Design and Modelling of a Portable Pico Linear Generator for Wave Energy Conversion System

by

Muhammad Faris bin Mohammad Naafi

14274

Dissertation submitted in partial fulfillment of

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CERTIFICATION OF APPROVAL

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Approved by,

____

(Dr Taib Ibrahim)

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 2014

CERTIFICATION OF ORIGINALITY

This is to certify 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.

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MUHAMMAD FARIS BIN MOHAMMAD NAAFI

ABSTRACT

Ocean wave energy is continuous, concentrated, predictable and resourceful since two third of the world is covered by the sea compared to the wind energy and solar energy. Therefore the researchers has invented many types of wave energy converters to generate electricity. However, these wave energy converters are mostly huge, fixed at one place, not portable and uses for the large application. Hence, this research will focus on designing and modelling the portable pico linear generator for the wave energy converter application. The linear generator has gained more attention because of the simple design which uses less mechanical part and make it less maintain. The aim for this research is to develop a permanent magnet linear generator which has the weight less than 20 kg and can produce up to 80W. A thorough literature review has been done on type of configurations, stator structure, magnetization and type of cored to select the best features of the linear generator. These selected features then are implemented to the three proposed designs with the same parameters but difference shape of magnet. Three proposed designs of the permanent magnet linear generator is simulated using the Ansys Maxwell software to come up with the preliminary result. After that, all the three designs are optimized with all design parameters to produce the best efficiency. Lastly, the chosen optimize parameters will then again simulated to obtain the optimize result and to compare with the preliminary result. In the discussion and result part, comparison on the preliminary result such as the air gap flux distribution, back-emf, flux linkage and thrust force of the three proposed designs will be shown and discussed. For the optimization part, there are 3 parameters which will be optimized which are L_s/L_r, T_{mr}/T_p and R_m/R_e. The optimization for each parameters will be shown and discussed and compare with the preliminary result. The optimize parameters for each proposed design is used to obtain the result after the optimization and compare with the preliminary result. Throughout this research, we can conclude that, the variation of the magnet shape can yield the different result even using the same material, volume and parameters of the linear generator.

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Abbreviations and Nomenclatures

A	Ampere
DC	Direct Current
FYP	Final Year Project
OWC	Oscillating Water Column
PM	Permanent Magnet
mT	mili Tesla
N	Newton
PTO	Power Take Off
s	second
V	Volts
W	Watt
Wb	Weber
WEC	Wave Energy Converter

CHAPTER 1

INTRODUCTION

1.0 Introduction

This chapter discussed on background of the project which are comparison of renewable energy, the data of the wave energy in Malaysia, the technologies of wave energy converter and last but not least the generator that been used in wave energy converter. Besides, the problem statement will be elaborated based on the current technologies and the objective will be explained on the aim of the project.

1.1 Background

Oil crisis in 1970s has forced the researchers into harnessing energy from waves [1]. In addition, the climate change and also with rising amount of carbon dioxide released once again make the research on harnessing the wave energy to electrical energy becoming more important nowadays. Approximately, the potential energy which can be harnessed from the worldwide wave is 2 TW [1].

Wave energy where wave created when the wind touches the top surface of sea water. Wave energy is really resourceful energy as shown in Figure 1**.** This research focused on the peninsular Malaysia where it can produce annual power mean density of 70-80 kW/m. Moreover, wave energy is far more concentrated compared to wind and solar energy, it is non-stop and continuous, plus it is able to be predicted than wind energy [2].

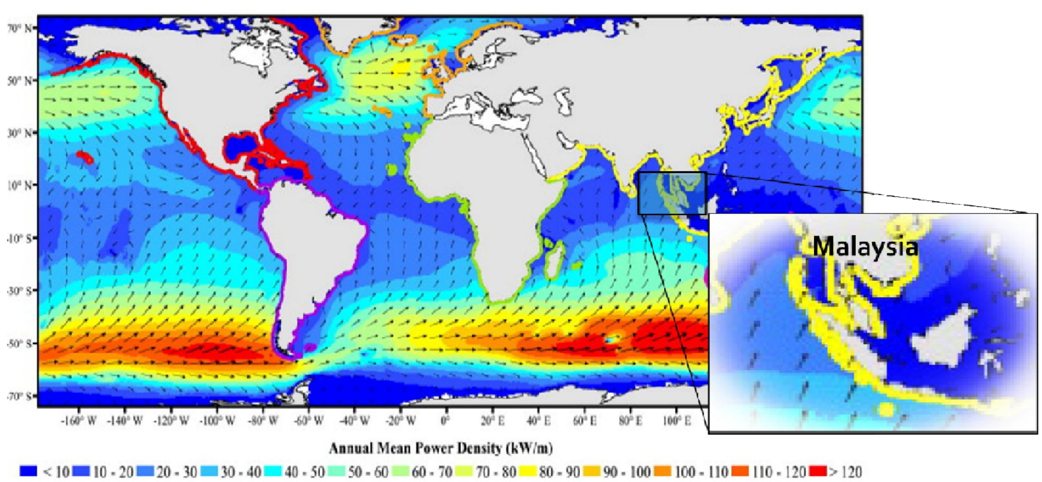


Figure 1. Wave Energy Distribution around the World [3]

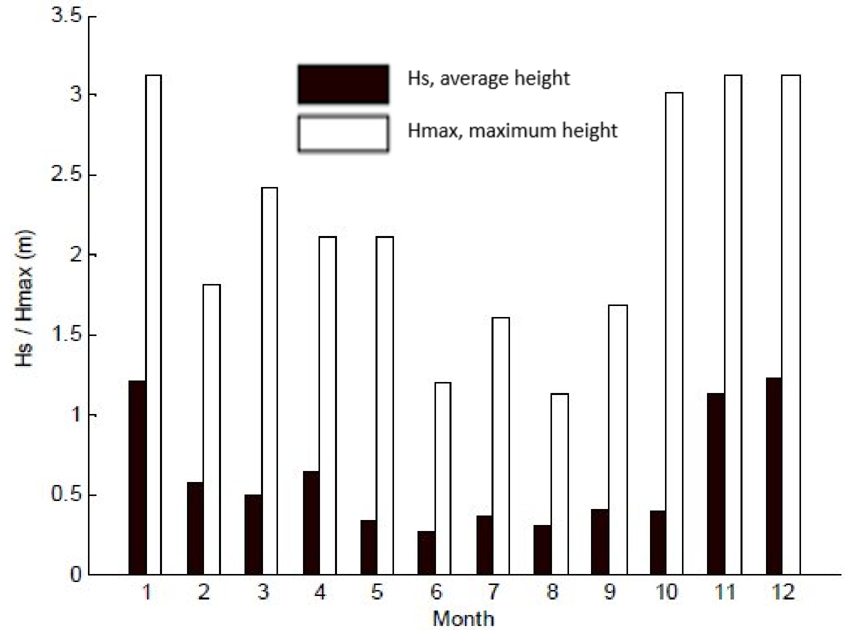


Figure 2. Monthly height of wave at latitude 5° 35’N and longitude 102° 55.5’E

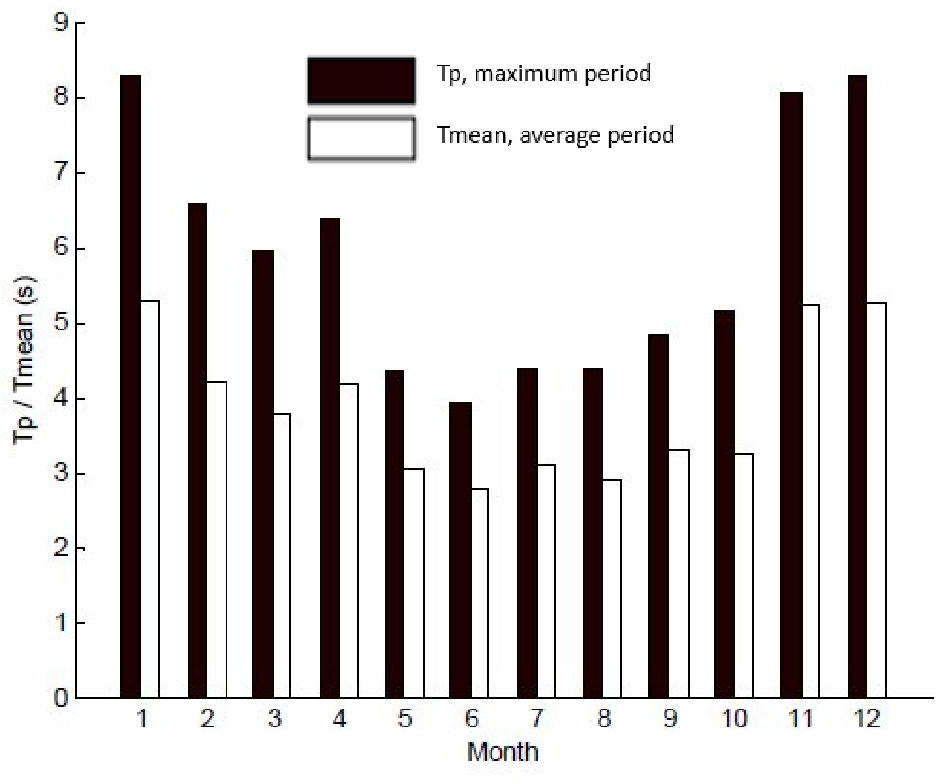


Figure 3. Monthly mean of wave at latitude 5° 35’N and longitude 102° 55.5’E

Figure 2 and Figure 3 show the data from [4] which cover peninsular Malaysia with collection of data from January 1998 to August 2009. From the research, the area produce 60% of the annual wave which wave height less than 1.2m and with period of 8s for about 70%. Even though the current wave energy is low, the accessible wave energy at peninsular Malaysia still can be consider as one of the energy source. Besides, current technologies of wave energy converter surely can increase the efficiency of the energy conversion result can be improved.

Many technologies have been used to capture the wave energy to convert as electrical energy such as Oscillating Water Column (OWC), Overtopping devices, Hinged Contour devices and Buoy technology.

OWC consists of turbine and chamber with two openings for air and sea water as in Figure 4. OWC efficiency is depends on the efficiency at each conversion of energy stages which are converting wave energy to pneumatic energy in the chamber, pneumatic energy to mechanical energy when the turbine rotates, and mechanical energy to electrical energy that happen in the generator [5]. OWC is a type of devices where it has to be fixed at one place and not portable.

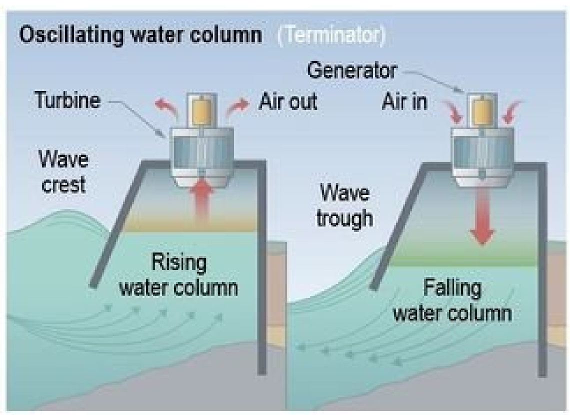


Figure 4. Oscillating water column [6]

Next is overtopping device is a device that can trap water in its own reservoir and return the sea water back through the outlet which installed with turbine that located at the bottom of reservoir as illustrates in Figure 5. The advantage of this device is that it can produce less fluctuation because this device dealing with the calm trapped sea water in the reservoir. Besides that, overtopping devices can be merged with other coastal facilities such as wall breaker thus making this device is economical to be installed [7]. However, the overtopping device has to be huge in order to trap large amount of water to turn the turbine.

