CHAPTER 1
INTRODUCTION

1.1 Background of Study

Renewable energy is becoming popular alternative to the fossil fuels energy such as petroleum, gas and coal. As the fossil fuels reserve will be extinct and the environmental impact they have, the renewable energy has a good potential to be explored. One of the extremely promising energy sources is the ocean wave energy. The world potential of harnessing the ocean's untapped energy is between 200GW to 5000GW at the offshore, 10GW to 500GW at near shore and 1GW to 50GW at the shoreline [1].

The conversion of ocean wave energy requires a device that will intercept the linear motion of the wave and converts the portion of the energy into mechanical energy first and then to electrical energy. Various types of wave energy devices have been patented, depending on the location of the devices whether shoreline, near shore or offshore.

Permanent magnet linear generator buoy [2] is an experimental ocean wave device. It employs the vertical motion of ocean wave to move the armature coil (mounted on the buoy) relative to permanent magnet field (mounted on the central translator shaft which is anchored to the sea floor). Then, the voltage is induced in the coil. Besides that, Surfing Wave Energy Converter (SWEC) [3] employs the wave to move several paddles horizontally. These paddles are connected to a common drive train to drive the electrical machines and generating the power. Other mechanism used to absorb wave energy is submerged pressure devices which exploit the pressure variation on a submerged chamber as wave crests pass to cause the chamber to expand and contract. (i.e the Archimedes Wave Swing) [3].

The long stroke permanent magnet generator will be designed to harness the ocean wave energy to generate electricity. In this project, several linear permanent magnet motor topologies will be studied and analysed using Finite Element Method and analytical model.

1.2 Problem Statement

The electricity demand of Malaysia will increase by 4.7 percent per year over the outlook period, to reach 274 TWh in 2030 [4]. As the cost of generating electrical power from the fossil fuel increases and growing demand of electrical power, there is a need to overcome this problem through renewable and clean energy.

One of the renewable energy is ocean wave energy. Ocean wave has powerful force, but its frequency is extremely low of about 0.1 Hz (equivalent to 6 rpm) [1]. While the success of generating electricity from this source demands the frequency is raised to equivalent of 500 – 1500 rpm. Therefore, three phase long stroke linear permanent magnet generator will be designed by analysing its performance as the motor. This is because the machine can be inter-convertible base on its energy sources.

1.3 Objectives and Scope of Study

The objective of this project is to design and modelling long stroke permanent magnet linear generator for tidal wave system. The specific objectives of this project are:

- To conduct literature review for various type of linear machine
- To propose new linear machine design for tidal wave generating system
- To design, model and simulate the proposed design
- To choose the best design base on findings from simulation.

CHAPTER 2

LITERATURE REVIEW

2.1 Linear Motor Concept

According to *A Dictionary of Physics* [5], linear motor is a form of induction motor in which the stator and armature are linear and parallel, rather than cylindrical and coaxial. Principally, linear machine configuration can be realised from every rotary electrical machine configuration. Figure 1 and Figure 2 show the process of realising linear motor from the induction motor and the permanent magnet motor.

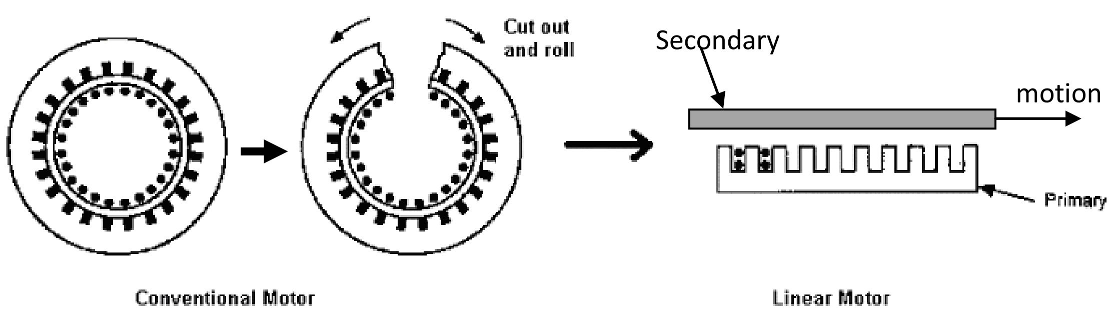

Figure 1 Realisation of linear induction motor from rotary induction motor [6]

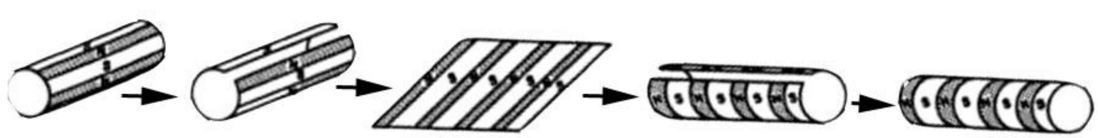

Figure 2 Realisation of linear permanent magnet motor from rotary permanent magnet motor [7]

A conventional rotating induction motor has circular rotor and stator. The coils in the rotor and stator are mounted in circular array. However, linear induction motor has both flat or tubular rotor and stator. The linear induction motor can be realised from the rotary induction motor by slicing and unrolling it as shown in Figure 1. The same process can be used to obtain either flat or tubular linear permanent magnet motor as shown in Figure 2.

A linear machine produces linear force to the load without any rotary to linear transmission devices such as belt and pulley, rack and pinion etc.

