ferromagnetic tube will be used in the quasi- Halbach magnetized shaft with rectangular and trapezoidal magnets since this results in a stronger air-gap and therefore, a better force capability.

3.3.1 Design with rectangular arrangement of permanent magnet

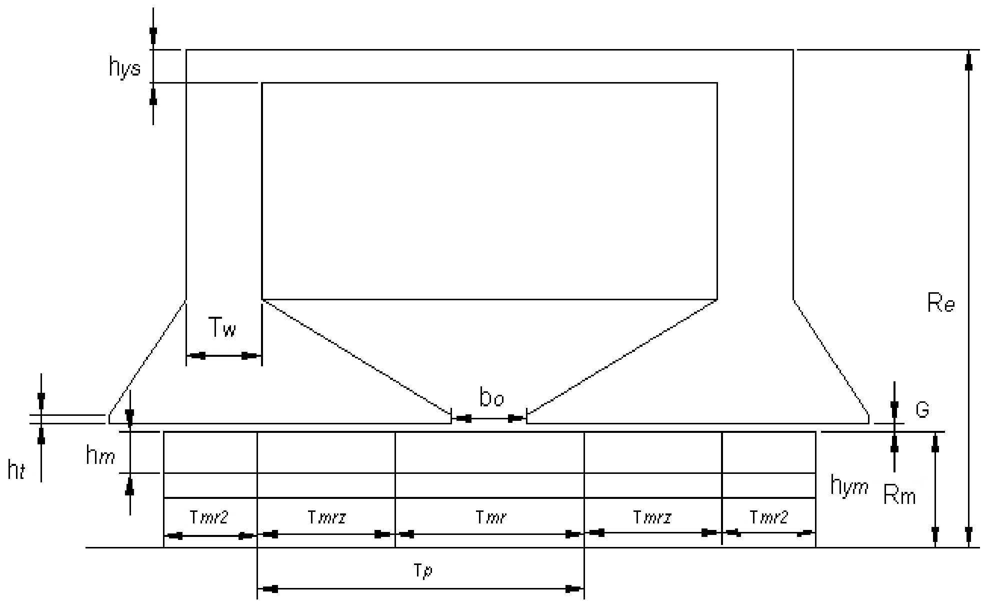

Figure 7: Rectangular arrangement of quasi- Halbach permanent magnet

Table 1: Initial design specification for linear generator with rectangular arrangement of quasi- Halbach permanent magnet

Description	Value	Units
Slot opening width, b_o	10.00	mm
Airgap length, G	1.00	mm
Tooth tip height, h_t	1.00	mm
Outer radius of stator core, R_e	60.00	mm
Magnet height, h_m	5.00	mm
Supporting tube height, h_{ym}	3.00	mm
Yoke thickness, h_{ys}	4.00	mm
Pole pitch, T_p *(rectangular shape)*	43.00	mm
Axial length of radially magnetized magnet, T_{mr}	16.50	mm
Axial length of radially magnetized magnet, T_{mr2}	8.25	mm
Axial length of axially magnetized magnet, T_{mz}	26.50	mm
Tooth width, T_w	10.00	mm
Frequency	50.00	Hz
Permanent magnet material	NdFeB	-
Stator core material	Somaloy 700	-

3.3.2 Design with trapezoidal arrangement of permanent magnet

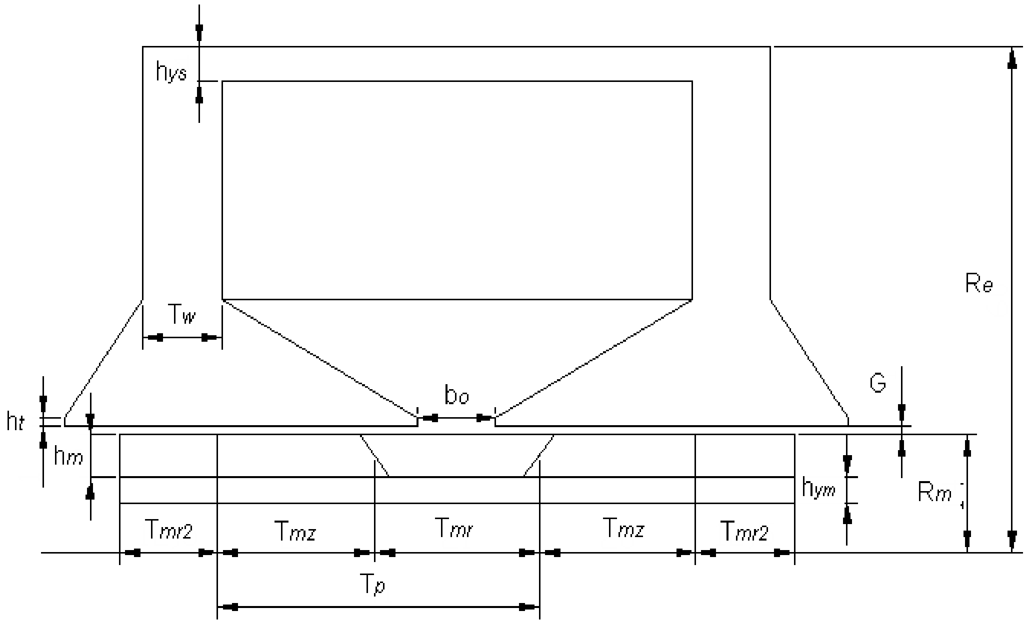

Figure 8: Trapezoidal arrangement of quasi Halbach permanent magnet

Table 2: Initial design specification for linear generator with trapezoidal arrangement of quasi- Halbach Permanent Magnet

Description	Value	Units
Slot opening width, b*o*	10.00	mm
Airgap length, G	1.00	mm
Tooth tip height, h*t*	1.00	mm
Outer radius of stator core, R*e*	60.00	mm
Magnet height, h*m*	5.00	mm
Supporting tube height, h*ym*	3.00	mm
Yoke thickness, h*ys*	4.00	mm
Pole pitch, T*p (trapezoidal shape)*	41.00	mm
Axial length of radially magnetized magnet, T*mr*	17.50	mm
Axial length of radially magnetized magnet, T*mr2*	8.75	mm
Axial length of axially magnetized magnet, T*mz*	22.50	mm
Tooth width, T*w*	10.00	mm
Frequency	50.00	Hz
Permanent magnet material	NdFeB	-
Stator core material	Somaloy 700	-

3.4 Elements Determinations

In this project, a linear permanent magnet generator is decided to be designed. The elements that drive to the success key of this linear generator need to be determined and studied in details. A few studies about the elements of the linear generator have been conducted.

3.4.1 *Size of the road bump that determines the size of the linear generator*

Table 3: Size of road bump

Road Bump	Size
Height	76mm to 100mm
Width	Less than or near to 300mm
Length	Depends on road width, but normally 3.0m to 4.3m

3.4.2 *Numbers of vehicles registered in UTP in year 2008 till 2010*

The data is obtained from the Security Department of Universiti Teknologi PETRONAS.

Table 4: Numbers of cars in UTP from year 2008 till 2010

	Vehicle	Year		Total
		2008/2009	2009/2010	
Staff	Car	1914	1391	3305
	Motorcycle	258	270	528
Student	Car	1943	2052	3995
	Motorcycle	919	1016	1935
Vendor	Car	246	260	506
	Motorcycle	204	205	409

3.4.3 *Magnet*

Neodymium Iron Boron (NdFeB) permanent magnet will be used in linear generator and is attached at the rotor part. This magnet is used due to its high remanance if compared to other types of magnet. NdFeB permanent magnet is able to produce better magnetic flux.

Table 5: Comparison of magnetic performance of Neodymium magnets with other types of permanent magnets

Magnet	***M*$_r$ (T)**	***H*$_{ci}$ (kA/m)**	***BH*$_{max}$ (kJ/m^3)**	***T*$_C$ (°C)**
$Nd_2Fe_{14}B$	1.0–1.4	750–2000	200–440	310–400
$SmCo_5$	0.8–1.1	600–2000	120–200	720
Sm(Co, Fe, Cu, Zr)$_7$	0.9–1.15	450–1300	150–240	800
Alnico	0.6–1.4	275	10–88	700–860
Sr-ferrite	0.2–0.4	100–300	10–40	450

3.4.4 Arrangement of permanent magnet

Besides, the arrangement of magnet can determine the performance of the linear generator as well. Quasi- Halbach arrangement of magnet will be used since it is able to reduce to the cogging force at the starting point of a machine.