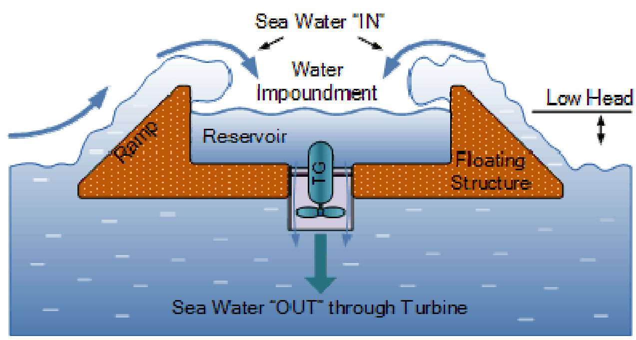


Figure 5. Overtopping device [8]

Hinged Contour Device is actually the combination of few joints floating on the surface of the sea water that will move according to the motion of waves. One of the invention that using this concept is Pelamis as in Figure 6. Pelamis has three joints that with 150 m long and weighted 380 tons which can generate 750 kW. It has average efficiency of 80% and this device can withstand with the harsh condition at sea because it built with the strong material. Hinged Contour Device has very huge structure which length can go up to 150m so, this technology is not suitable for this research.

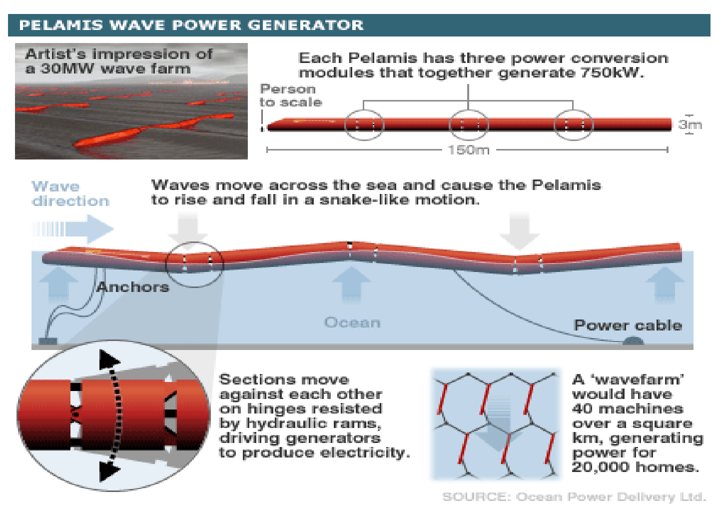


Figure 6. Hinged Contour Device [9]

Meanwhile for buoy technology, it is divided by two which are submerged buoy technology as in Figure 7 and floating buoy technology as in Figure 8. Submerged buoy technology is using the pressure changes in order to create the movement to form the electricity. In order the device to be submerged, the base has to be heavy and it is fixed at bottom of the sea. Lastly is floating buoy technology, this device is floating and it using the wave energy to create a movement to generate electricity. This technology will be used for this research as it is light and portable device which is meet the requirement of this research.

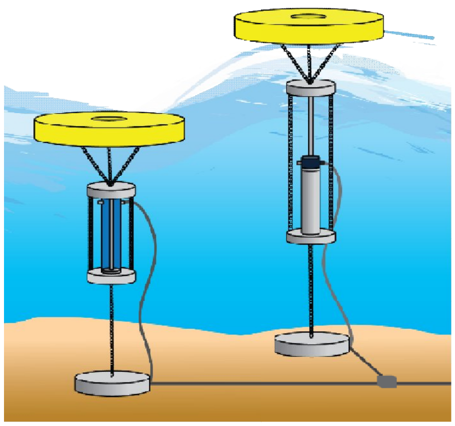


Figure 7. Submerged buoy technology [10]

Figure 8. Floating buoy technology [10]

There are a few types of rotating generators which are induction generator, synchronous generator, and DC generator which been used in the WECs technology. Induction generator is designed with strong form, economical maintenance and less usage of brushes [11]. However induction generator needs excitation from external supplied because it is not self-starting. To solve this problem, they researcher came out with the idea by applying correcting capacitor. Next is synchronous generator where it is self-starting type that does not require external supply to produce magnet field and yield high efficiency [12]. Despite generating large power and has a small size, it has disadvantage which hard to control the output [13]. Other than that, during the generator rotates in high frequency, the temperature increase and iron loss happened. Last but not least is DC generator which is easy to control because the output voltage is kept constant event though rotation and load are changing by controlling the field current [14]. However, DC generator uses brush where it will need replacement after it wears out.

Due to the earlier generation of WECs and generators are complicated, the recent technology which is floating buoy technology that using the linear generator is invented. The research is focused mainly to produce the high efficient, portable pico linear generator which weighed 20 kg, able to produce 80W, with dimension of 400 mm length and 90.2 mm width that will be used to convert wave energy to electrical energy. An extensive literature review of linear generators for various topologies and technologies will be carried out and proposed the suitable design variants of linear generators for Wave Energy Conversion (WEC) system. The parameters will be designed using finite element method (ANSYS software), which can accommodate more complex geometries and material non-linearities for better results. The optimization of leading design parameters will be carried out in order to obtain optimum performance of generators.

1.2 Problem Statement

There are many technologies and types of WECs that's been invented nowadays. Some of the systems are huge which cannot use as the potable WEC and applied complex operational method which cause the system frequently damage and need to maintain many times. Few of them can be access easily for the maintenance, but for the wave energy system that located far from the onshore is hard to get access for the maintenance.

To conclude, all wave energy systems are bulky and not suitable to use for small application especially for outdoor activities.

1.3 Objectives

The wave energy converters are not invented to be portable because they are huge and heavy. Therefore this aim of the research is to design and model a small scale and portable linear wave generator system for use in shoreline which is suitable for outdoor activities which near to wavy water such as to light up the small camp site at beach.

The specific objectives are:

i. To identify the most promising candidate topologies of linear generators in terms of their stroke, mass, efficiency and cost.
ii. To design and optimize the most appropriate linear PM generators using by finite element analysis, ANSYS.

1.4 Scope of Study

Firstly, the research focused on the current WECs and generators which used nowadays and the best WEC will be selected for this research. Next, the thorough literature review on the selected WEC will be conducted and the technologies used are selected based on the comparison among them. After that, the research came up with the proposed design of linear generator. The proposed design will be simulated in the ANSYS software to compare on the performance of each proposed design. The research will continue with the optimization process to get the best efficiency for each proposed design. The optimize parameters are used to obtain the mass and cost approximation.

1.5 Conclusion

Through background study, the research has come up with the problem statement of the current WECs nowadays. Therefore, the research has established the objective of this research. In the next chapter which is the literature review will be explained on the past research papers findings. From the findings the best features of the linear generator will be selected.

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

Chapter 2 focused on the comparison of the generator, the literature review on the different features of linear generator and the previous design of linear generator by other researchers. At the end of this chapter, the research came up with the three proposed designs by implementing the selected features of the linear generator.

2.1 Linear Generator and Rotating Generator

Wave energy is a free renewable energy that yet not to be fully utilized for electricity purposes. There are several methods that involved in capturing energy in converting the wave energy to electrical energy. Figure 3 shows the stages of each Power Take-Off (PTO) mechanism to achieve the final product which is electrical energy.

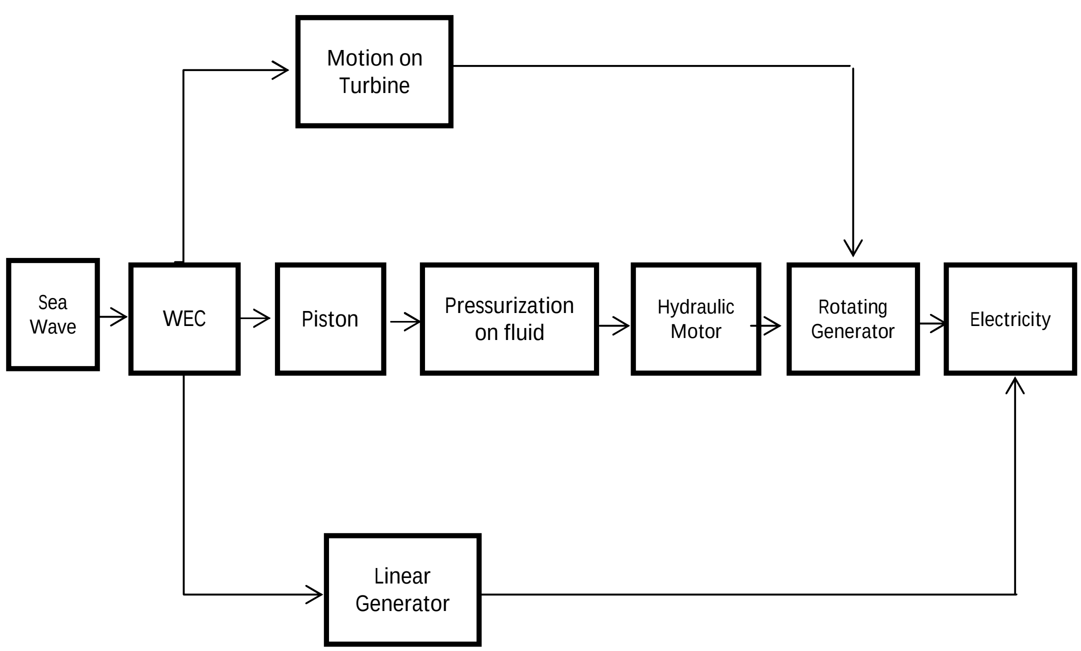


Figure 9. Linear Generator and Rotating Generator Flow Process

Turbine and Hydraulic PTO are using the rotating generator to convert the mechanical energy to electrical energy meanwhile linear generators are only suitable for device that moves in single axis or vertical motion. Linear generator is classified as a high force (based on the size of the WEC) and a slow speed [15]. The biggest advantage of using linear generator is it uses less mechanical part compare to the rotating generator as you can see in Figure 9. Therefore, linear generator simplifies the mechanical design by removing the complicated part in transforming the linear force of the waves to the rotational movement by hydraulic or turbine system [16]. Thus by reducing the crankshaft and spinning part can reduce the maintenance issues which have to be minimized especially in offshore environment.

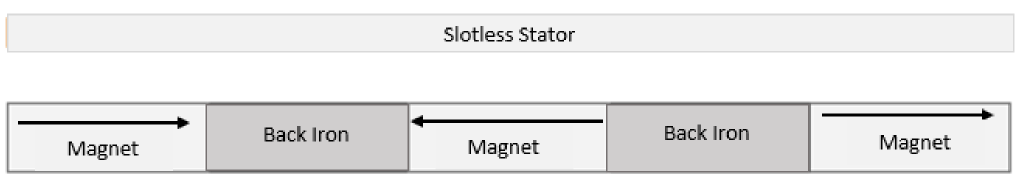
2.2 Different features of the Linear Generator

There are three type configurations of linear generators which are tubular, planar and four-sided structures as illustrate in Figure 10. Among those configurations, tubular configuration has the biggest advantage where it gives the highest power density [17]. By comparing to tubular and four-sided structures, tubular provides consistent magnetic flux density through the whole air gaps however four-sided configurations produce inconsistency magnetic flux density when it reaches the corner of the permanent magnet [18]. Other than that, the four-sided structures used longer coil compare to tubular thus this will increase the power loss of the linear generator which using four-sided structures [18]. Meanwhile, tubular configuration has higher efficiency than planar configuration because the stator is designed to be in the closed loop and due to this arrangement the magnetic flux is concentrated and fully utilized [19].