2.2 Linear Permanent Magnet Motor

Linear permanent magnet motor reduces the manufacturing and operating cost due to its simplicity of construction. Besides that, it also uses permanent magnet as the field unit, thus eliminate the need for field winding. These two factors make linear permanent magnet motor more favourable than other direct linear motor [8].

Linear motor comes with various topology such as iron core, air core and slotless. The advantages of iron core linear motor are it has high thrust force and good heat dissipation. By utilizing lamination in the armature, the magnetic flux can be concentrated to produce high thrust force. Heat generated from the coil can be dissipated through the iron lamination. Air core linear motor produces high acceleration moving armature due to low mass moving armature. Slotless and slotted topologies also can reduce the cogging force and increase the thrust force respectively [9].

Generally, linear permanent magnet motor can be categorised into three configurations, which are [9]:

i. moving-coil
ii. moving-iron
iii. moving-magnet

2.2.1 Moving-coil motor

The structure of moving-coil linear motor consists of coil winding at the armature and permanent magnet at the stator either axially magnetised permanent magnet or radially magnetised permanent magnet. Rectangular ironless moving coil linear motor [10] shown in Figure 3 has no cogging forces (the attraction between the moving coil and the permanent magnet) and lower mass armature due to the ironless coil assembly.

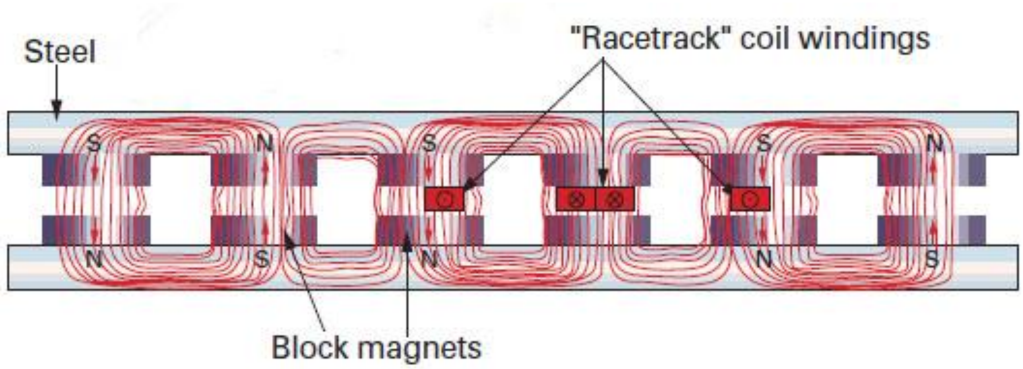

Figure 3 Rectangular ironless moving coil linear motor [10]

The radially magnetised magnets configuration as in Figure 3 provides faster returning fluxes and significant in reducing the thickness of steel, thus reduce the material cost [9].

Figure 4 shows rectangular iron core linear permanent magnet motor. The slotted iron core significantly decreases the working magnetic air gap, thus yields high thrust force. The cogging force also exists because of the strong attractive force between the permanent magnet and the iron core. However, it can be reduced by skewing the magnet.

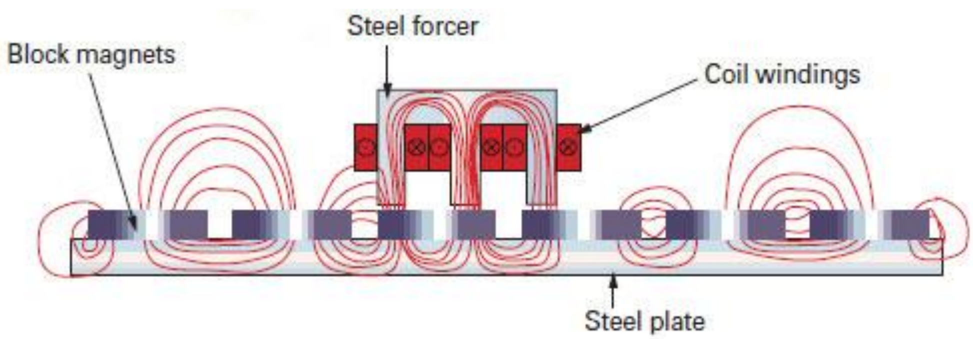

Figure 4 Rectangular iron core linear permanent magnet motor [10]

A tubular moving coil linear generator [2] shown in Figure 5 can reduce the cogging force by using annular shape pole piece and permanent magnet. The magnets are stacked in pairs such that opposing magneto-motive forces (mmfs) drive the flux through the soft iron. This 0.320m total length generator will produce 25V rated voltage, 3A rated current and 50W output power.