3.4.4.1 Trapezoidal arrangement of permanent magnet

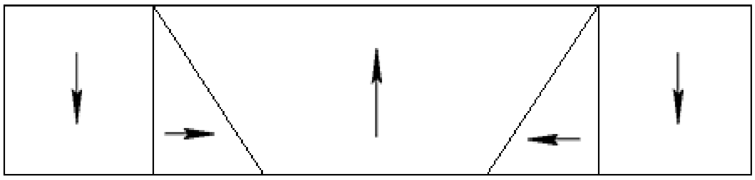

Figure 9: Trapezoidal arrangement of quasi-Halbach PM in the centre

Advantages of trapezoidal arrangement of permanent magnet:

i. Higher flux density

ii. Higher force capability

iii. Higher EMF induced

iv. Higher voltage induced

Disadvantages of trapezoidal arrangement of permanent magnet:

i. Harder to fabricate trapezoidal shape of permanent magnet

ii. High manufacture cost

iii. Higher iron loss

3.4.4.2 Rectangular arrangement of permanent magnet

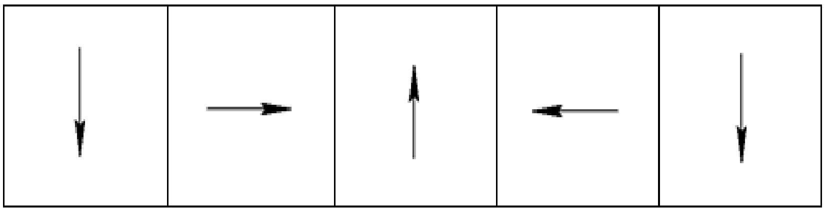

Figure 10: Rectangular arrangement of quasi-Halbach PM

Advantages of rectangular arrangement of permanent magnet

i. Easy to fabricate rectangular shape permanent magnet

ii. Low manufacture cost

iii. Lower iron loss

Disadvantages of rectangular arrangement of permanent magnet

i. Low flux density

ii. Low force capability

iii. Low voltage induced

3.5 Application Tool

The finite element method (FEM) (its practical application often known as finite element analysis (FEA)) is a numerical technique for finding approximate solutions of partial differential equations (PDE) as well as of integral equations. The solution approach is based either on eliminating the differential equation completely (steady state problems), or rendering the PDE into an approximating system of ordinary differential equations, which are then numerically integrated using standard techniques such as Euler's method, Runge-Kutta[4]. Finite Element Analysis will be used to analyze the magnetic characteristic, magnetic flux density and the voltage induced that is shown in ANSYS. ANSYS is a finite element analysis (FEA) code widely used in the computer-aided engineering (CAE) field. ANSYS software allows engineers to construct computer models of structures, machine components or systems; apply operating loads and other design criteria; and study physical responses, such as stress levels, temperature distributions, pressure, etc. It permits an evaluation of a design without having to build and destroy multiple prototypes in testing. The ANSYS program has a variety of design analysis applications, ranging from such everyday items as dishwashers, cookware, automobiles, running shoes and beverage cans to such highly sophisticated systems as aircraft, nuclear reactor containment buildings, bridges, farm machinery, X-ray equipment and orbiting satellites. A 2-Dimensional axisymmetry shape of linear permanent magnet generator will be drawn in ANSYS. The analysis and comparison about the flow of magnetic flux, air gap flux and back EMF (electromotive force) will be conducted.

3.6 Conclusion

The initial specifications of the both designs have been discussed. The characteristic of the permanent magnet have been determined whereby Neodymium Iron Boron (NdFeB) will be used as the permanent magnet in the design as it has highest remanence compared to the other of magnet and it is able to have higher magnetic flux. The advantages and disadvantages of the arrangement of rectangular and trapezoidal shape of permanent magnet have been discussed. It shows that trapezoidal shape of permanent magnet is able to have higher force capability, higher efficiency, higher flux density and higher induced EMF. For rectangular shape of permanent magnet, it is easy to manufacture and thus it reduces the manufacturing cost. Finite element software, ANSYS has been used to analyze the design. It is able to determine the magnetic flux and air gap flux density in the design.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter illustrates the results and discussion on linear generators which are proposed in Chapter 3 whereby the results are concentrated in air gap flux density and induced Electromotive force (EMF). Besides, the optimization of the linear generator is discussed.

4.2 Flux Distribution of Air- cored Magnetized Motor with Rectangular Magnet

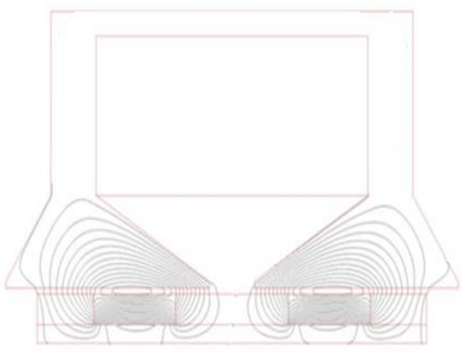

Figure 11: z = 0.0mm

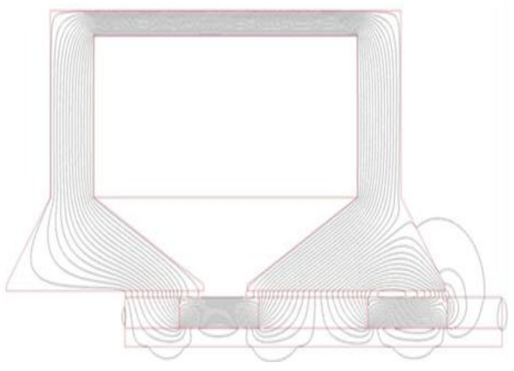

Figure 12: z = 20.0mm

Figure 11 and 12 show air gap flux distributions corresponding to two armature positions which are zero displacement and the maximum stroke position. As will be seen, leakage flux in the inner bore of the air- cored quasi-Halbach magnetized armature with the rectangular magnets is relatively small, which justifies the use of a non- magnetic support tube [9].

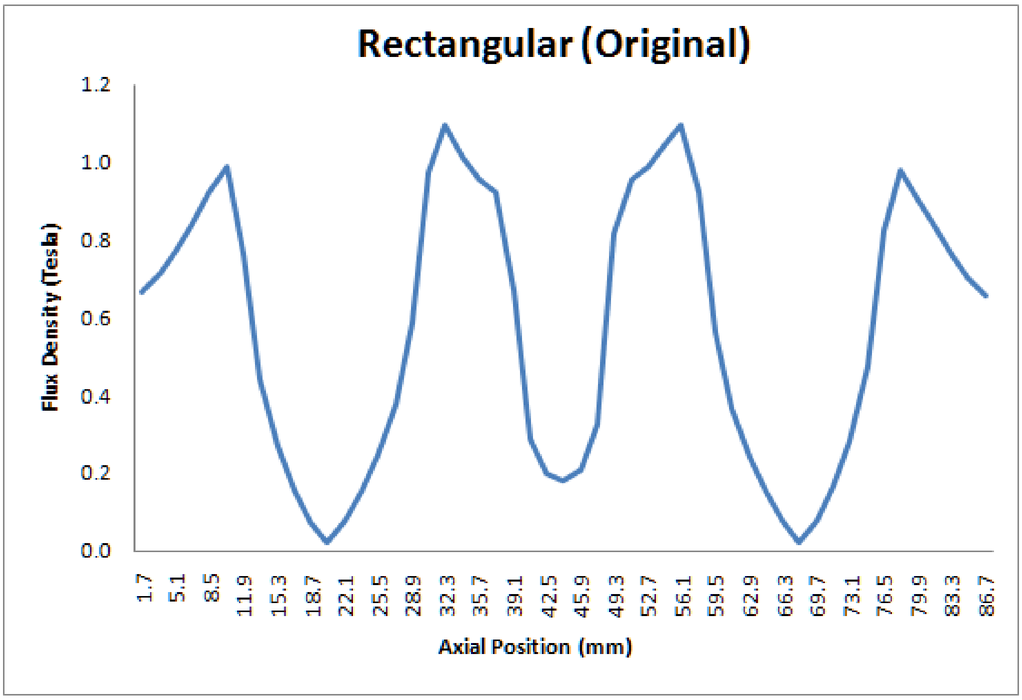

Figure 13: Air gap flux density reaches 1.0941T at z = 0.0mm

Figure 13 shows the air gap flux density of rectangular arrangement of permanent magnet in linear generator. It is able to reach to 1.0941T at the highest peak. The dropping point shows the axially arrangement of permanent magnet where it is transferring the air gap flux to the radially arrangement of permanent magnet.

4.3 Flux Distribution of Air- cored Magnetized Motor with Trapezoidal Magnet

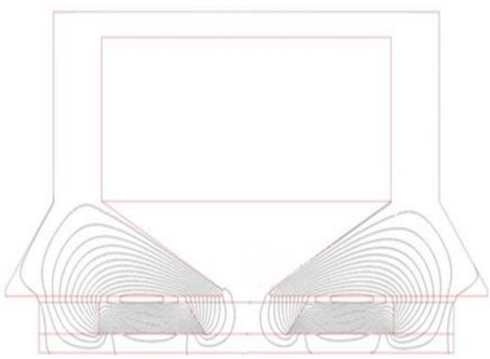

Figure 14: z = 0.0mm

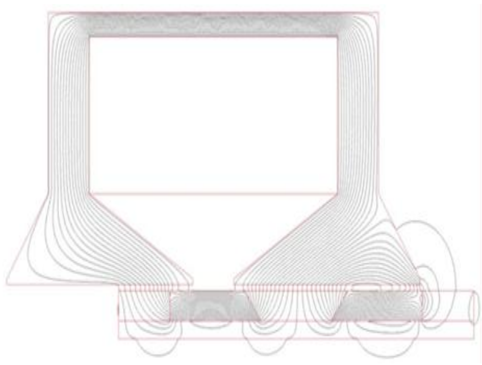

Figure 15: z = 20.0mm

Figure 14 and 15 show no- load flux distribution of initial position and maximum position respectively. For the initial position, the flux distribution is symmetrical with respect to the axial centre. Hence, the coil flux linkage is zero. As the armature move to the left, the flux linkage increases and reaches nearly a maximum value at the maximum stroke position [6].