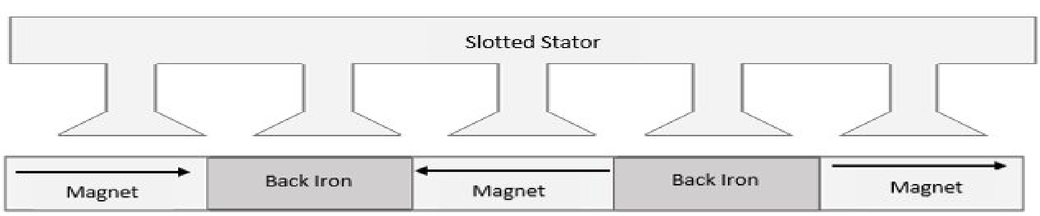
(i) (ii) (iii)

Figure 10. Configuration of linear generator (i) tubular (ii) four sided structures (iii)planar

The stator structure can be divided into two which are slotted stator and slotless stator as shown in Figure 11. The slotted stator can yield higher power density compare to slotless stator but slotted stator can cause cogging. Cogging normally happened at the magnet border [20]. Cogging will affect the motion of the piston to become unsmooth and unstable motion and cause damage to air gap [21]. This instability will cause the fluctuation to the output of the linear generator. However, removing the slot will also decrease the flux density hence the induced electromotive force (EMF) will also be reduced [19]. Therefore, slotless stator can minimize cogging from happening which can damage the magnet and ensure the motion of the piston is smooth and stable.



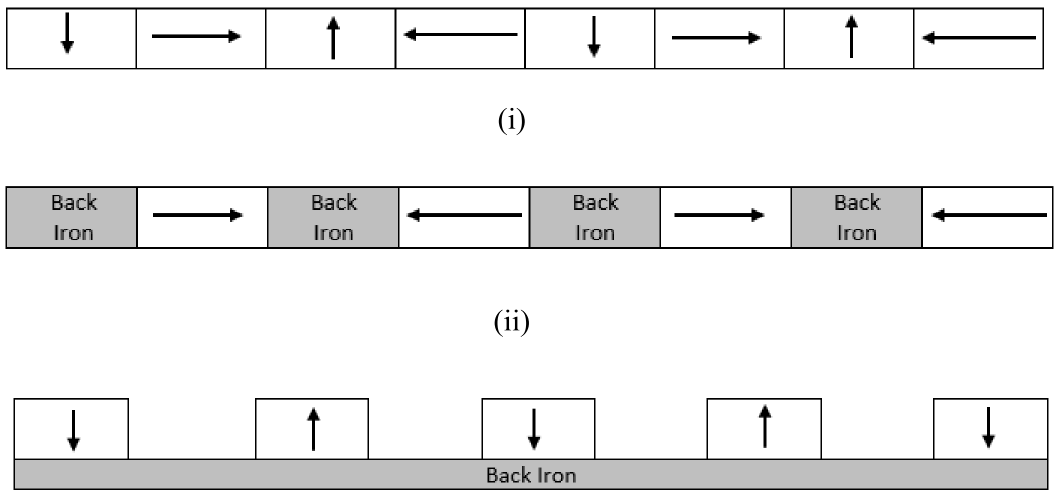
(i)



(ii)

Figure 11. Stator structure (i) Slotless (ii) Slotted

According to [21], magnetization is divided into three parts which are axial, radial and last but no least is halbach as you can see in Figure 12.



(iii)

Figure 12. Configuration of halbach (i), axial (ii), and radial (iii)

Halbach offers non- magnetic material to replace back iron because it has self-shielding characteristics features, higher power density, the magnetic field is more sinusoidal, and also provides better efficiency [22]. However, axial and radial magnetization need back iron or in the other word as ferromagnetic materials which need to attach to magnet for controlling magnetic path. Based on the comparison above, this paper will be utilizing halbach magnetization for the proposed model because of the benefits it has.

Linear generator which using iron-cored basically has more advantages compare to the air-cored because iron cored produced higher flux density compare to air cored therefore by implementing iron-cored at the design will yield 14 times higher voltage and power compare to air-cored [23]. However, implementing iron-cored will cause cogging force become higher as the translator will attract to the iron therefore the motion of the translator becomes not smooth and fluctuation of the output may occur.

Besides that, the iron cored has the ability to direct the magnetic flux as the magnetic flux attract to the iron compare to the air therefore the magnetic flux will be more concentrated and yield better output.

Stator of the linear generator can be moving coil or moving magnet. Moving magnet can generate high efficiency and power density however it has several downsides such as the movement of the translator result the high temperature of the mover hence the demagnetization of the magnet may occurred [24]. Moreover, the force of the frequent movement of the magnet can cause the magnet strength decreasing. Meanwhile, the moving coil can reduce the temperature inside the linear generator. Demagnetization of the magnet will take time because of the low temperature and magnet is static therefore the impact of the movement will not cause the magnet to demagnetize.

2.3 Previous Design of Linear Generator

Linear generator previous design from [18] which talk about the tubular and four-sided configurations that using axial magnetization. Figure 13 shows the magnetic flux density of tubular configuration and figure 14 shows the magnetic flux of four-sided configurations. The magnetic flux density is higher when it is close to the edge of permanent magnet which near to 2.25T, however the magnetic flux density started to decrease when it reaches the air gap because of flux leakage happened.

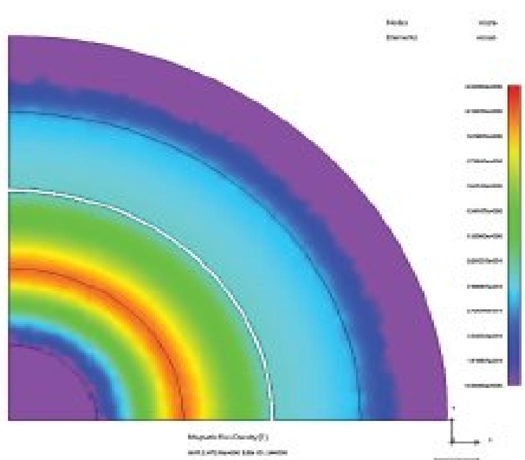


Figure 13. Magnetic Flux Density for tubular configurations

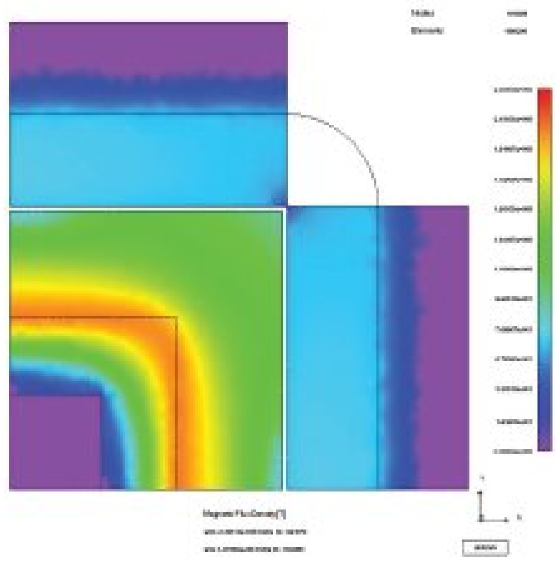


Figure 14. Magnetic Flux Density for four-sided configurations

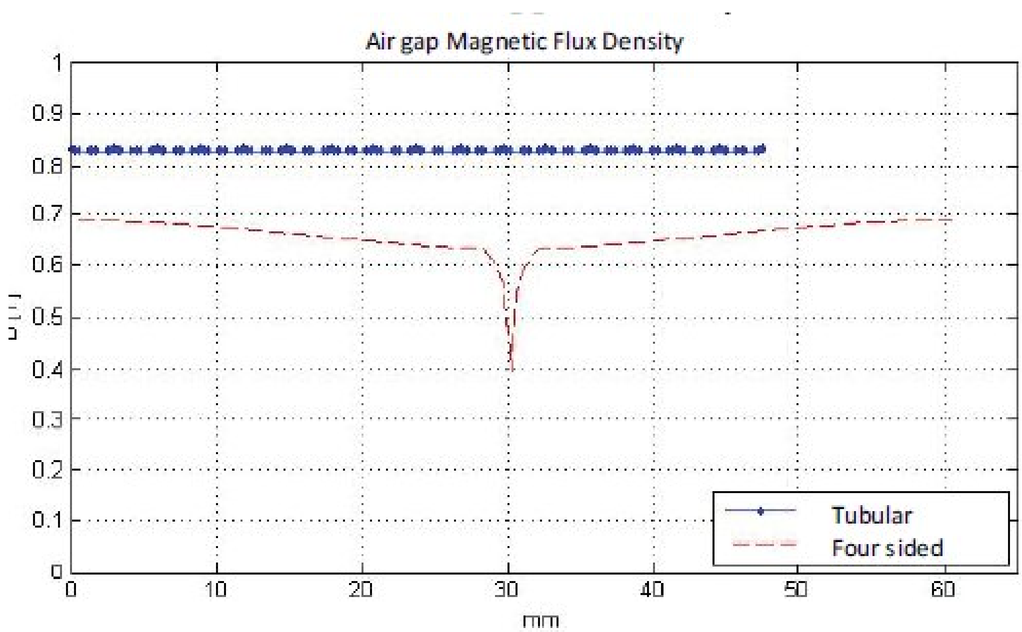


Figure 15. Comparison of Air Gap Flux Density between Tubular and Four-Sided

Figure 15 shows the magnetic along the air gap of tubular and four-sided configuration. For tubular configuration, the magnetic flux density is constant to the value of 0.83T, meanwhile for four-sided configuration varies from 0.68T and 0.39T. Sudden drop of magnetic flux density is due to the big air gap at the corner of the design.

Next previous design which done by [25] is basically discussing on the magnetization which are axial, radial and halbach. This paper concludes that the axial results a high cogging force due to stator and rotor that interact to each other therefore the researcher came up with combination of axial and radial which form Halbach.

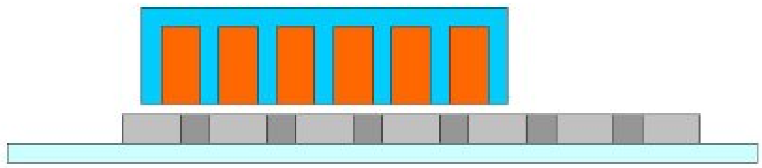


Figure 16. 2D Linear Generator Model

The Figure 16 shows one half of the section in the linear generator. With the speed of generator 0f 3000 cycles per minute, it can generate up to 5kW of output power.