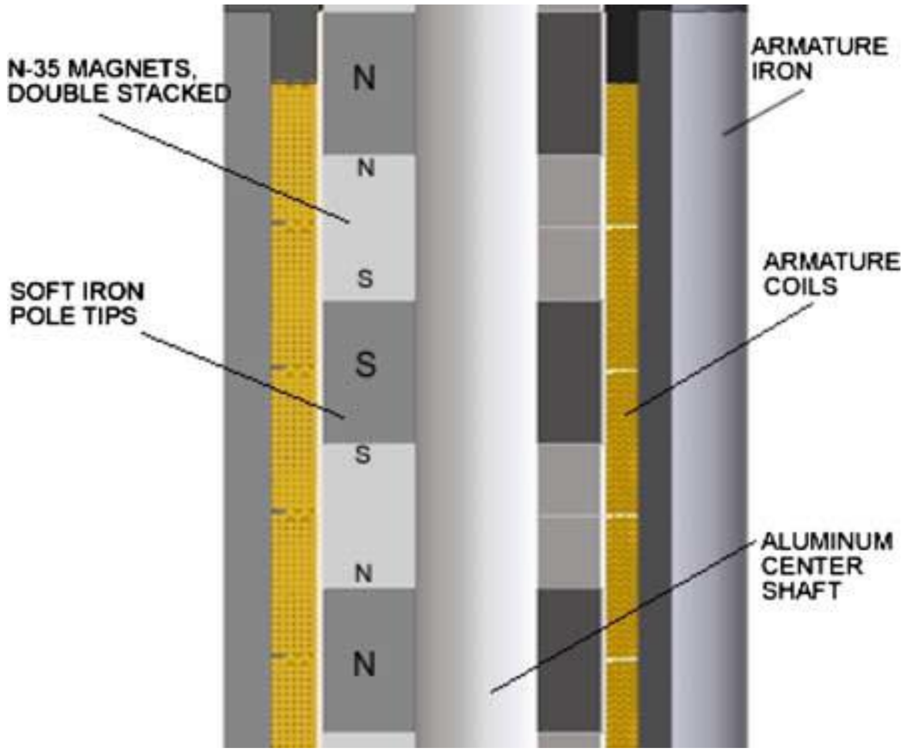

Figure 5 Moving-coil linear generator [2]

2.2.2 *Moving-iron motor*

Moving-iron permanent magnet linear motors have simpler designs because they are usually required to have a uni-directional force capability and use a mechanical spring to reverse the motion of the plunger when the motor is de-energised [9].

A small linear permanent magnet generator for generating electrical power was developed by Wang et al [11] as illustrated in Figure 6 [9]. The generator is a two-phase tubular device, the stator having both permanent magnets and coils, while the moving armature is a simple salient iron core. The axially magnetized permanent magnets and the laminated pole-pieces in the stator produce an essentially radial air-gap field. The stator winding flux linkage is modulated by the linear movement of the armature, and generates an induced electromotive force (EMF). This 48mm axial stroke linear generator produces 3mJ energy and its average speed is 0.3m/s.

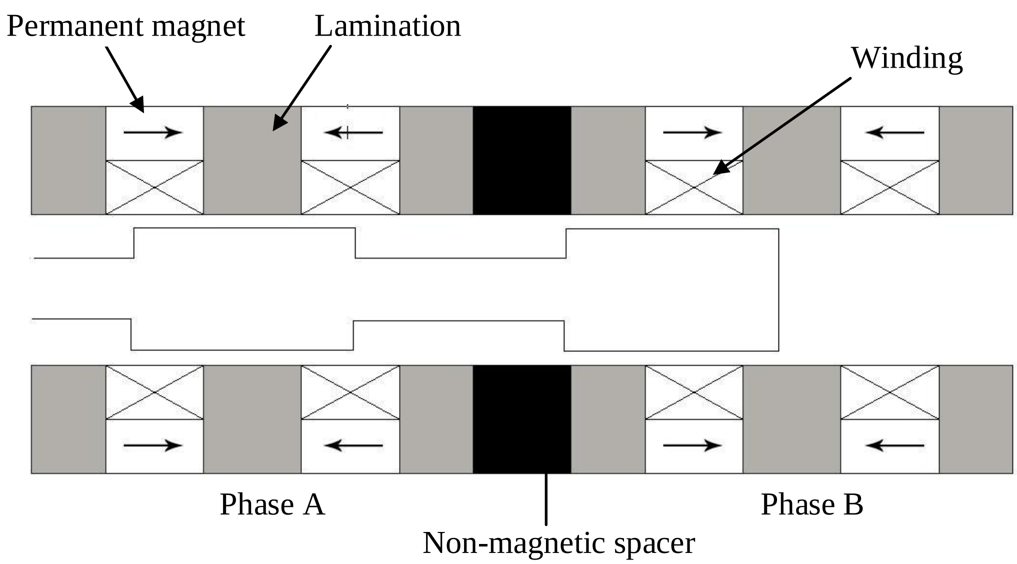

Figure 6 Moving-iron linear generator for low power application [9]

Throughout comparison of the previous topologies of moving-iron motor, the conclusion is the moving-coil motor suffers some disadvantages such as:

i. Heavy weight of moving mass
ii. Relatively low thrust force

Therefore, moving-iron topologies will not be considered for designing the long stroke linear permanent magnet generator.

2.2.3 Moving-magnet motor

There are many topologies for moving-magnet motor. The moving-magnet motor can have different permanent magnet magnetisation direction which are radially or axially magnetised as shown in Figure 7 and Figure 8. Axially magnetised topology has higher specific force capability than the radially magnetised topology. It also offers lower manufacturing cost, because its permanent magnets are simply magnetised.

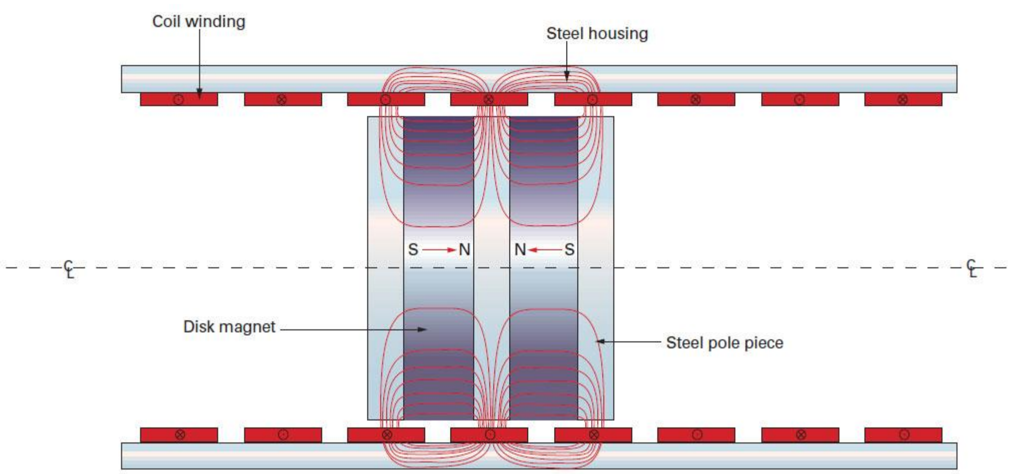

Figure 7 Axially magnetised cylindrical moving magnet linear motor [10]