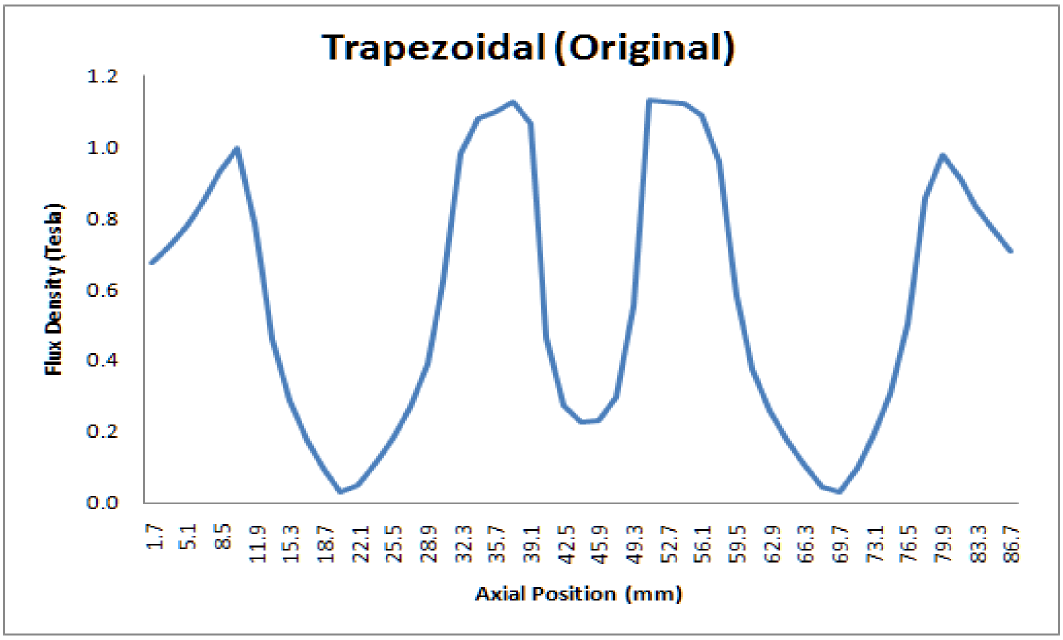

Figure 16: Air gap flux density reaches 1.1314T at z = 0.0m

Figure 16 shows the air gap flux density of rectangular arrangement of permanent magnet in linear generator. It is able to reach to 1.1314T at the highest peak. The dropping point shows the axially arrangement of permanent magnet where it is transferring the air gap flux to the radially arrangement of permanent magnet.

4.4 Optimization – Both Designs of Linear Generator

Optimization work will be carried out to three main areas:

i. The ratio of outer radius of rotor to outer radius of stator core, Rm/ Re

ii. The ratio of axial length of radially magnetized magnet to pole pitch, Tmr/ Tp

iii. Tooth width, Tw

4.4.1 Influence of Rm/ Re with respect to flux density

The ratio of Rm/ Re represents the optimal balance between electrical loading and magnetic loading in order to achieve maximum motor efficiency [10]. In this study, the air gap flux density is optimized with respect to this ratio.

4.4.1.1 Influence of Rm/ Re for rectangular arrangement of permanent magnet

There are six optimized ratios have been studied which are Rm/ Re = 0.23, 0.30, 0.35, 0.40, 0.45 and 0.50. From the graph below, it shows that the flux density that is generated with the changes in the outer radius of rotor, Rm which is in the range of 1.0901T to 1.1471T.

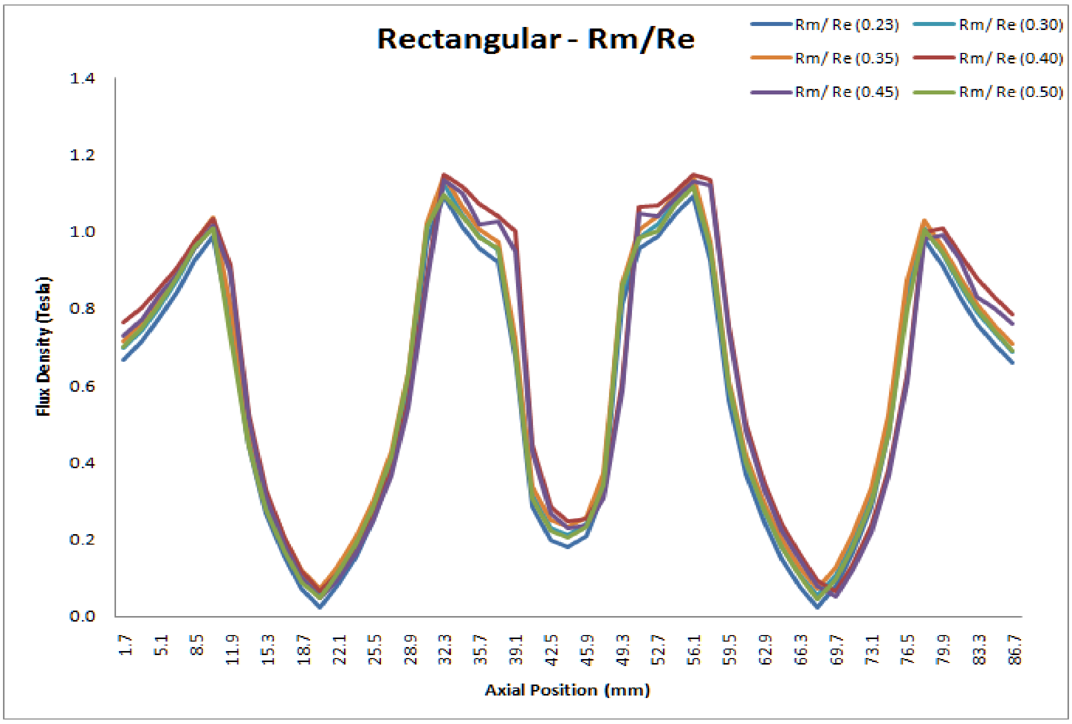

Figure 17: Ratio of Rm/ Re (rectangular design) with respect to flux density

The graph is drawn to prove that the optimization between the radius of rotor to the radius of stator is reached. From the graph, it can be seen that the optimized ratio for outer radius of rotor (Rm) to the outer radius of stator core (Re) is 0.40 whereby Rm is set to be 24mm and Re is a fixed value which is 60mm. The highest flux density that is able to produce by having the ratio of 0.4 is 1.1471T.

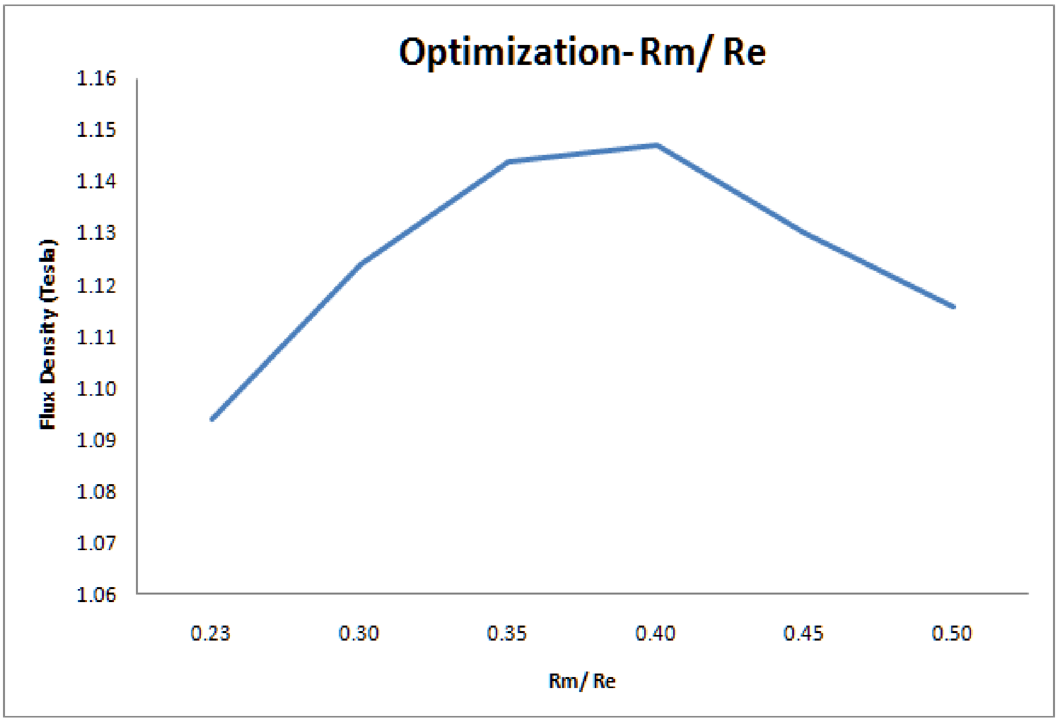

Figure 18: Optimized ratio graph of rectangular design for Rm/ Re

4.4.1.2 Influence of Rm/ Re for trapezoidal arrangement of permanent magnet

There are six optimized ratios have been studied which are Rm/ Re = 0.23, 0.30, 0.35, 0.40, 0.45, 0.50. From the graph below, it shows that the flux density that is generated with the changes in the outer radius of rotor, Rm which is in the range of 1.1314T to 1.200T.