2.4 The Selected Features for the Linear Generator

Based on the reviews, this paper will select tubular configuration compare to planar and four-sided configurations where it gives the highest power density. The slotless stator will be selected as it can minimize the cogging from happening which can damage the magnet. Halbach magnetization will be applied as it offers non-magnetic material to replace back iron. Iron-cored will be implemented at the stator because it can produce stronger magnetic density compare to air-cored. Lastly is to use the moving magnet for stator because it can generate high efficiency and power density. The velocity of the wave is approximately 1 m/s therefore the movement of the translator will not affect the temperature of the magnet significantly.

2.5 Linear Generator 2D Proposed Design

After a deep study on literature review, the research has come up with the design of linear generator which has the features of tubular shape, iron cored, halbach magnetization, slotless stator, and moving magnet. The linear generator specification has to be less than 20 kilogram weight which can be portable and can produce up to 80W output power for small application purposes.

As the research will implement the moving magnet concept, the halbach magnet and ferromagnetic material will become the moving part (rotor) meanwhile winding and yoke (iron-cored) are as the stator part. Magnetization of halbach will form two circles of magnetic flux based on the polarity arranged.

The linear generator working based on the Faraday's law of electromagnetic induction as in the eq. (1)

$$e = \frac{d\lambda}{dt} \qquad (1)$$

where voltage, *e* will be induced inside the coil as it cutting through the flux linkage, λ which varies with the time, *t*.

The flux linkage, ψw, of the stator coil can be obtained by integrating the radial component of flux density and is given by [26]

$$\psi_w = \sum_{n=1}^{\infty} \emptyset_{wn} \, sin m_n z_d \qquad (2)$$

where z_d is the axial displacement of the armature

$$\begin{aligned}
\emptyset_{wn} &= 2\pi N_{wp} K_{rn} K_{dpn} / m_n \\
N_{wp} &= number\ of\ turns\ on\ the\ coils \\
K_{dpn} &= winding\ factor \\
&= K_{dn} K_{pn} \\
K_{dn} &= \frac{\sin m_n b_o/2}{m_n b_o/2} \\
K_{pn} &= -1 \\
K_{rn} &= R_{se}[a_{In} B I_1(m_n R_{se}) + b_{In} B K_1(m_n R_{se})]
\end{aligned}$$

The induced voltage in the coil is obtained as [26]

$$e_w = -\frac{d\psi_w}{dt} = -\left(\sum_{n=1}^{\infty} K_{En} cos m_n z_d\right)\frac{dz_d}{dt} = K_E(z_d)v \qquad (3)$$

where is the induced voltage coefficient and v is the velocity of the armature.

Parameter	Dimension (mm)

Injected current in the stator coil is *i,* the instantaneous thrust force can be obtained from [26]

— (4)

Figure 17 shows the schematic design used for all proposed design. The whole parameters are constant to ensure the comparison based on the result from the finite element software is reliable. Table 1 shows the list of specific parameters and dimension which use in all proposed designs.

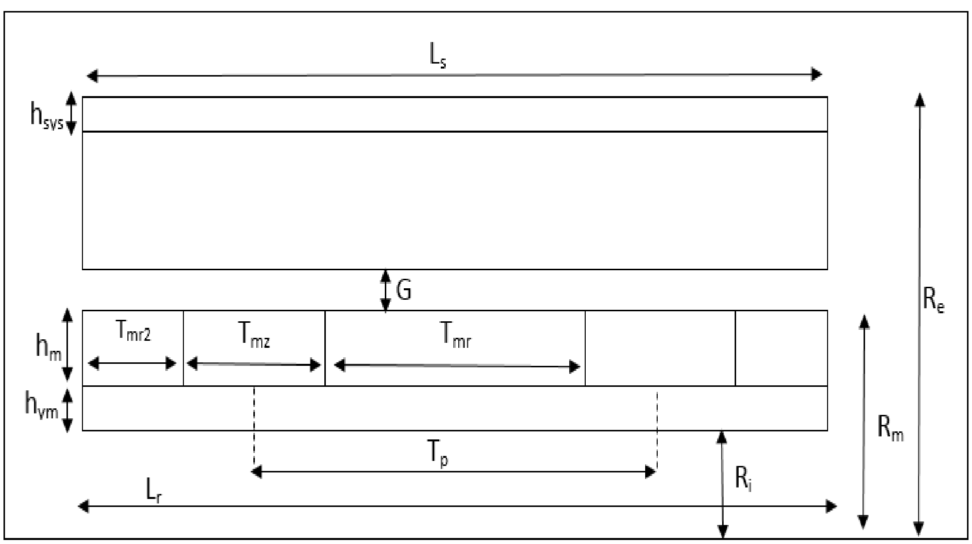


Figure 17. Schematic design of the proposed design

Outer radius of stator core, R_c	45.1
Yoke thickness of stator core, h_{sys}	3.3
Length of stator, L_s	400
Length of rotor, L_r	400
Outer radius of magnet, R_m	21
Radial thickness of supporting tube, h_{ym}	3.5
Radial thickness of magnets, h_m	5
Inner radius of supporting tubes, R_i	12.5
Pole pitch, T_p	200
Axial length of radically magnetized magnet at the centre, T_{mr}	114.3
Axial length of axially magnetized magnet at two end, T_{mr2}	57.15
Axial length of axially magnetized magnets, T_{mz}	85.7
Air gap length, G	0.8

Table 1. Schematic design parameter

Based on the parameters tabulated in Table 1, three designs will be proposed which will be vary in permanent magnet design but keeping other parts as constant. The variation of the permanent magnet design will yield the different result although the three proposed designs are implementing the same features of linear generator which has the same dimension.

Based on this selected features and parameters, the research has come up with 3 proposed designs.

2.5.1 First Proposed Design

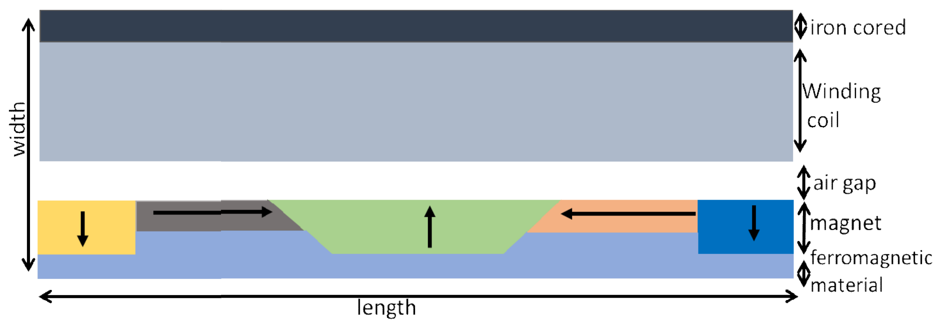


Figure 18. M-Halbach

Figure 18 shows the first proposed design is named as M-Halbach as the five parts of magnet assemble letter ‘M’. The advantage of this design is it easy to construct compare to the other designs.

2.5.2 Second Proposed Design

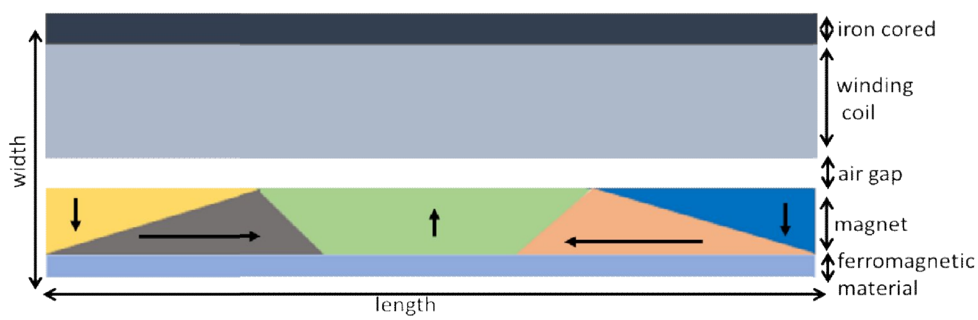


Figure 19. Triangular Halbach

Second proposed design as you can see in Figure 19 is named as Triangular-Halbach as most of magnet parts are in triangle shaped. The advantage of this design is it gives large area for both ends therefore it is expected the more flux lines created.

2.5.3 Third Proposed Design

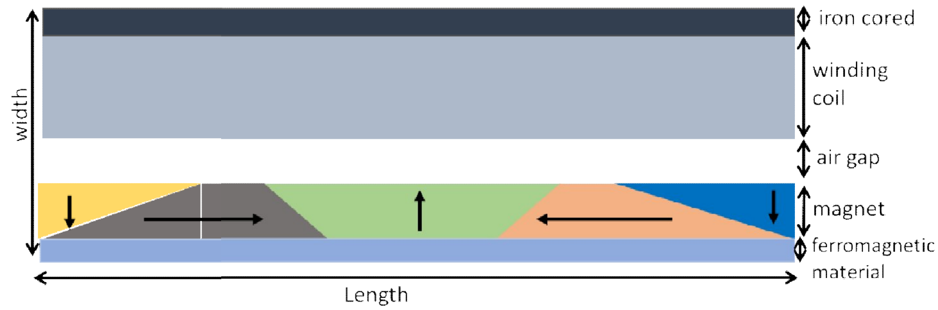


Figure 20. Triple Trapezoid Halbach

Figure 20 shows the third proposed design is named as Triple Trapezoid Halbach as most of magnet parts are in trapezoid shaped. The advantage of this design is the second and fourth magnet gives area facing the air gap which will help the formation of flux lines compare to the Triangular Halbach.

2.6 Conclusion

These proposed designs will be simulated in the Ansys Maxwell software and the result will be discussed in the Chapter 4. Next, in chapter 3 will be describe on the method on the flow of the research and the proposed design of linear generator.