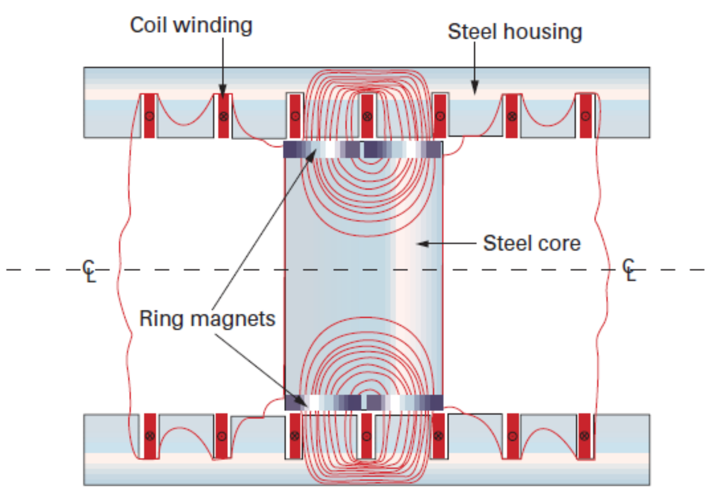

Figure 8 Radially magnetised cylindrical moving magnet linear motor [10]

As for the linear motor in Figure 7, the magnetic flux is squeezed through the pole piece between the oppositely polarized magnets. Thus, it increases the magnetic field (0.6 – 1.2 times the magnet material's B_r value) [10]. Figure 9 shows the magnetic field is channelled from the permanent magnet into the coil by the pole piece. While the linear motor in Figure 8 has very small working magnetic air gap and yields higher forces via a higher magnetic field.

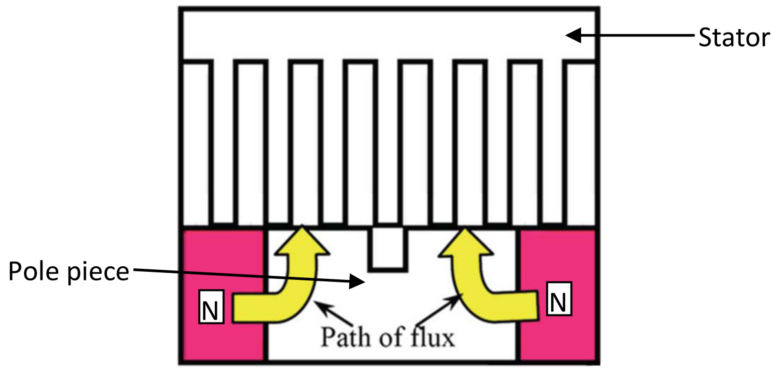

Figure 9 Pole piece between two blocks of permanent magnet [4]

Moving-magnet linear motor has some advantages such as higher efficiencies than moving-coil linear motor. Besides that, it also requires smaller volume of permanent magnet than the moving-coil linear motor for the same output power. Moving-magnet linear motor also does not have flying leads connected to its armature, thus making it more reliable, rugged and suitable for higher duty operation [9].

2.3 Finite Element Method

Finite element method is an engineering analysis of engineering design to predict the performance of the design by calculating the field, which is defined as a quantity that varies with position within the device analysed. In this project, the magnetic field will be analysed together with its potential; magnetic vector potential. The field is related to the potential as its derivatives with respect to position.

The finite element model contains information about geometry (subdivided into finite elements), materials, excitation and constraints. The material properties are needed to describe materials in electromagnetic problems. There are three electromagnetic material properties which are permeability, permittivity (or dielectric constant) and electrical conductivity. These material properties may vary with temperature or frequency or other physical parameters.

In this project, two-dimensional (2D) axisymmetric finite element model of motor will be developed using open source software. 2D finite element means by definition, it connects three or more grid points forming a 2D plane, and all potentials and fields in the element can vary in the two directions of the plane. Figure 11 and 12 show how three-dimensional (3D) cylinder in Figure 10 is modelled as axisymmetric problem and planar problem respectively.