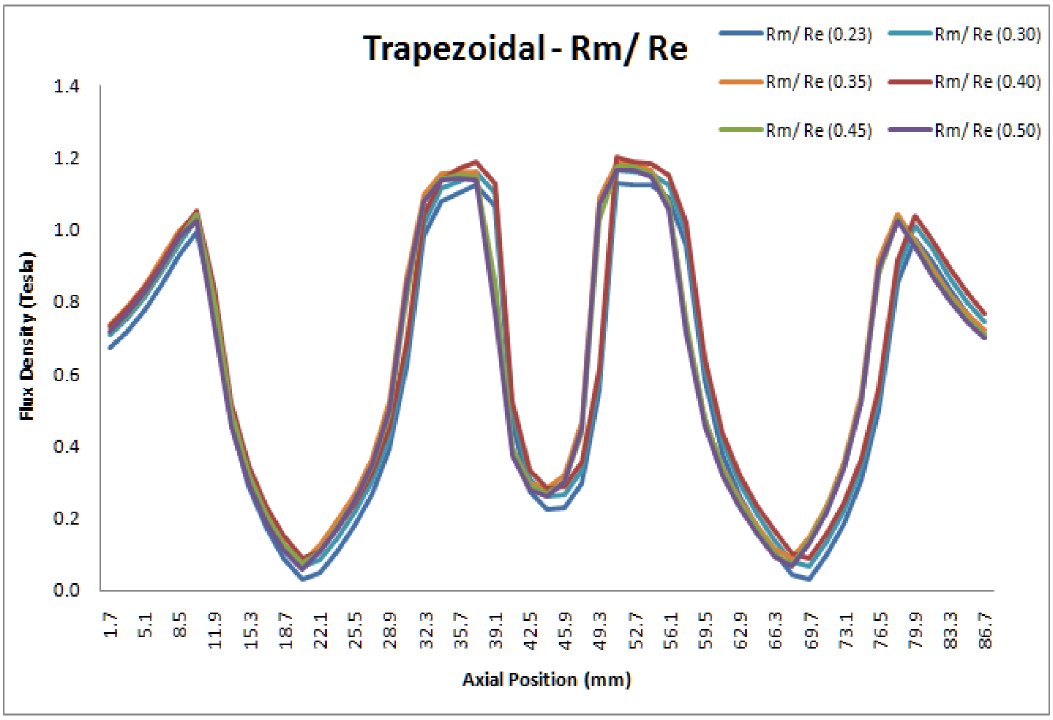

Figure 19: Ratio of Rm/ Re (trapezoidal design) with respect to flux density

The graph is drawn to prove that the optimization between the radius of rotor to the radius of stator is reached. From the graph, it can be seen that the optimized ratio for outer radius of rotor (Rm) to the outer radius of stator core (Re) is 0.40 whereby Rm is set to be 24mm and Re is a fixed value which is 60mm. The highest flux density that is able to produce by having the ratio of 0.4 is 1.200T.

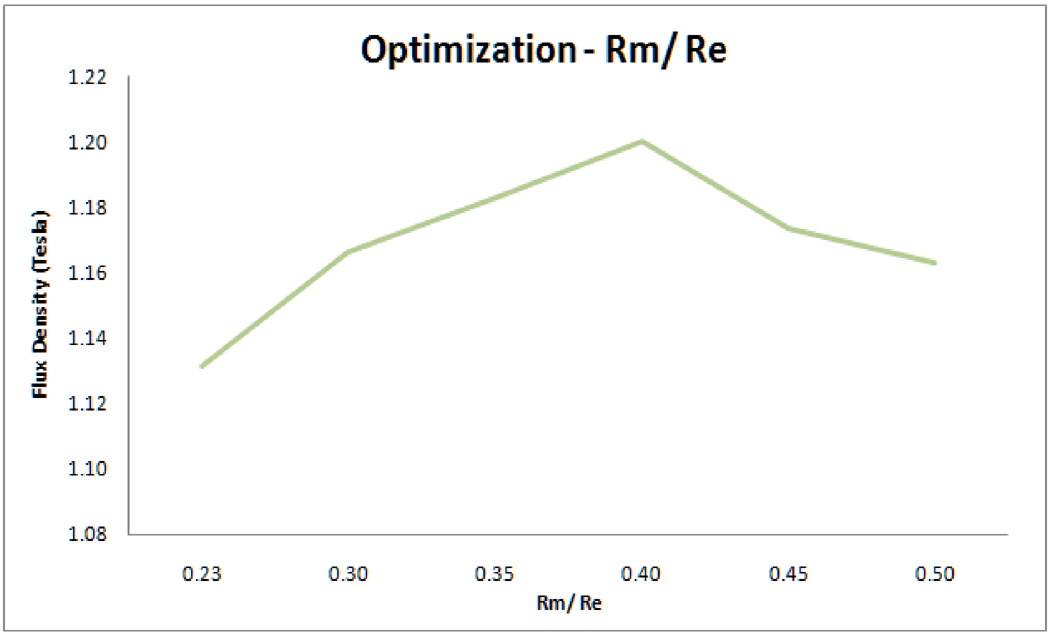

Figure 20: Optimized ratio graph of trapezoidal design for Rm/ Re

4.4.2 Influence of Tmr/ Tp with respect to flux density

The ratio of Tmr/ Tp represents the combined effect of radially and axially magnetized magnets in order to produce a maximum fundamental radial flux density in the air gap [11].

4.4.2.1 Influence of Tmr/Tp for rectangular arrangement of permanent magnet

After the optimization of the outer radius of rotor to the outer radius of stator core (Rm/ Re) where the optimization value is 24mm and 60mm respectively. The optimized radius value is applied into the optimization of ratio of axial length of radially magnetized magnet to the pole pitch, Tmr/ Tp. There are six optimized ratios have been studied which are Tmr/ Tp = 0.38, 0.42, 0.46, 0.50, 0.54 and 0.58. From the graph below, it shows that the flux density that is generated with the changes in the axial length of radially magnetized magnet, Tmr which is in the range of 1.0938T to 1.1823T.

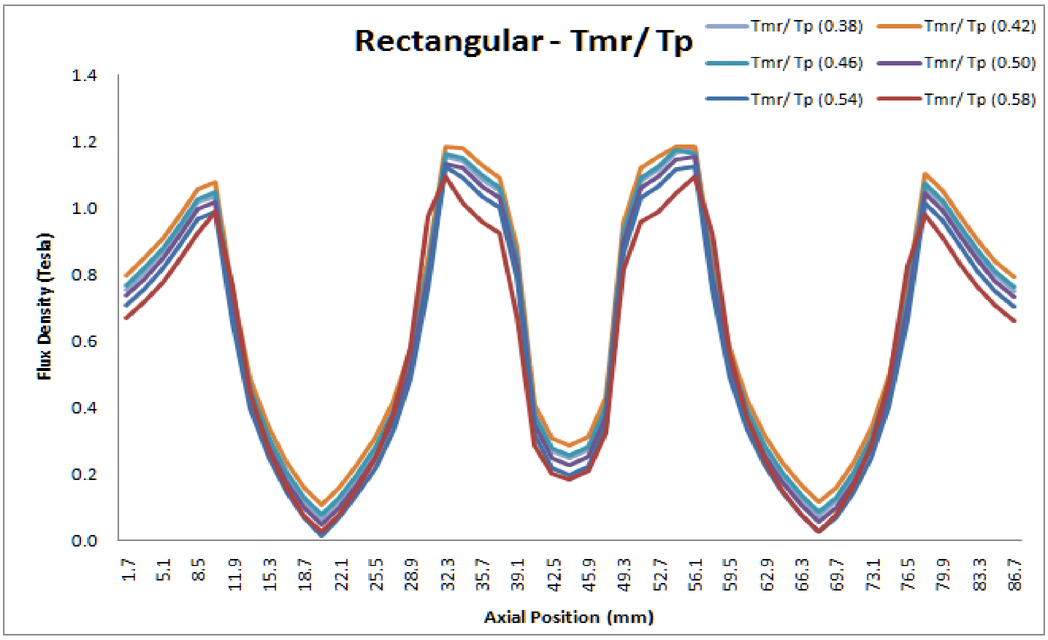

Figure 21: Ratio of Tmr/ Tp (rectangular design) with respect to flux density

The graph is drawn to prove that the optimization between the axial length of radially magnetized magnet to the pole pitch is reached. From the graph, it can be seen that the optimized ratio for axial length of radially magnetized magnet (Tmr) to the pole pitch is 0.42 whereby Tmr is set to be 18mm and Tp is a fixed value which is 43mm. The highest flux density that is able to produce by having the ratio of 0.42 is 1.1823T.