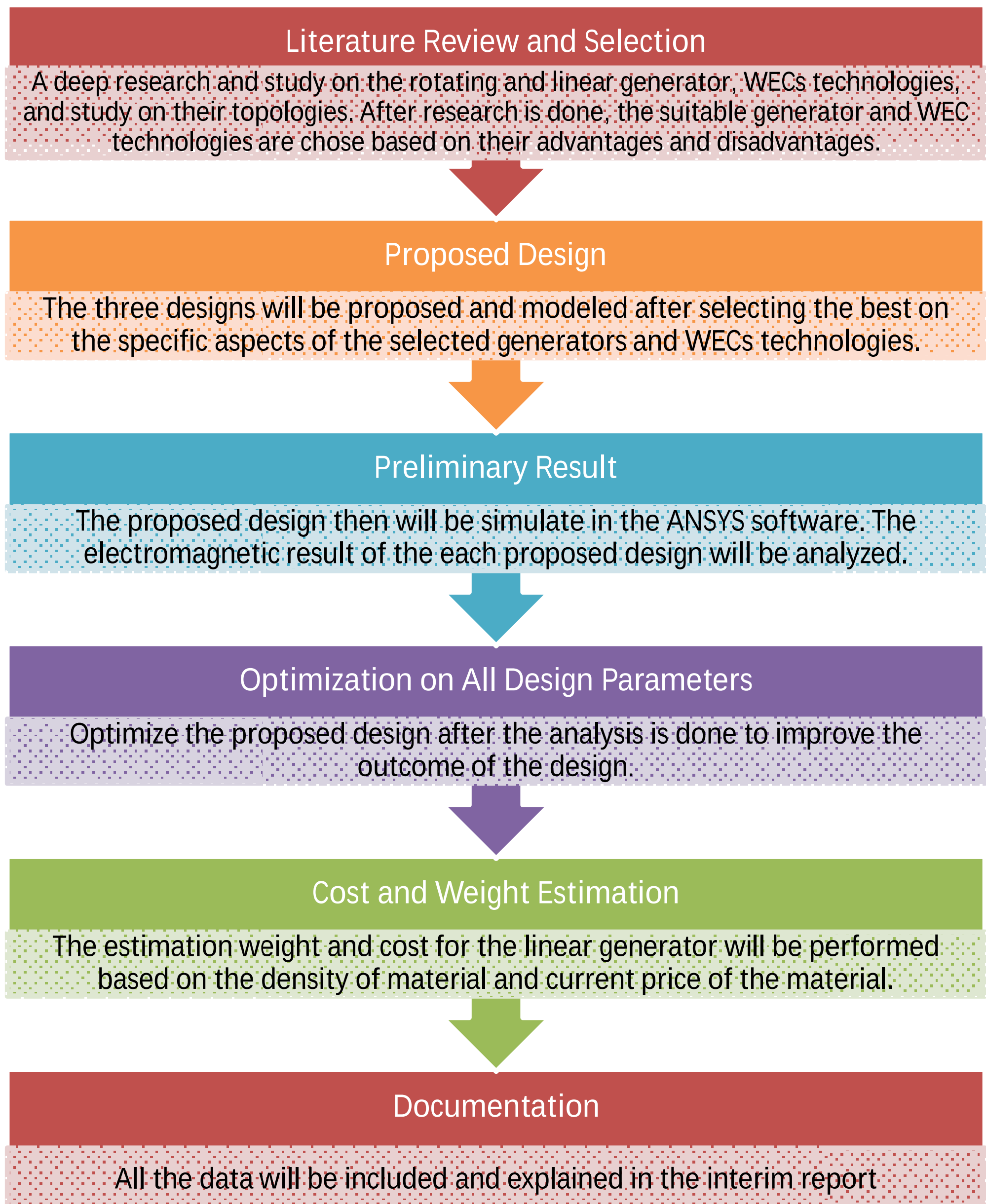
CHAPTER 3

METHODOLOGY/PROJECT WORK

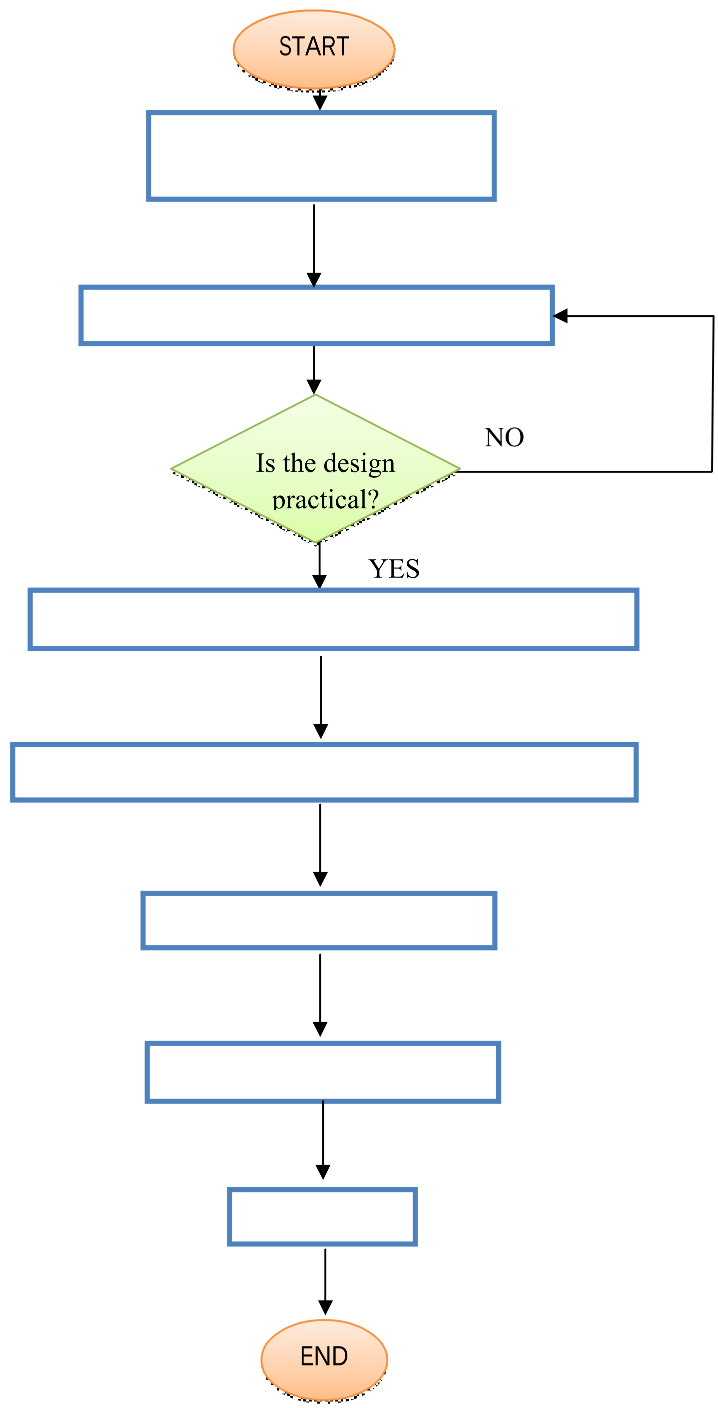
3.0 Introduction

This chapter will be described on the process chart and flow chart of the project and each flow will be explained in the process chart.

3.1 Process Chart of the Project



3.2 Flow Chart of the Project

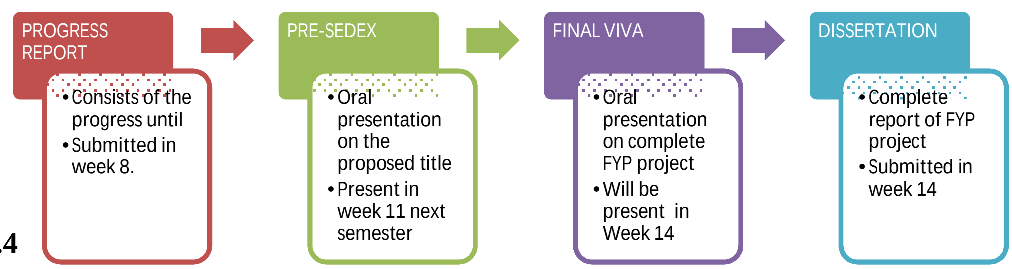


3.3 Key Milestones

In Key Milestones is described on the document and presentation that need to be done and submitted before the given deadline.

<u>FYP1</u>

<u>FYP2</u>



3.4 Conclusion

The research has completed the flow chart and the milestones for the research. The detail of the project flow can be refer in Gant Chart attached in Appendix A. In Chapter 4, the result on the each proposed design will be shown and discussed.

CHAPTER 4

RESULT AND DISCUSSION

4.0 Introduction

In this chapter will be discussing on the result of each proposed design. The result will be divided into six parts which are:

(i) Flux Lines and Flux Density of 3 proposed designs
(ii) Air Gap Distribution
(iii) Open Circuit Test
(iv) Optimization of all designs parameters
(v) Weight Estimation
(vi) Cost Estimation

4.1 Flux Lines and Flux Density of 3 Proposed Designs

In this part, the results on the flux lines and flux density each proposed design is shown. Each of the obtained result will be elaborated and explained.

4.1.1 Flux Lines of Proposed Designs

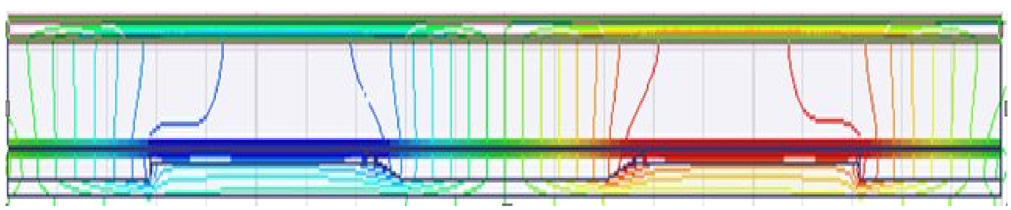


Figure 21. M Halbach Flux Lines

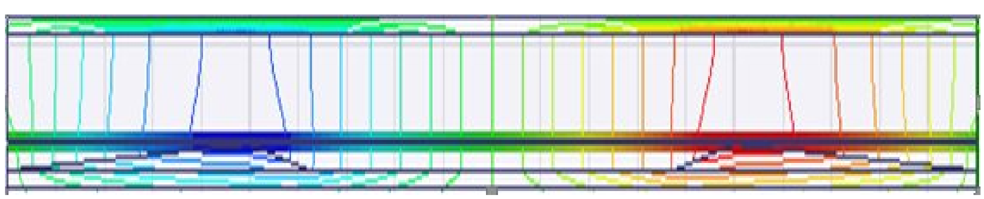


Figure 22. Triangular Halbach Flux Lines

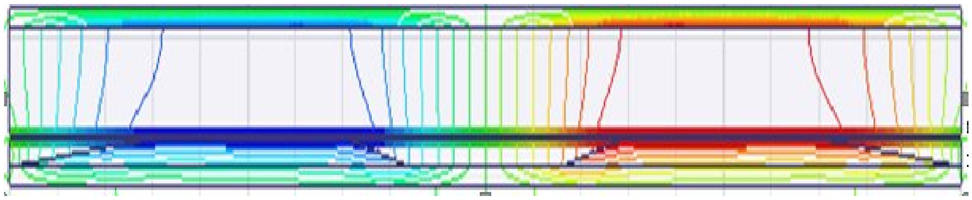
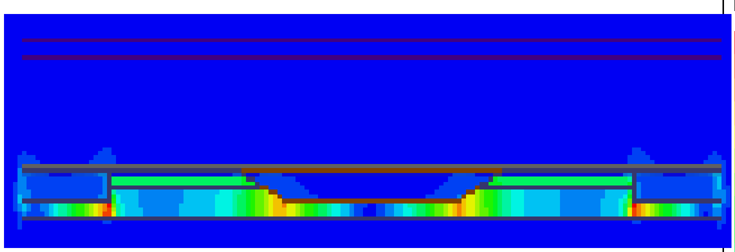


Figure 23. Triple Trapezoid Flux Lines

Figure 21 to 23 show the result of flux lines for the three proposed designs. The halbach configuration will form two circles of flux line. From the Figure 22, Triangular Halbach gives the best outcome by having flux lines along the linear generator compare to others proposed design which did not occupy with the flux lines at certain places. This is due to of the larger surface area of the triangle at the both end of the magnet.