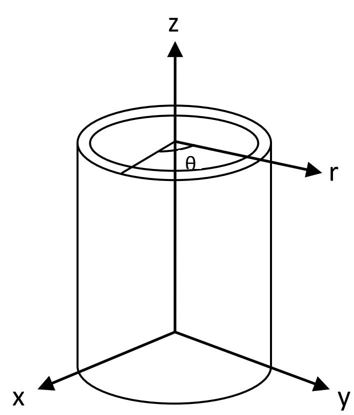

Figure 10 3D cylindrical tube

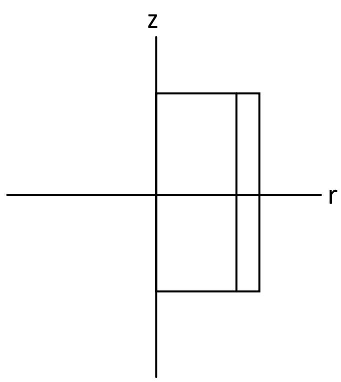

Figure 11 Axisymmetric problem

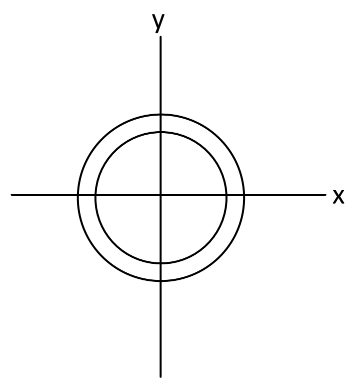

Figure 12 Planar problem

2.3.1 Boundary Condition

There are five boundary conditions exist for the magnetic and electrostatic problem, which are [12]:

a. ***Dirichlet.*** In this type of boundary condition, the value of potential A or V is explicitly defined on the boundary, *e.g.* $A = 0$. By defining $A = 0$ along a boundary in magnetic problem, keeping magnetic flux from crossing the boundary.
b. ***Neumann.*** This boundary condition specifies the normal derivative of potential along the boundary. In magnetic problems, the homogeneous Neumann boundary condition, $\frac{\partial y}{\partial n} = 0$ is defined along a boundary to force flux to pass the boundary at exactly a 90° angle to the boundary. This sort of boundary condition is consistent with an interface with a very highly permeable metal.
c. ***Robin.*** The Robin boundary condition is sort of a mix between Dirichlet and Neumann, prescribing a relationship between the value of A and its normal derivative at the boundary. An example of this boundary condition is:

$$\frac{\partial A}{\partial n} + cA = 0$$

This boundary condition is most often in FEMM to define "impedance boundary conditions" that allow a bounded domain to mimic the behavior of an unbounded region.
d. ***Periodic***. A periodic boundary conditions joins two boundaries together. In this type of boundary condition, the boundary values on corresponding points of the two boundaries are set equal to one another.
e. ***Antiperiodic.*** The antiperiodic boundary condition also joins together two boundaries. However, the boundary values are made to be of equal magnitude but opposite sign.

CHAPTER 3
METHODOLOGY

3.1 Procedure Identification

Literature review of linear machine has been conducted. It is done through collecting information from electrical and electronic journal, thesis, textbooks and websites. This literature review covers the linear motor theory, types of linear machine and the various topologies of linear machine. There are many types of linear machine such as linear induction machine, linear synchronous machine, linear switched reluctance machine, linear DC machine and linear permanent magnet machine. However, the scope of the literature review will focus only on the linear permanent magnet machine. The topologies of linear permanent magnet machine can be grouped into three major groups which are moving-magnet machine, moving-iron machine and moving-coil machine.

Through the findings from literature review, two new topologies of linear permanent magnet machine have been proposed. The performance of the proposed machine topologies is analysed by using finite element analysis. Finite element analysis is being carried out to analyse the magnetic flux distribution and motor's efficiency. Then, optimisation of the motor's parameters will be done base on the result of the finite element analysis. The project procedures are summarised in the Figure 13.