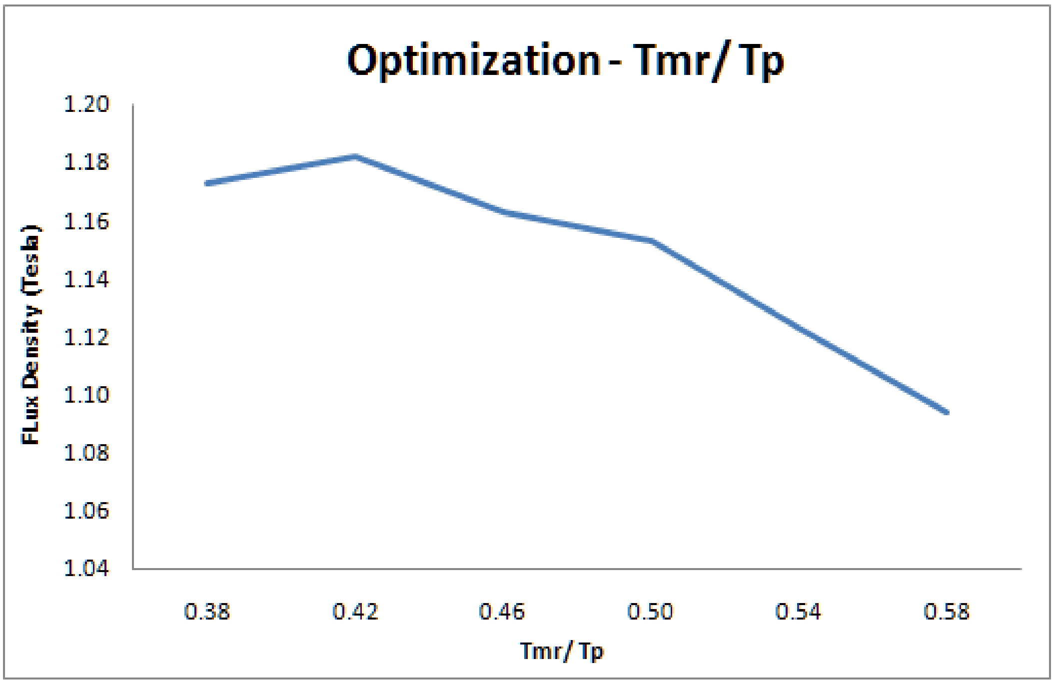

Figure 22: Optimized ratio graph of rectangular design for Tmr/ Tp

4.4.2.2 Influence of Tmr/Tp for trapezoidal arrangement of permanent magnet

After the optimization of the outer radius of rotor to the outer radius of stator core (Rm/ Re) where the optimization value is 24mm and 60mm respectively. The optimized radius value is applied into the optimization of ratio of axial length of radially magnetized magnet to the pole pitch, Tmr/ Tp. There are six optimized ratios have been studied which are Tmr/ Tp = 0.43, 0.47, 0.51 and 0.55. From the graph below, it shows that the flux density that is generated with the changes in the axial length of radially magnetized magnet, Tmr which is in the range of 1.0086T to 1.2093T.

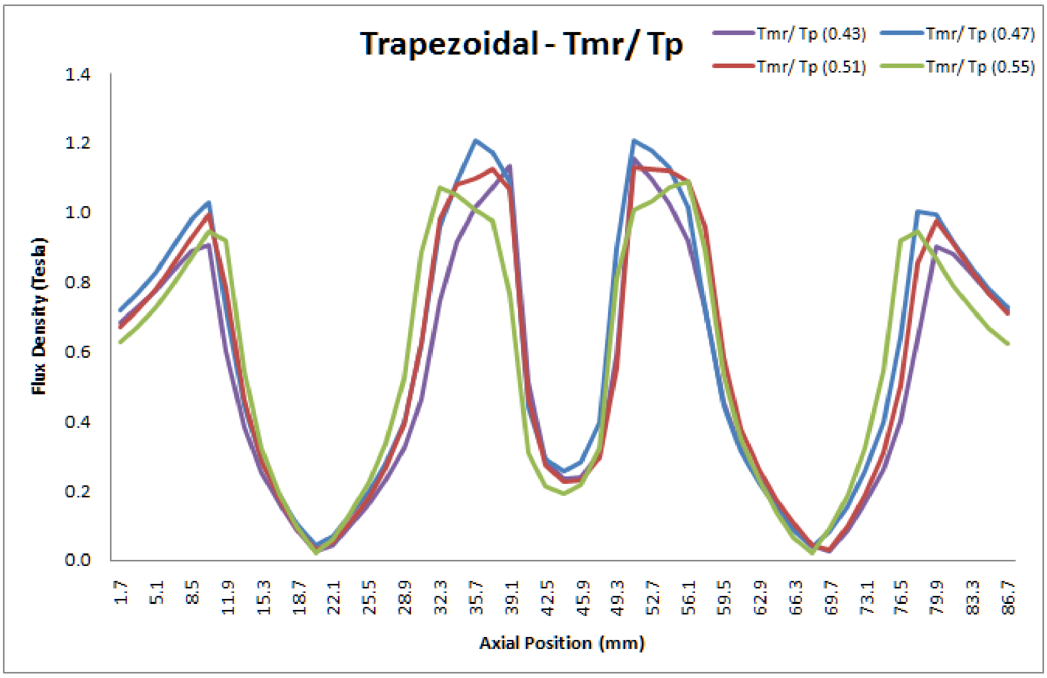

Figure 23: Ratio of Tmr/ Tp (trapezoidal design) with respect to flux density

The graph is drawn to prove that the optimization between the axial lengths of radially magnetized magnet to the pole pitch is reached. From the graph, it can be seen that the optimized ratio for axial length of radially magnetized magnet (Tmr) to the pole pitch is 0.47 whereby Tmr is set to be 19.5mm and Tp is a fixed value which is 41mm. The highest flux density that is able to produce by having the ratio of 0.47 is 1.2093T.

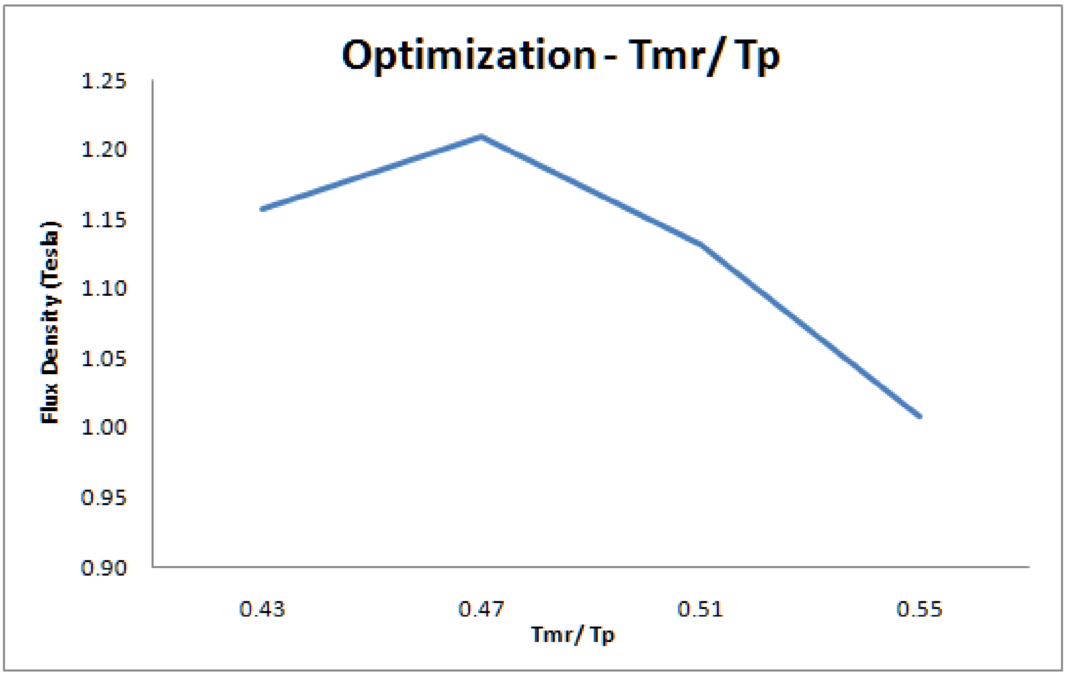

Figure 24: Optimized ratio graph of trapezoidal design for Tmr/ Tp

4.4.3 Influence of Tw with respect to flux density

The Tw represents the changes that will be made on the tooth width which it influences on the copper loss and core loss. If the tooth area increases, the flux density will decrease due to the equation below and it results in reduce of iron loss.

Flux Density = Number of flux / Area

While increase the size of slot area, it brings the effect of increment in resistance of the machine whereby it results in the increase of copper loss.