4.1.2 Flux Density of Proposed Designs



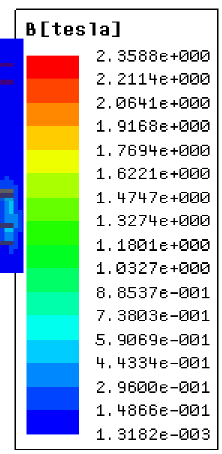
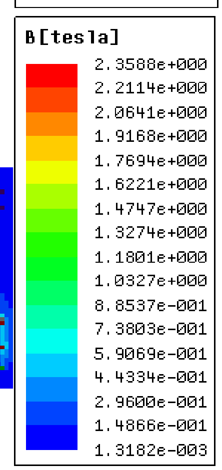


Figure 24. M Halbach Flux Density



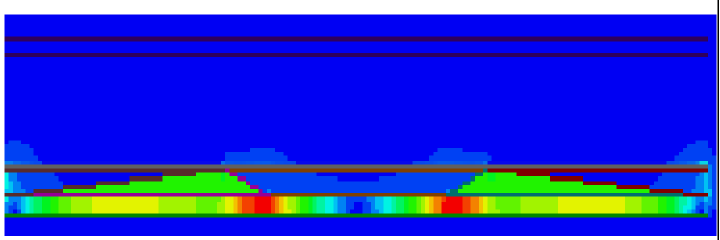


Figure 25. Triangular Halbach Flux Density

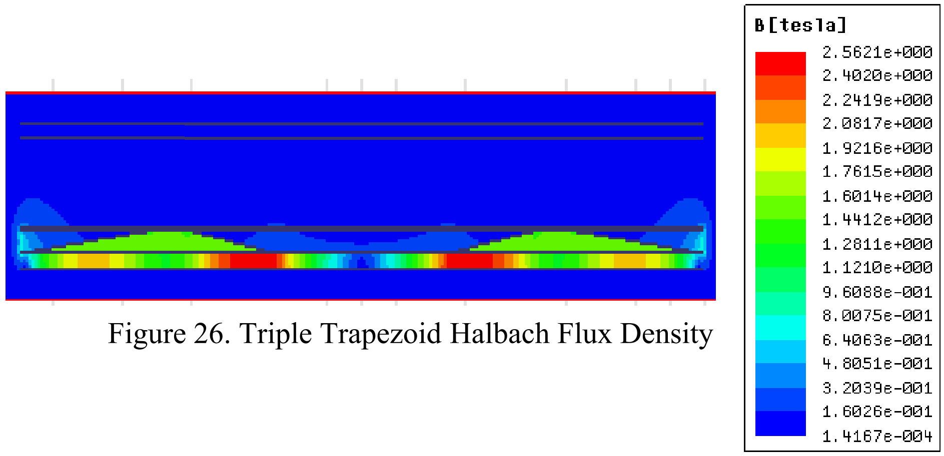


Figure 26. Triple Trapezoid Halbach Flux Density

Flux density is the important parameter where the strength of the flux can be determine. Figure 24 to 26 show the result of flux density of each proposed design. All proposed designs gives almost the same pattern since the same volume of magnet is used for all designs.

4.2 Air Gap Flux Distribution

The three proposed designs are compared based on the result of flux line and flux distribution along the air gap.

4.2.1 Flux Line vs Axial Position

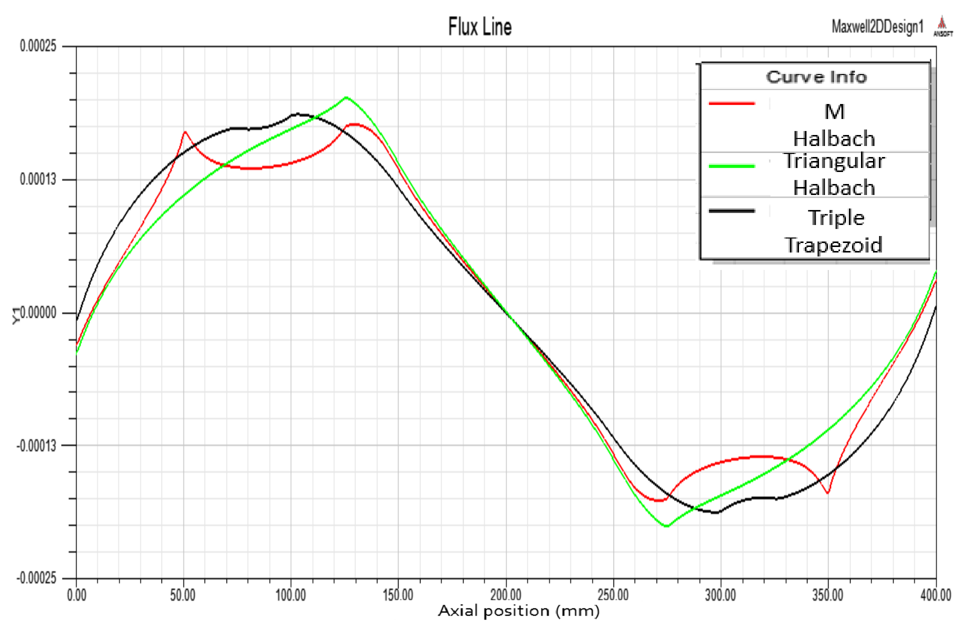


Figure 27. Flux Line vs Axial Position

Table 2.

Flux Line	M Halbach	Triangular Halbach	Triple Trapezoid Halbach
Maximum	1.76×10^{-4}	2.01×10^{-4}	1.86×10^{-4}
Average	0	0	0

Maximum and Average Value of Flux Line

Figure 27 shows the result of flux line against distance for the three proposed designs. The result proved the one of characteristics of halbach which is symmetrical sinusoidal wave form. From Table 2, Triangular Halbach yields the highest maximum flux line as in Figure 22 this design by having flux lines along the linear generator compare to others proposed design which did not occupy with the flux lines at certain places. The result follows by the Triple Trapezoid in second and the M halbach is the last.

4.2.2 Flux Distribution vs Axial Position

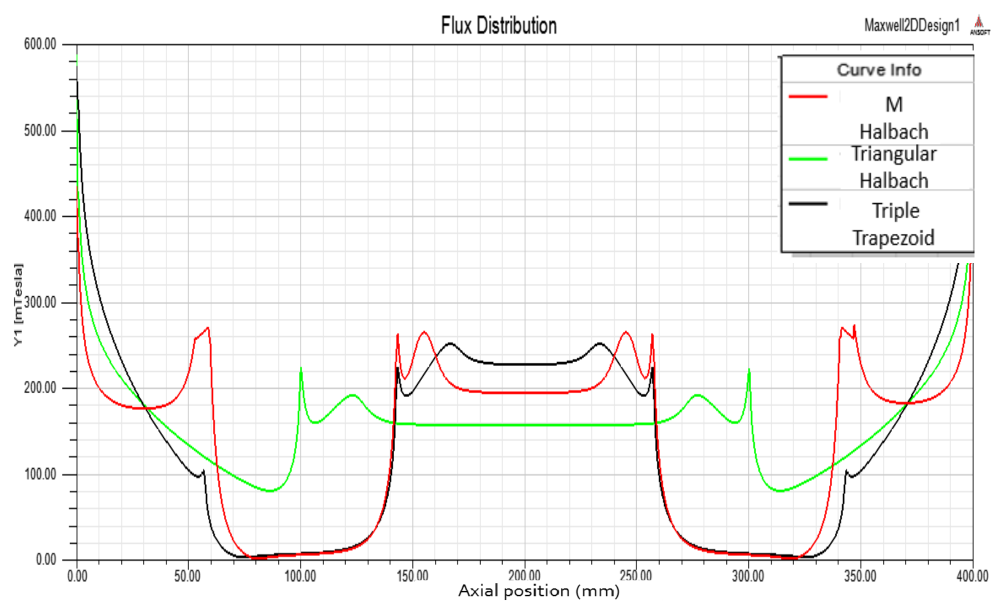


Figure 28. Air Gap Flux Distribution vs Axial Position

Flux Density	M Halbach	Triangular Halbach	Triple Trapezoid

Maximum(mT)	444.5809	451.5981	577.6356
Average(mT)	123.1045	118.2312	126.3186

Table 3. Maximum and Average Value of Flux Density

Figure 28 shows the comparison on flux distribution along the air gap of the three proposed designs. The result is symmetric as the halbach configurations produced two loops of magnetic line. By referring to Table 3, Triple Trapezoid Halbach has the highest average and maximum flux density. The Triangular Halbach has the maximum flux density higher compare to the M halbach, however in average, M Halbach produced higher flux density compare to the Triangular Halbach.

4.3 Open Circuit Test

All proposed designs then will be compared on flux linkage and induced voltage with using the parameters in the Table 4.

Table 4. Parameters of Open Circuit Simulation

Parameters	**Value**
Stop time	0.005 s
Time Step	0.0005 s
Step Size	0.0005 s
Velocity	1 m/s

4.3.1 Flux Linkage vs Time

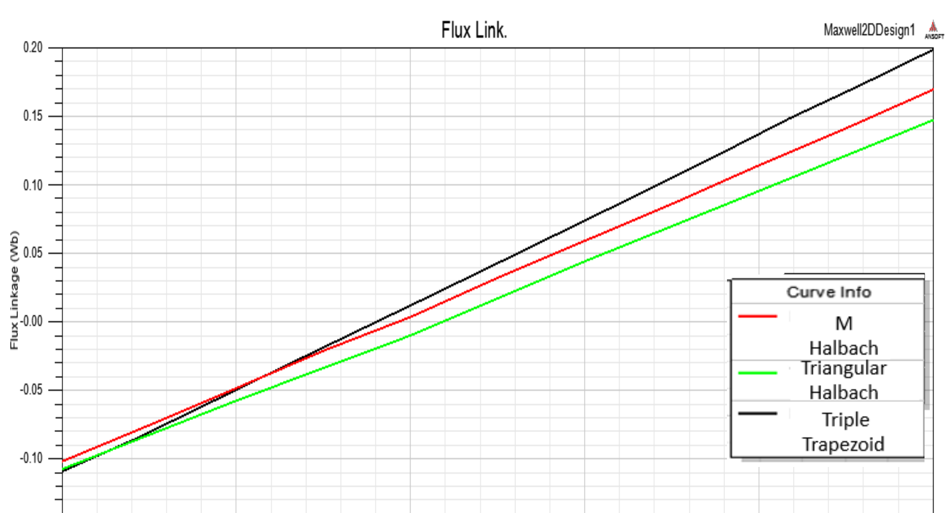


Figure 29. Flux Linkage vs Time

Table 5. Maximum and Average of Flux Linkage

Flux Linkage	M Halbach	Triangular Halbach	Triple Trapezoid
Maximum(Wb)	0.1693	0.1471	0.1985
Average(Wb)	0.0325	0.0184	0.0434

Figure 29 shows the comparison on flux linkage of the three proposed design. The flux linkage can be obtained depends on the amount of flux formed when the rotor is moving. The result is approaching a linear graph where the flux is proportional to the stroke. From Table 5, Triple Trapezoid Halbach has the highest maximum and average flux linkage compare to the other proposed design. This result is reflect back to the Figure 28 where Triple Trapezoid has the best air gap flux distribution, therefore it will produce the highest flux linkage. The result follows by the M halbach in second and the Triangular halbach is the last.