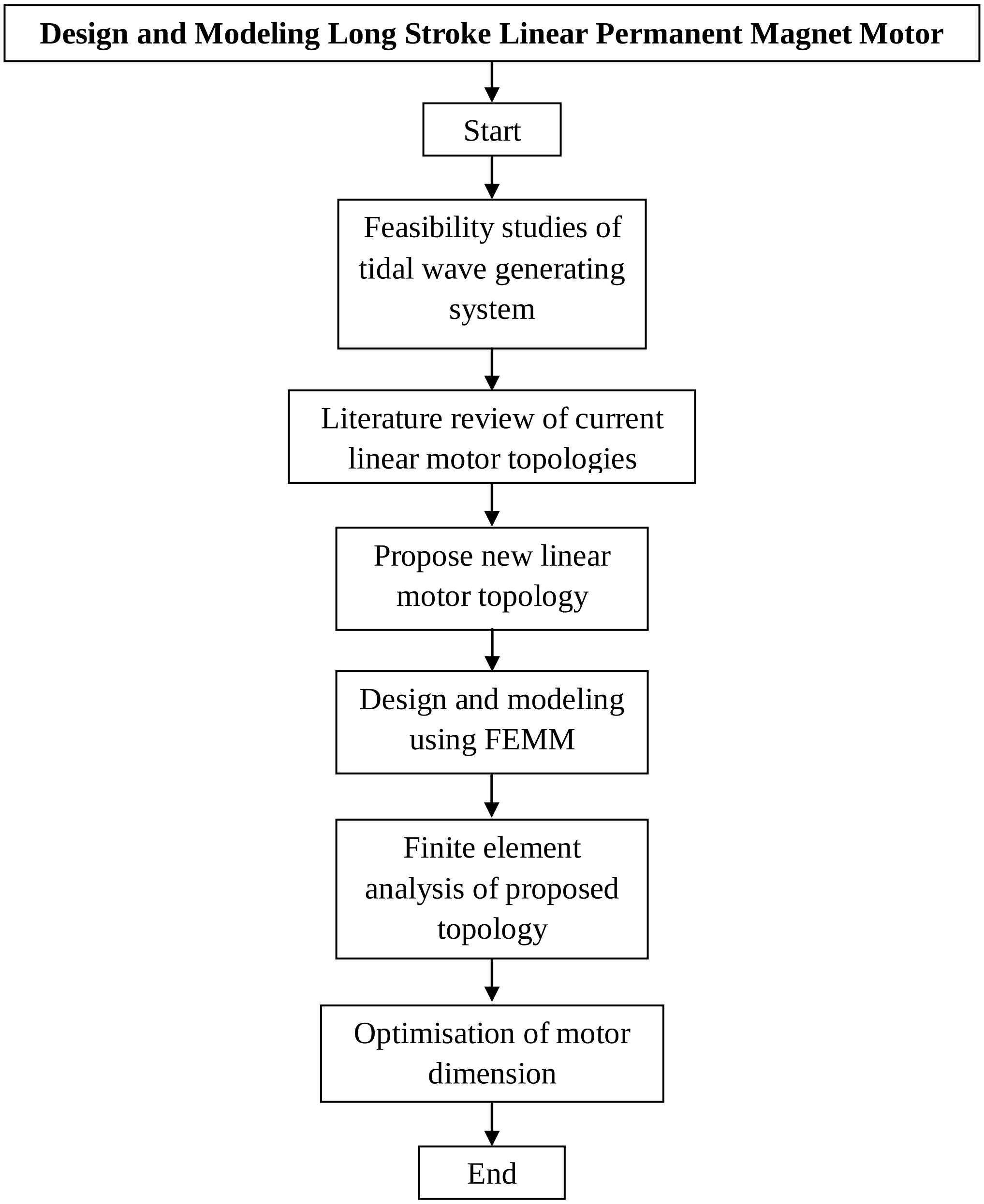

Figure 13 Project methodology

3.2 Methodology

The important activity in this project is the finite element analysis of the design. The geometry of the design will be drawn using FEMM and all the material needed will be assigned to the parts of the machine. The magnetic flux distribution of the machine under no load condition will be analysed at its initial position and at maximum stroke length. If the magnetic flux distribution is symmetrical at both tooth of the stator when the armature is at initial position, then, magnetic flux distribution of the machine will be analysed when the armature is at the maximum stroke length. After that, the efficiency of the machine will be calculated. Efficiency of the machine is affected by the power losses which are copper loss, iron loss and eddy current loss. Based on the finite element result, dimension of the motor will be optimised such as magnet length, width of back iron, height of the slot, radius of the air-cored, and width of the stator slot opening.

The future works of this project involves analytical analysis of the machine's design using the Matlab Simulink. Both results of finite element analysis and analytical analysis will be validated.

3.3 Tools and Equipment Required

3.3.1 Finite Element Method Magnetic

Finite Element Method Magnetic version 4.2 (FEMM v4.2) will be used to do finite element analysis of the linear permanent magnet machine design. An analysis in FEMM involves three distinct steps, which are:

a. **Preprocessing**: The user provides data such as the geometry, materials and element type to the program.
b. **Solution:** The user defines the type of analysis, set boundary conditions, apply loads, and initiate finite element solutions.

c. **Post processing:** The user reviews the results of the analysis through graphical displays and tabular listing.

Design optimisation of the proposed new topology of linear permanent magnet machine will be done base on the result of the finite element analysis.

CHAPTER 4
RESULTS AND DISCUSSION

4.1 The Proposed Designs

The most important criterion that will be analysed for the long stroke linear permanent magnet machine are the stroke's length, the magnetic field and its flux distribution, the thrust force, motor's efficiency and cost-effectiveness. Base on these criterions, moving magnet topology has been chosen for the design of long stroke linear permanent magnet machine. Two designs have been proposed for further analysis, which are three phase air-cored quasi-hallbach magnetised machine with rectangular magnet and three phase air-cored quasi-hallbach magnetised machine with trapezoidal magnet. Both machine are tubular motors with slotted stator made of mild steel. Figure 14 and 15 show the air-cored quasi-Halbach magnetised machine with rectangular magnet and air-cored quasi-Halbach magnetised machine with trapezoidal magnet, respectively.