4.4.3.1 Influence of Tw for rectangular arrangement of permanent magnet

After optimization of both values of the outer radius of rotor and also the axial length of radially magnetized magnet, the optimum values are applied into the optimization of tooth width, Tw. There are four optimized sizes that have been studied which are Tw = 8mm, 10mm and 12mm and 14mm. From the graph below, it shows that the flux density that is generated with the changes in the tooth width, Tw which is in the range of 1.0519T to 1.2135T.

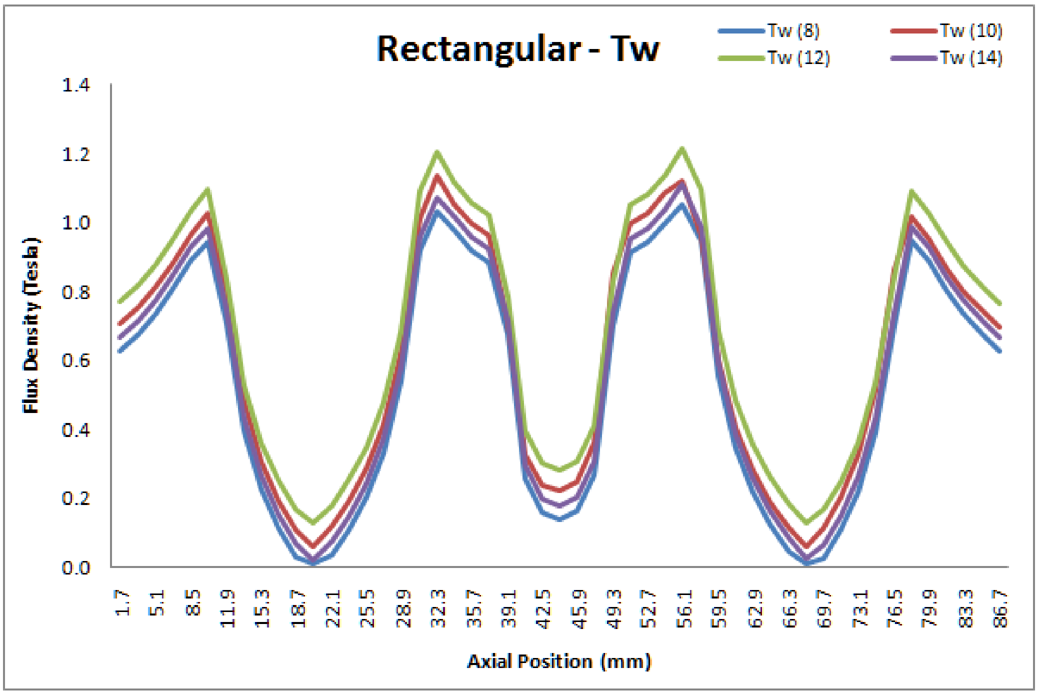

Figure 25: Size of Tw (rectangular design) with respect to flux density

The graph is drawn to prove that the optimization of tooth width is reached. From the graph, it can be seen that the optimized value for tooth width, Tw is 12mm. The highest flux density that is able to produce by having the tooth width at 12mm is 1.2135T.

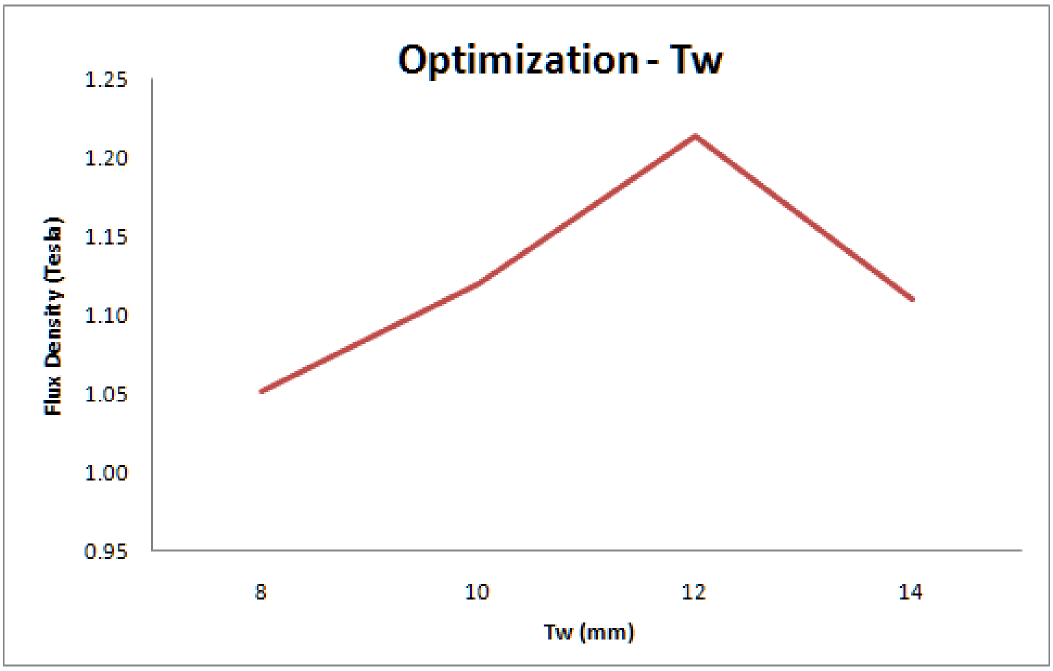

Figure 26: Optimized value graph of rectangular design for Tw

4.4.3.2 Influence of Tw for trapezoidal arrangement of permanent magnet

After optimization of both values of the outer radius of rotor and also the axial length of radially magnetized magnet, the optimum values are applied into the optimization of tooth width, Tw. There are four optimized sizes that have been studied which are Tw = 8mm, 10mm and 12mm and 14mm. From the graph below, it shows that the flux density that is generated with the changes in the tooth width, Tw which is in the range of 1.1244T to 1.2149T.

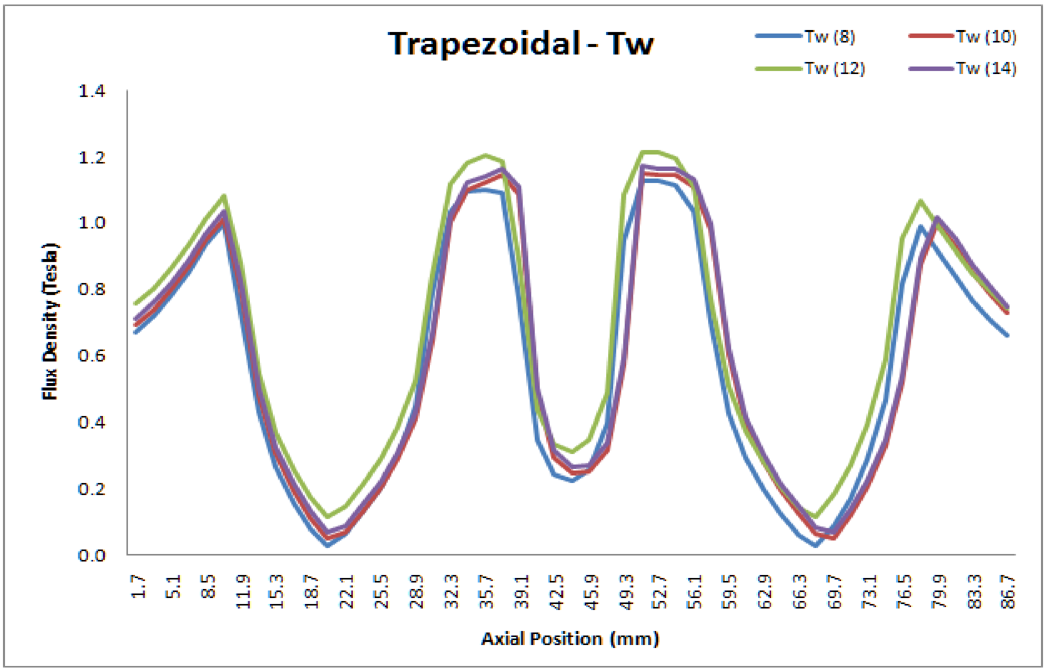

Figure 27: Size of Tw (trapezoidal design) with respect to flux density

The graph is drawn to prove that the optimization of tooth width is reached. From the graph, it can be seen that the optimized value for tooth width, Tw is 12mm. The highest flux density that is able to produce by having the tooth width at 12mm is 1.2149T.