4.3.2 Induced Voltage vs Time

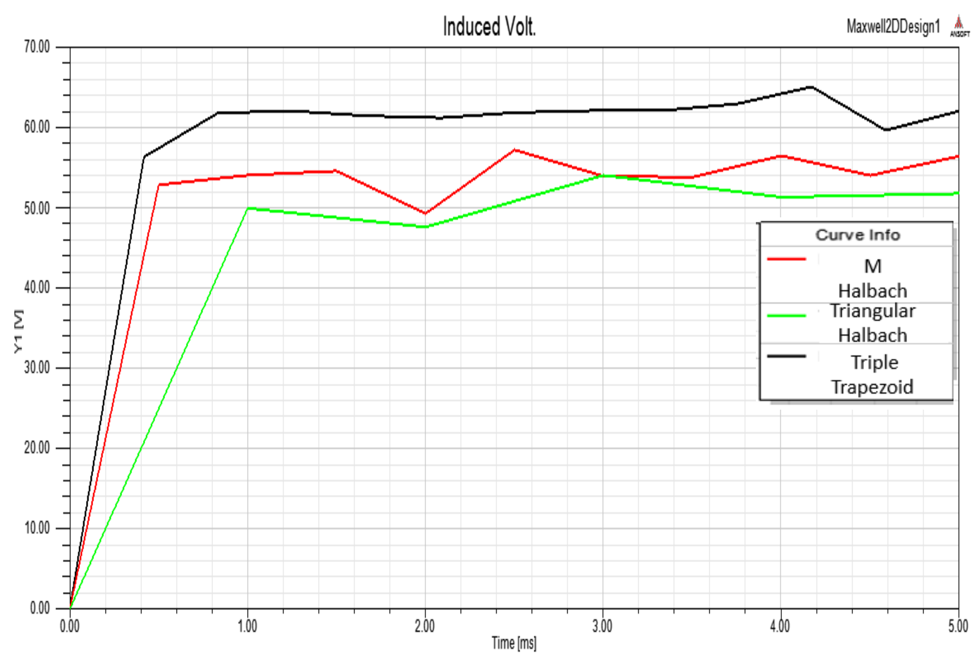


Figure 30. Induced Voltage vs Time

Table 6. Maximum and Average of Induced Voltage

Induced Voltage	M Halbach	Triangular Halbach	Triple Trapezoid
Maximum(v)	57.15	54.00	66.00
Average(v)	51.40	45.72	58.91

Figure 30 shows the comparison result of induced voltage for the three proposed design. From Table 6, Triple Trapezoid Halbach has the highest maximum and average value compare to the others design. Based on Faraday's Law, the amount of induced voltage is depends on the flux linkage. This result correspond to the result in Figure 27 where Triple Trapezoid also has the highest result of lux linkage and followed by M Halbach and lastly Triangular Halbach.

4.3.3 Thrust Force vs Time

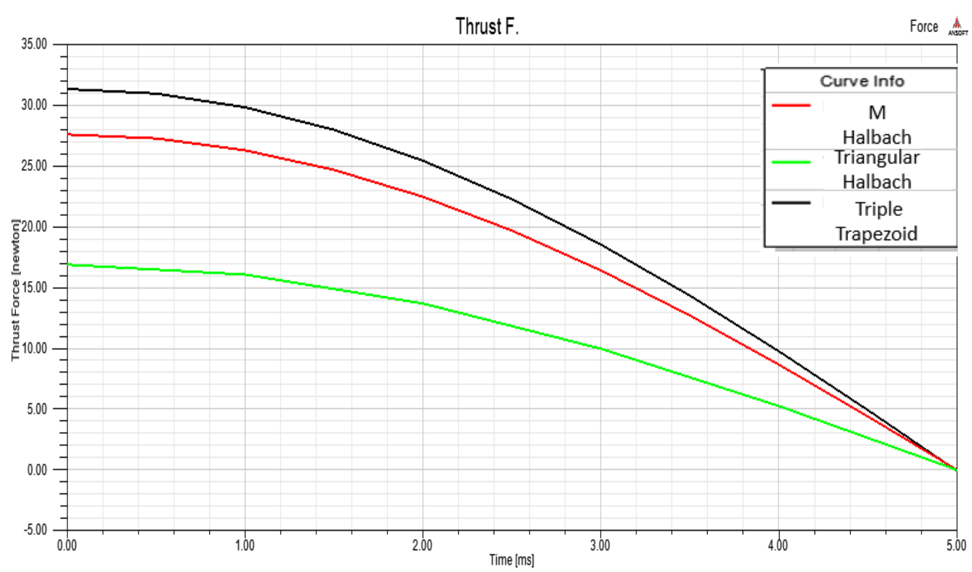


Figure 31. Thrust Force vs Time

Table 7. Maximum and Average of Thrust Force

Thrust Force	M Halbach	Triangular Halbach	Triple Trapezoid Halbach
Maximum(N)	27.5665	16.8731	31.3003
Average(N)	17.6107	10.6746	19.9339

Figure 31 shows the thrust force of the three proposed design. The thrust force is inversely proportional to stroke. From Table 7, triple trapezoid halbach produced the highest maximum and average thrust force compare to other designs. This proved that Triple Trapezoid halbach has better magnetic field compare to M halbach and Triple Tapezoid halbach.

4.4 Optimization of all design parameters

All the three proposed designs will be optimized. There are 3 parameters which will be optimized which are L_s/L_r, T_{mr}/T_p and R_m/R_e. By neglecting the friction loss, the efficiency of the generators, η are evaluated by:

$$\eta = \frac{P_o}{P_{in}} * 100\% = \frac{P_o}{P_o + P_{fe} + P_c} * 100\%$$

$$P_o = Fv$$

where, F is thrust force and v is velocity.

The power output which is 80W will be constant by varying the excitation current. However the losses which are iron loss, P_{fe} and copper loss, P_c will be different for each optimization.

i) L_s/L_r

L_s is the stator length which will be optimize by changing the length and keeping the L_r fixed which the length of rotor. The range of L_s/L_r which from 1 to 0.125 will be simulated and the result on the efficiency will be recorded.

ii) T_{mr}/T_p

T_{mr} is the axial length of radically magnetized magnet at the centre which will be optimize by changing the length and keeping the T_p

fixed which the pole pitch. The range of T_{mr}/T_p which from 0.5465 to 0.6965 will be simulated and the result on the efficiency will be recorded.

iii) R_m/R_e

R_m is the outer radius of magnet which will be optimize by changing the length and keeping the R_e fixed which the outer radius of stator core. The range of R_m/R_e which from 0.421 to 0.776 will be simulated and the result on the efficiency will be recorded.

4.4.1 Optimization of L_s/L_r parameters

The result of optimization on L_s/L_r for all proposed designs will be shown and discussed.

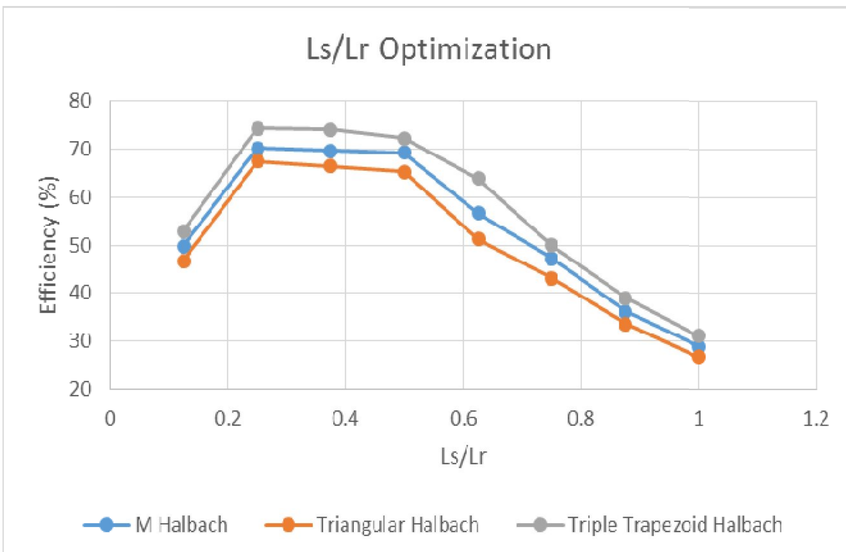


Figure 32. Optimization on L_s/L_r for the three proposed design

Figure 32 shows the efficiency against L_s/L_r for all proposed designs. From the graph, as the length of stator is decrease, the coil at the stator become more compacted and concentrated therefore causing the magnetic flux to be induced more effective. However, as the length of stator become shorter, the copper loss become higher, hence from this optimization, the research can select the optimize length of the stator with the best efficiency. The research can conclude that the Triple Trapezoid Halbach produced the highest efficiency for each optimization which is 71.10% follow by M Halbach with 67.54% and lastly Triangular Halbach with 60.89%. All the proposed designs has the best efficiency at the length of stator at 100mm.

The optimization will continue with T_{mr}/T_p parameters with the new length of stator of 100 mm for all three proposed designs.

4.4.2 Optimization on T_{mr}/T_p

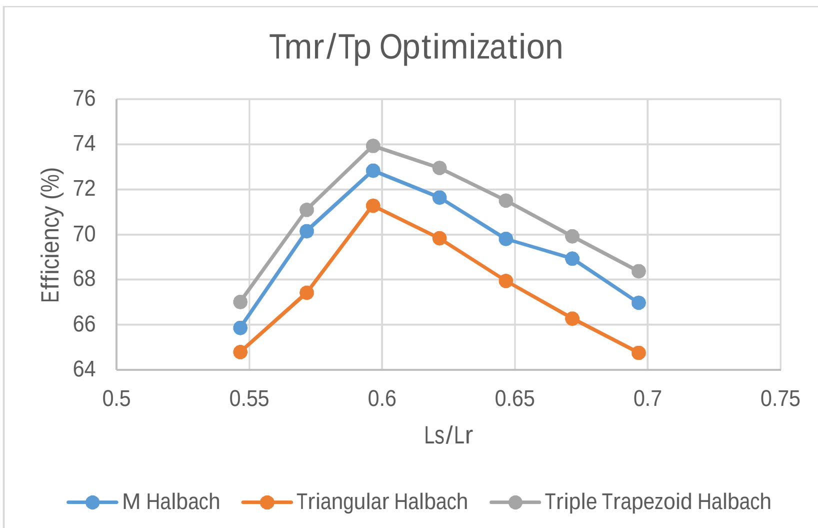


Figure 33. Optimization on R_m/R_e for the three proposed design

Figure 33 shows the efficiency against T_{mr}/T_p for all proposed designs. T_{mr} will be optimized by changing the length and keeping the T_p fixed which the pole pitch. From the graph, the research can select the best length of T_{mr} for the design that optimize flux density and flux line to provide the best efficiency for each proposed design. Based on the pattern shown in the graph, Triple Trapezoid Halbach produced the highest efficiency for each optimization which is 73.93% follow by M Halbach with 72.84%and lastly Triangular Halbach with 71.28%. All the proposed designs has the best efficiency at the length of T_{mr} at 119.3 mm

The optimization will continue with R_m/R_e parameters with the new length of T_{mr} of 119.3 mm for all three proposed designs.