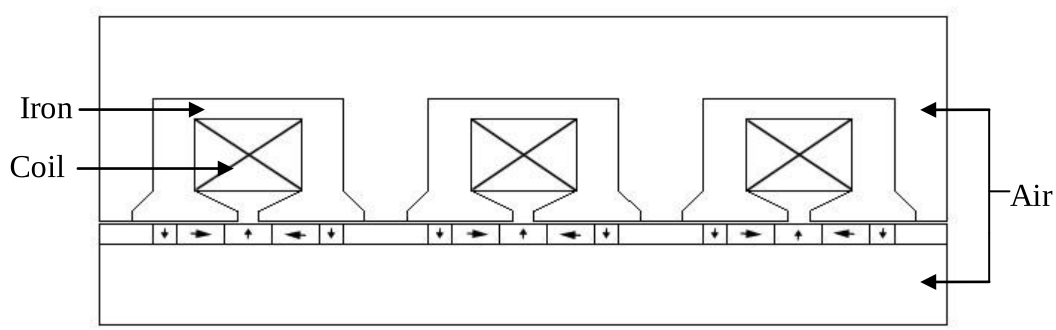

Figure 14 Air-cored quasi-hallbach magnetised machine with rectangular magnets

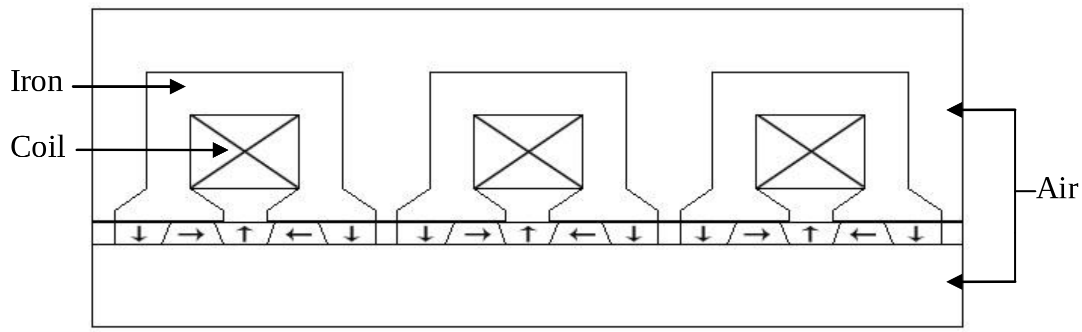

Figure 15 Air-cored quasi-halbach magnetised machine with trapezoidal magnets

The design parameters and specification of tubular long stroke linear permanent magnet machine are shown in Table 1. Details of the design parameters for both machines are included in the Appendix III and Appendix IV.

Table 1: Design parameters and specification of the machines

Item	**Value**	**Units**
Outer diameter of stator	300	mm
Axial length of machine	400	mm
Length of pole-pitch	10	mm
Height of the air-gap	1	mm
Height of the magnet	10	mm
Permanent magnet material	Sintered NdFeB	
Remanence of permanent magnet	1.045	T
Coercivity of permanent magnet	891300	A/m

4.1.1 Air-cored Quasi-Hallbach Magnetised Machine with Rectangular Magnet

The advantage of air-cored machine is it has low mass moving armature. Thus, the machine will produce high thrust force. Besides that, it also has low iron loss and no eddy current loss in armature. The slotted stator also provides good heat dissipation and reduces the working magnetic air gap. Therefore, it will produce high force. The quasi-hallbach arrangement of the permanent magnet reduces the magnetic flux leakage because the axially magnetised permanent magnet provides a returning path for the radial air gap magnetic flux linkage. This will reduce the magnetic flux linkage in the back iron and the width of the back iron will also be reduced. Therefore, the cost of the stator's material will be reduced. However, this topology suffers high cogging force due to the slotted stator but it can be reduced by skewing or stepping the magnet, and optimize the permanent magnet width and axial length [13].

Figure 16 shows the three dimension (3D) view of the air-cored quasi-hallbach magnetised machine with rectangular magnet.

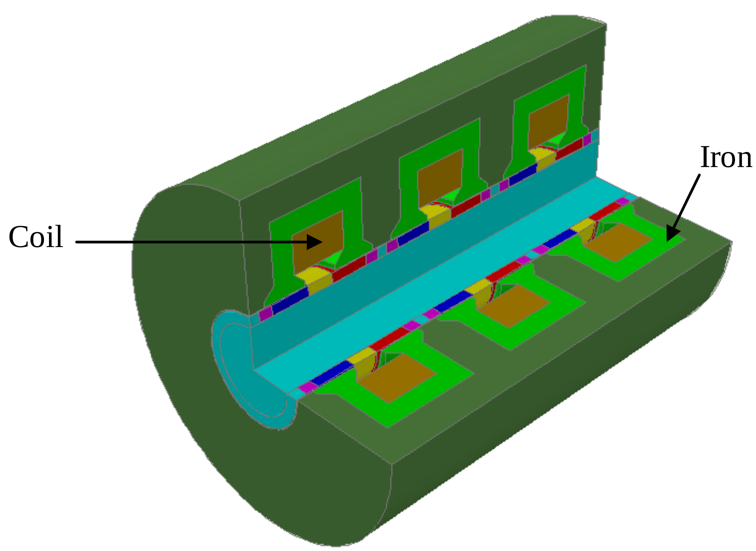

Figure 16 3D view of air-cored quasi-hallbach magnetised machine with rectangular magnet

4.1.2 Air-cored Quasi-Hallbach Magnetised Machine with Trapezoidal Magnet.

In the second design, the trapezoidal NdFeB permanent magnets are used instead of rectangular magnet. The advantage of trapezoidal magnet is it will eliminate or reduce the irreversible demagnetization at the top corner of axially magnetised permanent magnet and the bottom corner of radially magnetised permanent magnet [14]. Figure 17 shows the three dimensional (3D) view of air-cored quasi-hallbach magnetised machine with trapezoidal magnet.