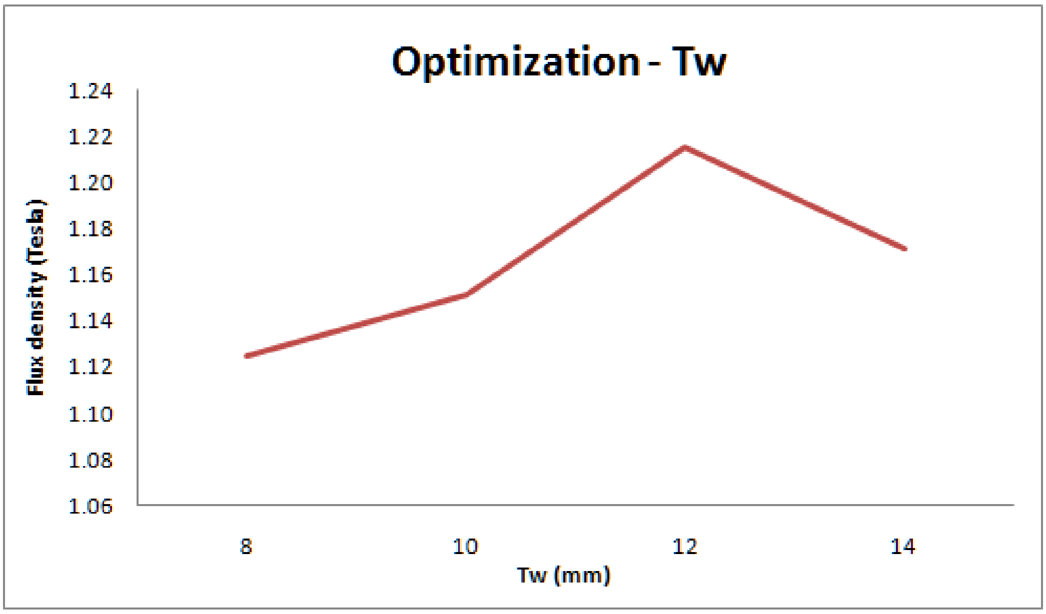

Figure 28: Optimized value graph of trapezoidal design for Tw

4.5 Discussion

The new design of linear generator should have a result where it can reach a good performance when it is applied into the road bump and it can be fitted perfectly into the road bump as well. In the meantime, it is able to generate electricity when car crosses on the road bump. Though there are pros and cons of the design, a balance point of the design should be made. It means, in terms of performance, the best linear generator should be chosen, however, the manufacture cost needs to be considered as well. Thus, an optimization task and re- justification work is carried out.

4.5.1 Discussion on rectangular arrangement of permanent magnet

At zero position, where it is assumed that no force is applied on the rotor and the magnetic flux is yet flows to the stator part. It can be referred to Figure 11. Once the rotor is pushed, where it is assumed that a force is applied on the rotor, the magnetic flux flows through the stator and EMF will be induced. It can be seen from Figure 12. The air gap flux density at zero position for rectangular arrangement permanent magnet is in the range of 1.094T where it can be referred to Figure 13. It has lower flux density compared to trapezoidal arrangement of permanent magnet design. Thus, it has lower force capability and it cannot generate high voltage. However, lower force does have its advantage. The design with lower force capability means it has lower iron loss. Some assumptions have been made to estimate the induced EMF (E) that will be generated in rectangular shape of permanent magnet design by using the following formula [12]:

$$E = 4.44\, f BAN$$

Where,

f = frequency, 50 Hz

B = flux density generated

A = area of magnet (5.0mm x 16.5mm)

N = number of turns of coil

Thus,

$$E = 4.44\ (50)\ (1.094)\ (82.5 \times 10^{-6})\ (1024)$$

$$= 20.52\ V$$

There are three areas where changes have been done on the rectangular arrangement of magnet design. The optimization and modification on the tooth width (Tw), outer radius of rotor (Rm) and axial length of radially magnetized magnet (Tmr) on rectangular design are carried out. The result of the induced EMF has a significant increase. By applying the same formula, the induced EMF can be compared.

$E = 4.44\, f\, BAN$

Where,

f = frequency, 50 Hz

B = flux density generated

A = area of magnet (5.0mm x 18.0mm)

N = number of turns of coil

Thus,

$$E = 4.44\ (50)\ (1.2135)\ (0.9 \times 10^{-4})\ (1024)$$

$$= 24.83\ V$$

Table 6: Comparison table of generated EMF for rectangular arrangement of permanent magnet between original parameters with optimum parameters

	Original Design	Optimum Design
Rm/ Re	Rm = 13.80mm	Rm= 24.00mm
Tmr/ Tp	Tmr = 16.50mm	Tmr = 18.00mm
Tw	10.00mm	12.00mm
EMF	20.52 V	24.83 V

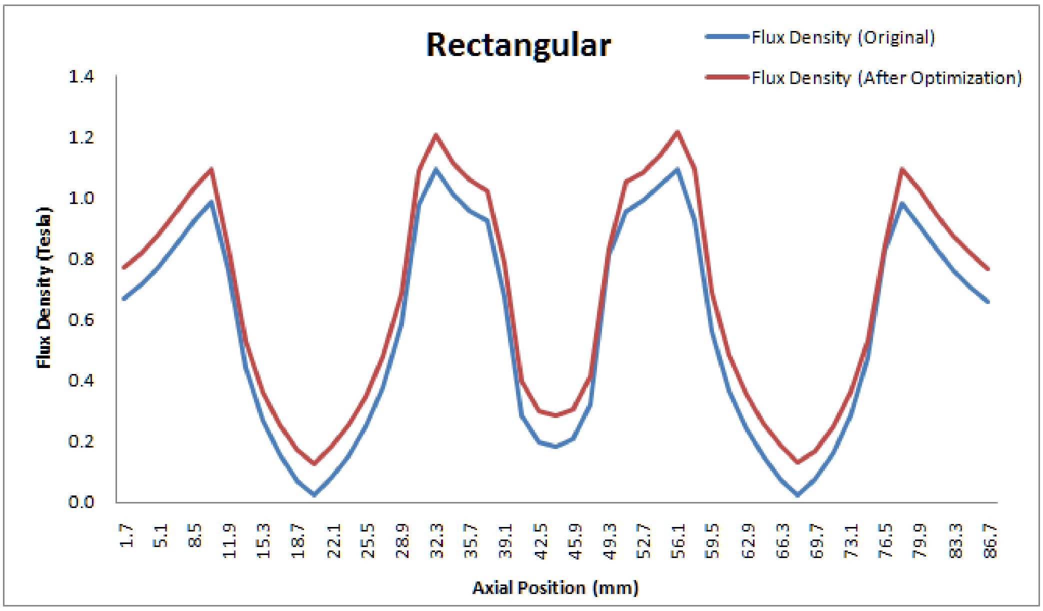

Figure 29: Difference between original parameters with optimum parameters

Table 7: Optimum parameters of rectangular arrangement of permanent magnet

Description	Value	Units
Slot opening width, b*o*	10.00	mm
Airgap length, G	1.00	mm
Tooth tip height, h*t*	1.00	mm
Outer radius of stator core, R*e*	60.00	mm
Magnet height, h*m*	5.00	mm
Supporting tube height, h*ym*	3.00	mm
Yoke thickness, h*ys*	4.00	mm
Pole pitch, T*p (rectangular shape)*	43.00	mm
Axial length of radially magnetized magnet, T*mr*	18.00	mm
Axial length of radially magnetized magnet, T*mr2*	25.00	mm
Axial length of axially magnetized magnet, T*mz*	9.00	mm
Tooth width, T*w*	12.00	mm
Frequency	50.00	Hz
Permanent magnet material	NdFeB	-
Stator core material	Somaloy 700	-

4.5.2 Discussion on trapezoidal arrangement of permanent magnet

At zero position, where it is assumed that no force is applied on the rotor and the magnetic flux is yet flows to the stator part. It can be referred to Figure 14. Once the rotor is pushed, where it is assumed that a force is applied on the rotor, the magnetic flux flows through the stator and EMF will be induced. It can be seen from Figure 15. The air gap flux density at zero position for trapezoidal arrangement permanent magnet is in the range of 1.131T where it can be referred to Figure 16. It shows that by having trapezoidal arrangement of permanent magnet, there is a higher force capability of trapezoidal arrangement of permanent magnet design compared to rectangular arrangement of permanent magnet design. A higher force means it is able to have higher EMF induced. However, at the same time, a higher force will lead to higher iron loss. Some assumptions have been made to estimate the induced EMF (E) that will be generated in trapezoidal shape of permanent magnet design by using the following formula [12]:

$E = 4.44\, f\, BAN$

Where,

f = frequency, 50 Hz

B = flux density generated

A = area of magnet (0.5 x 25.0mm x 10.0mm)

N = number of turns of coil

Thus,

$$E = 4.44\ (50)\ (1.131)\ (1.25 \times 10^{-4})\ (1024)$$

$$= 32.15\ \text{V}$$

There are three areas where changes have been done on the trapezoidal arrangement of magnet design. The optimization and modification on the tooth width (Tw), outer radius of rotor (Rm) and axial length of radially magnetized magnet (Tmr) on trapezoidal design are carried out. The result of the induced EMF has a significant increase. By applying the same formula, the induced EMF can be compared.