4.4.3 Optimization on R_m/R_e

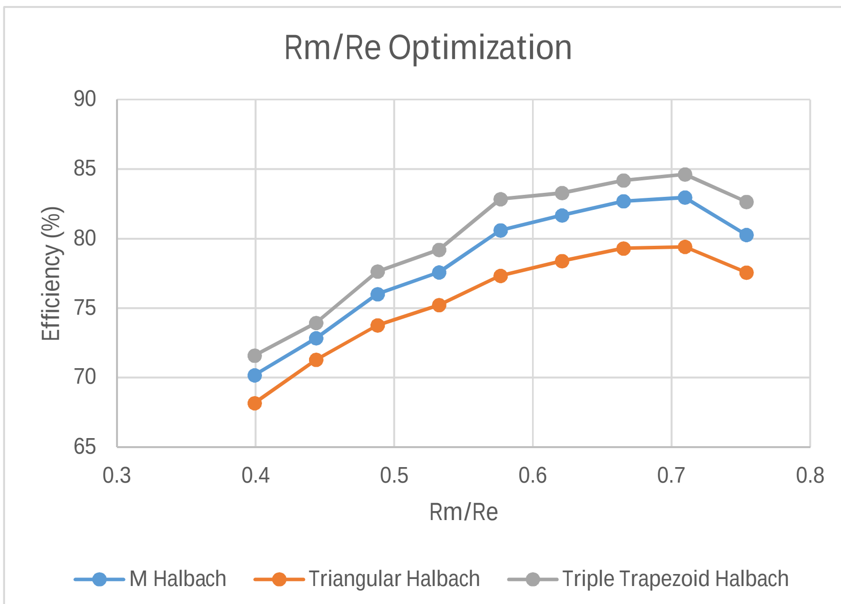


Figure 34. Optimization on R_m/R_e for the three proposed design

Figure 34 shows the efficiency against R_m/R_e for all proposed designs. R_m is optimized by changing the radius and keeping the R_c fixed which the outer radius of stator core. Based on the graph, as R_m/R_e increase, the efficiency of each proposed design will increase as the magnet radius become bigger thus producing higher flux density. However, as the R_m bigger, the copper loss increase as the radius of winding coil decrease therefore from Figure 32, the research can select the optimize radius of R_m with the best efficiency for each proposed design. As you can observe the pattern in the optimization graph, Triple Trapezoid Halbach produced the highest efficiency which is 84.62% for each optimization follow by M Halbach with 82.96% and lastly Triangular Halbach with 79.41%.

All the proposed designs has the best efficiency at the length of R_m at 33 mm.

This result for the optimization shows that the Triple Trapezoid has the best efficiency which is 84.62% and it is correspond to the preliminary result of all proposed design as Triple Trapezoid has the best performance compare to others proposed design. The result follow by the M halbach in second which produced efficiency of 82.96% and last but not least is Triangular halbach which is 79.41%.

4.5 Optimization Flux Linkage and Induced Voltage

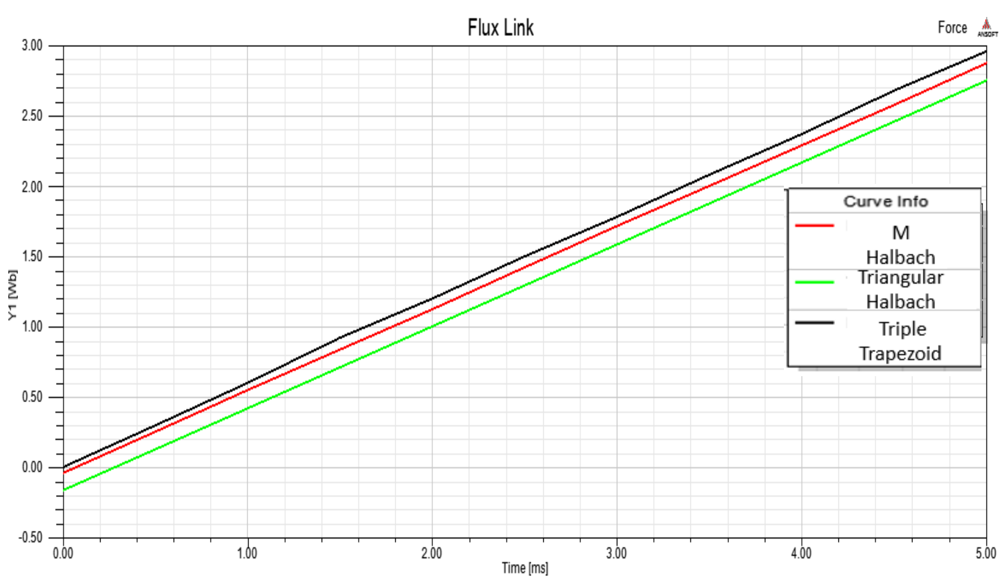


Figure 35. Optimization flux linkage

Table 8. Maximum and Average of Optimization Flux Linkage

Flux Linkage	M Halbach	Triangular Halbach	Triple Trapezoid
Maximum(Wb)	2.8752	2.7520	2.9593
Average(Wb)	1.4225	1.2977	1.4948

After the optimization stage, the research using the all optimize parameters for all proposed design of linear generators to compare on the flux linkage result after the optimization and flux linkage for preliminary result. As you can see from the Table 8, the flux linkage for all proposed designs increased significantly compare to the preliminary result.

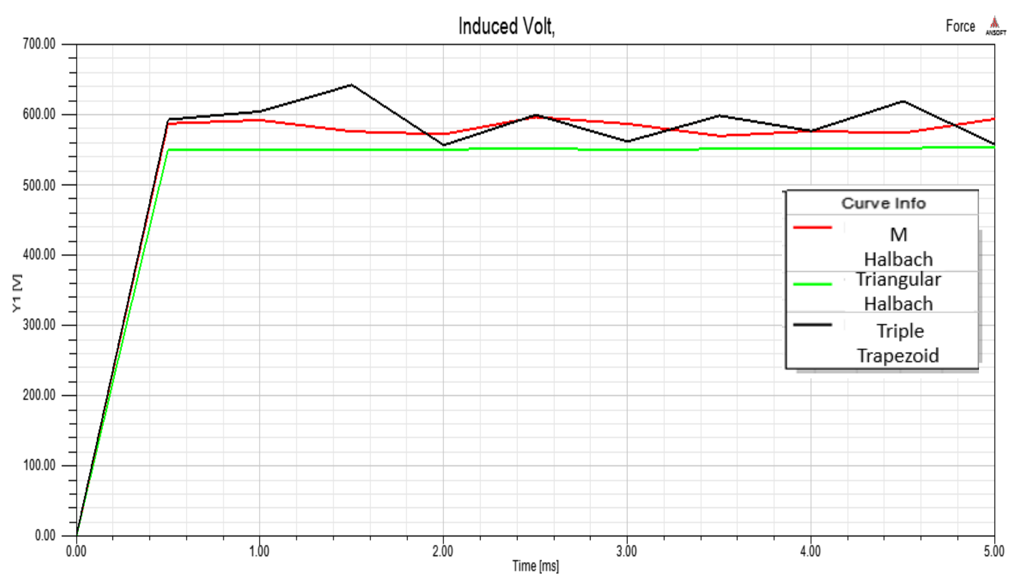


Figure 36. Optimization Induced Voltage

Table 9. Maximum and Average of Optimization Induced Voltage

Induced Voltage	M Halbach	Triangular Halbach	Triple Trapezoid
Maximum(v)	595.9339	553.1782	641.5988
Average(v)	552.2431	522.9219	562.4924

After the optimization stage, the research using the all optimize parameters for all proposed design of linear generators to compare on the induced voltage result after the optimization and induced voltage for preliminary result. As you can see from the Table 9, the induced voltage for all proposed designs increased significantly compare to the preliminary result.

The new length of L_s which equal to 100mm, T_{mr} which equal to 119.3 and R_m which equal to 33mm then now will be used to calculate the weight and cost estimation of the generator.

4.6 Weight Estimation of Linear Generator

Linear generator weight will be calculated to ensure the weight is in the portable range.

Weight of the overall generator can be calculate as,

$$Weight = V \, x \, D$$

where *D* is the material density and *V* is the volume of region.

Meanwhile volume can be define as,

$$V = h \, x \, \pi \, x \, r^2$$

h = height of the exerted region

r = radius of the exerted region

Table 10. Weight estimation of linear generator

Material	Density(kg/m^3)	Weight (Kg)
NdFe	7500	2.88
Mild steel	7800	1.8
Copper	8230	1.56
Iron	7870	0.709
Total		6.949

The total weight of the linear generator is approximately 6.949 kg. The value is still under the portable device range as the target of the research is 20 kg. All the designs use the same weight for since the same amount of materials are used.

4.7 Cost Estimation of Linear Generator

Cost estimation is calculated to approximate the cost of the linear generator based on the current price of the material used.

Price of the material used for the linear generator can be obtained by,

Price = Price per kg x weight of the material

Table 11. Cost estimation of linear generator

Material	Price (MYR/kg)	Price (MYR)
NdFe	290.50	836.64
Mild steel	1.27	2.29
Copper	22.69	35.40
Iron	0.90	0.64
Total		874.97

The total approximate cost is MYR 874.97 for each linear generator not including the cutting magnet price which depending on the complexity. The price of the linear generator is worth by looking at the high efficiency it can provide, the weight which is portable, low maintenance, and it is can be used for a very long time.

4.8 Conclusion

Throughout this chapter, the research managed to obtain the preliminary result to compare the performance the three proposed designs. During the optimization stage, the research managed to find the optimize parameters to be used and after that the cost and weight of the linear generator for the research can be estimated.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

Based on the result and discussion for preliminary result, Triple Trapezoid Halbach proposed design has showed the best performance compare to the M Halbach and Triangular Halbach. Through the simulation and the result obtained, Triple Trapezoid produced the best result as this design yields the stronger flux density for the linear generator compare to the others proposed design which the flux density is weak. Due to the good performance in the flux density, as the result the air gap flux distribution will also at its best performance as from the result obtained in the Figure 28. Besides, flux linkage of the Triple Trapezoid Halbach also produced the highest result and this is correspond to the induced voltage of the Triple Trapezoid Halbach which is also the highest among three proposed designs.

For the optimization on all design parameters, the research managed to optimize on L_s/L_r, T_{mr}/T_p and R_m/R_e. For all optimization parameters, Triple Trapezoid shows the highest power output compare to others two proposed designs as from the preliminary result Triple Trapezoid also gives the best performance. Throughout the optimization phase, the research managed to increase the efficiency more than 79%

for all proposed designs. After the optimization, the flux linkage and induced voltage had increased significantly compare to the preliminary result.

As the conclusion, the variation of the designs of the permanent magnet for the linear generator will cause the variation in the result obtained. Therefore, from this research, Triple Trapezoid Halbach is the best permanent magnet shape compare to the Triangular Halbach and M Halbach which produced the best result in air gap flux distribution, flux linkage, induced voltage, thrust force and yield the highest efficiency for all optimization parameters.

Based on the weight estimation, the overall weight of the linear generator is 6.949 kg which is in range of portable weight and it is meet the objective of the research to design the generator which less than 20 kg. Besides, cost estimation for each linear generator is MYR 874.97 which is worth to buy and it is also affordable.

At first, this research has problem with getting the correct result from the simulation even though the simulation has run for many times and also with help from the post graduate student to solve the problem. However, the problem has solved by using the latest version of the Ansys Maxwell.

As the recommendation, the research should continue by building the real prototype based on the parameters from this research. Other than that, the research also should continue with the floating structure of the linear generator in the future.

CHAPTER 6
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CHAPTER 7

APPENDIX

7.1 Appendix A

FYP1														
TASKS	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Selection of Topic														
Literature Review														
Familiarisation of ANSYS software														
Proposed Design and Analysis														
Extended Proposal Submission														
Simulation and Preliminary Result														
Proposal Defense														
Draft & Final Interim Report														
FYP2														
TASKS	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Optimize All Design Parameters														
Weight and Costing Estimation														
Progress Report														
Pre-Sedex														
Dissertation														