$E = 4.44\, f\, BAN$

Where,

f = frequency, 50 Hz

B = flux density generated

A = area of magnet (0.5 x 25.0mm x 14.0mm)

N = number of turns of coil

Thus,

$$E = 4.44\,(50)\,(1.2149)\,(1.75 \times 10^{-4})\,(1024)$$

$$= 48.33\ V$$

Table 8: Comparison table of generated EMF for trapezoidal arrangement of permanent magnet between original parameters and optimum parameters

	Original Design	Optimum Design
Rm/ Re	Rm = 13.80mm	Rm= 24.00mm
Tmr/ Tp	Tmr = 17.50mm	Tmr = 19.50mm
Tw	10.00mm	12.00mm
EMF	32.15 V	48.33 V

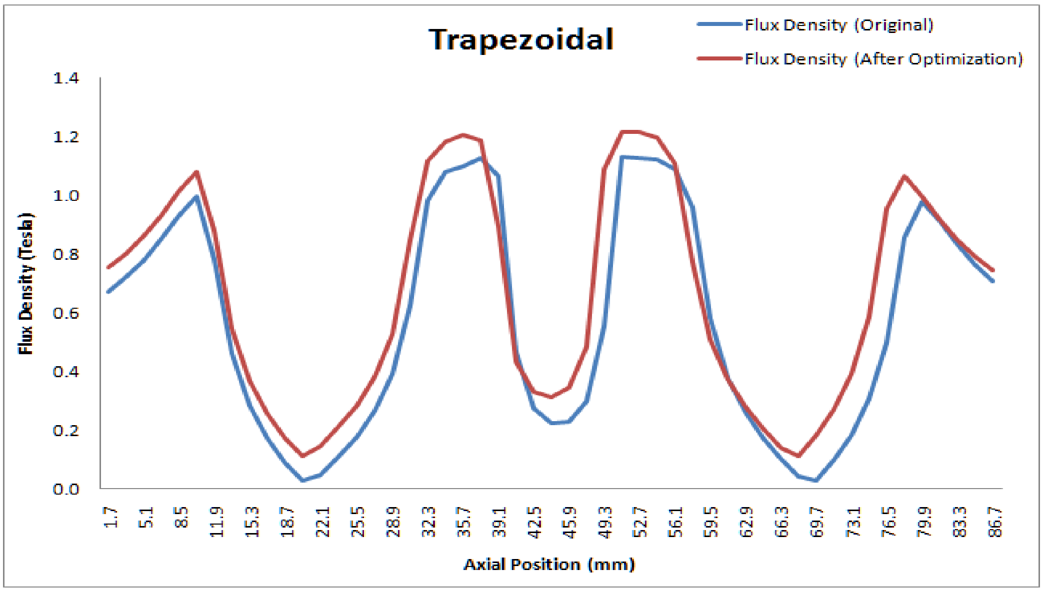

Figure 30: Difference between original parameters with optimum parameters

Table 9: Optimum parameters of trapezoidal arrangement of permanent magnet

Description	Value	Units
Slot opening width, b*o*	10.00	mm
Airgap length, G	1.00	mm
Tooth tip height, h*t*	1.00	mm
Outer radius of stator core, R*e*	60.00	mm
Magnet height, h*m*	5.00	mm
Supporting tube height, h*ym*	3.00	mm
Yoke thickness, h*ys*	4.00	mm
Pole pitch, T*p (trapezoidal shape)*	41.00	mm
Axial length of radially magnetized magnet, T*mr*	19.50	mm
Axial length of radially magnetized magnet, T*mr2*	21.50	mm
Axial length of axially magnetized magnet, T*mz*	11.75	mm
Tooth width, T*w*	12.00	mm
Frequency	50.00	Hz
Permanent magnet material	NdFeB	-

4.6 Conclusion

The trapezoidal permanent magnet design is able to focus more flux in the center and transfer it to the stator and thus it leads to higher flux density and higher induced EMF obtained. Besides, the overall performance has increased after the optimization work has been executed. For trapezoidal design of permanent magnet, the overall performance has increased 50% in the induced EMF meanwhile, for rectangular design of permanent magnet increases 21% in the induced EMF.

CHAPTER 5

CONCLUSION

5.1 Conclusion

As a conclusion, the project has reached to a stage whereby it fits to the level of obtaining the result between two designs for linear generator that is suitable to be applied into the road bump.

A research and literature review has been done based on the various linear machine topologies for instances, linear synchronous machine, linear dc machine, linear induction and linear permanent magnet machine. Linear permanent magnet machine has been chosen based on its good performance at low speed, high efficiency and high reliability. Besides, moving magnet design under the category of linear permanent magnet machine has been chosen since it is suitable to be used for heavy duty operation.

Two new designs have been proposed in order to improve the original design of linear permanent magnet machine. The major difference of both designs is the rectangular shape of permanent magnet and trapezoidal shape of permanent magnet. Rectangular shape of design is easy to be manufactured and thus lower the manufacturing cost of the design. For trapezoidal shape of permanent magnet, it is able to focus more of the flux in the center and transfer them to the stator and thus higher flux density and induced EMF can be obtained. However, the manufacturing cost for trapezoidal shape of permanent magnet is comparably higher than rectangular shape design.

The designs have been analyzed by using finite element software, ANSYS. The performance of the designs is determined by the air gap flux density and applies in the formula to determine the induced EMF. The higher of the air gap flux density, the higher of the induced EMF can be obtained. In order to improve the designs, optimization work has been carried out. It improves the machine efficiency and number of flux that flows through the stator.

From the result, it shows that trapezoidal shape of permanent magnet is able to generate more air gap flux density and thus it leads to higher induced EMF which is 48.33V. For the rectangular shape of permanent magnet, it is able to improve the performance in terms of air gap flux density and induced EMF as well which is 24.83V.

Thus, linear generator with trapezoidal shape of permanent magnet is the most suitable design to be applied into the road bump in order to generate more electricity based on the result that is obtained in Chapter 4.

5.2 Recommendation

5.2.1 New method to optimize the designs

Instead of focusing on the three main parts of optimization area which are the ratio of outer radius of rotor the outer radius of stator, Rm/ Re, the ratio of radially and axially of magnetized magnet, Tmr/ Tp and tooth width. There are some areas that can be optimized as well for instances the height of the permanent magnet, h*m* and the tooth tip height, h*t*.

5.2.2 Validate a prototype

A prototype can be produced in order to test and make sure it meets with the simulation results. Validation of the prototype can be carried out. It can be tested under the road bump and the electricity that is generated can be compared with the simulation and calculated result.

REFERENCES

[1] Hew Wooi Ping and Hamzah Arof, Wijono, “Design of a Permanent Magnet Linear Generator”, University of Malaya, IFOST 2006, Oct 18-Oct 20, 2006

[2] http://www.powergeneratorinfo.com/honda-generators/linear-induction generator.php

[3] Shunsuke Ohashi and Tatsuro Matsuzuka, “Basic Characteristics of the Linear Synchronous Generator Using Mechanical Vibration”, Kansai University, Suita, Osaka, IEEE Transactions on Magnetics, vol. 41, no. 10, October 2005

[4] http://en.wikipedia.org/wiki/Finite_element_method

[5] ANSYS Low- Frequency Electromagnetic Analysis Guide

[6] Taib Ibrahim, “Short- stroke, Single Phase Tubular Permanent Magnet Motor for Refrigeration Applications”, University of Sheffied, January 2009

[7] http://www.magnemotion.com/technology/LSM/main.shtml

[8] http://en.wikipedia.org/wiki/Piezoelectricity

[9] T.Ibrahim, J.Wang, and D. Howe, “ Analysis and experimental verification of a single phase, quasi- Halbach magnetized tubular permanent magnet motor” IEEE International Magnetic Conference, INTERMAG2008, Madrid, Spain, 4-8 May 2008

[10] J. Wang and D. Howe, “ Design optimization of radially magnetized iron cored, tubular permanent magnet machines and drive systems,” IEEE Transactions on Magnets, vol. 40, no. 5, pp.3262- 3277, September 2004.

[11] J. Wang and D. Howe, “ Tubular modular permanent magnet machines equipped with quasi- Halbach magnetized magnet – Part 1: Magnetic field distribution, EMF and thrust force,” IEEE Transactions on Magnetics, vol 41, no. 9, pp.2470- 2478, September 2005

[12] Jaime Sarabia, “An Investigation into the Use of Linear Generators in the Schneider Hydro- Power Generation System”, Massachusetts Institute of Technology, June 1998

[13] T.Yamada, S. Koganezawa, K. Aruga, and Y. Mizoshita, “ A high performance and low profile moving magnet actuator for disk drives,” IEEE Transactions on Magnetics, vol. 30, no. 6, pp. 4227- 4229, November 1994

APPENDICES

APPENDIX A

GANTT CHART

Task / Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
Meet with supervisor to discuss about task to do in semester 2	■							Mid Semester Break							
Refer and study on journal about animation of model in ANSYS		■													
Work on animation part of model			■	■											
Optimization work - Rm/ Rs (the ratio of stator height and rotor height) - Tmr /Tp (the ratio of the length of facing north magnet and total length of magnet) - Tw (tooth width)					■	■	■								
Progress Report									■						
Comparison between two types of linear machine									■	■					
Technical Report											■				
Pre - EDX												■			
Prepare for presentation slides													■		
Prepare for final report														■	
Final presentation (VIVA)															■
Final Report submission															■