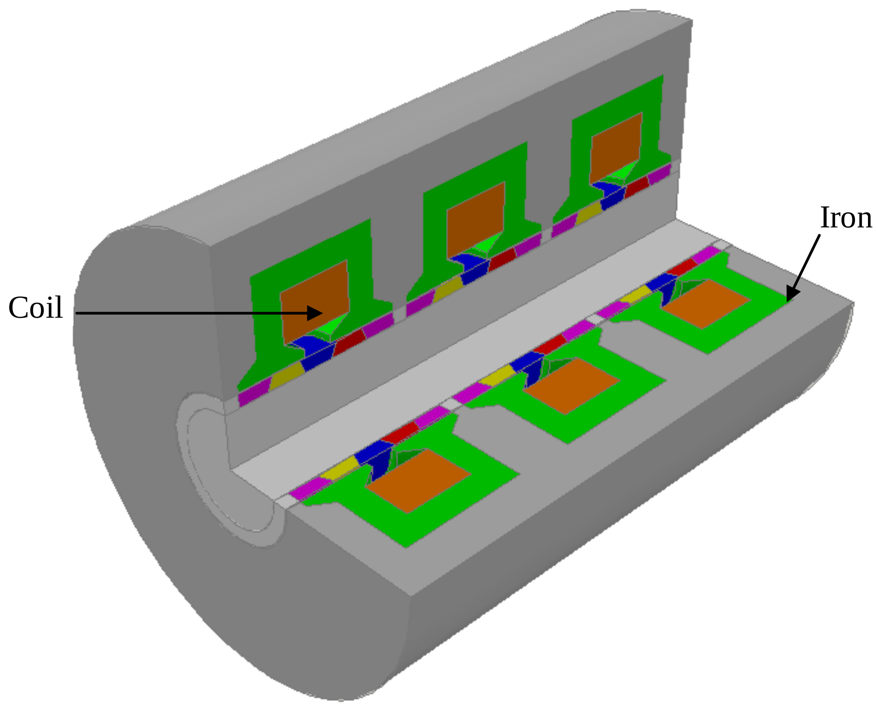

Figure 17 3D view of air-cored quasi-hallbach magnetised machine with trapezoidal magnet

4.2 Finite Element Analysis of Air-cored Quasi-Halbach Magnetised Machine with Rectangular Magnet

Figure 18 and 19 show the magnetic flux distribution for the air-cored quasi-hallbach magnetised machine with rectangular magnets when the moving magnet is at initial position, z=0mm and at maximum stroke position, z=18mm, respectively. In both cases, the frequency is set to zero and no load is applied to the motor. From the figure below, the magnetic flux is almost symmetry at both tooth of the iron core. This shows that the configuration of the permanent magnet is correct. There is no magnetic flux passing through the back iron of the stator because the magnetisation vector of permanent magnet set A is cancelling the magnetisation vector of permanent magnet set B.

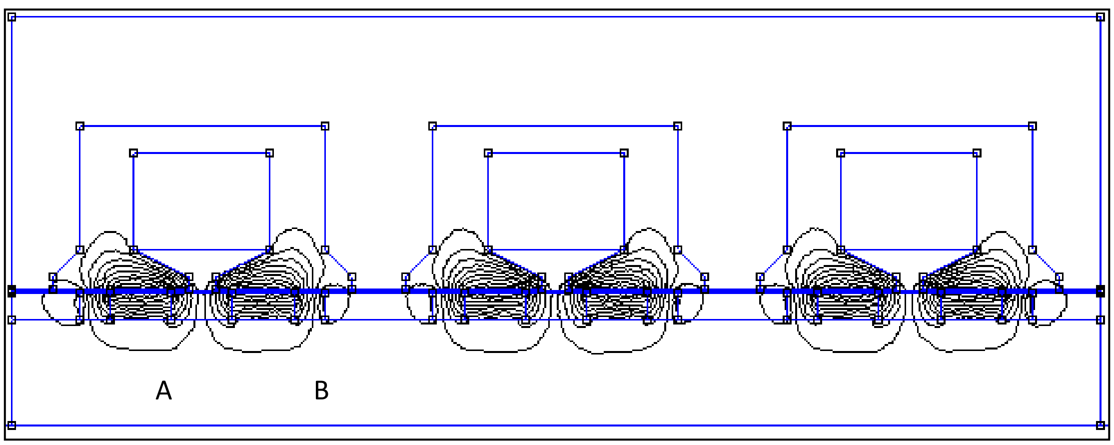

Figure 18 Magnetic flux distributions at initial position, z=0mm

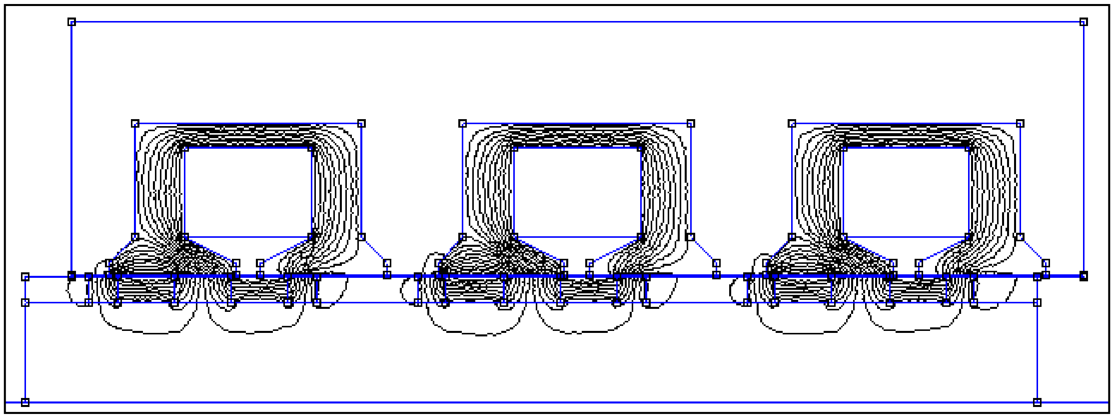

Figure 19 Magnetic flux distribution at maximum stroke position, z=18mm

Figure 20 shows the magnitude of air-gap magnetic flux density. There is a drop of magnitude of air-gap flux density at several points along the axial length of the machine. This is due to the slot effect of the machine. Besides that, the selection of good size of mesh will determine the accuracy of the result of finite element analysis of the generator especially the size of the mesh of the air gap between the stator and the moving permanent magnet. In this analysis, air gap region is divided into four regions with mesh's size of 0.2mm of each region.

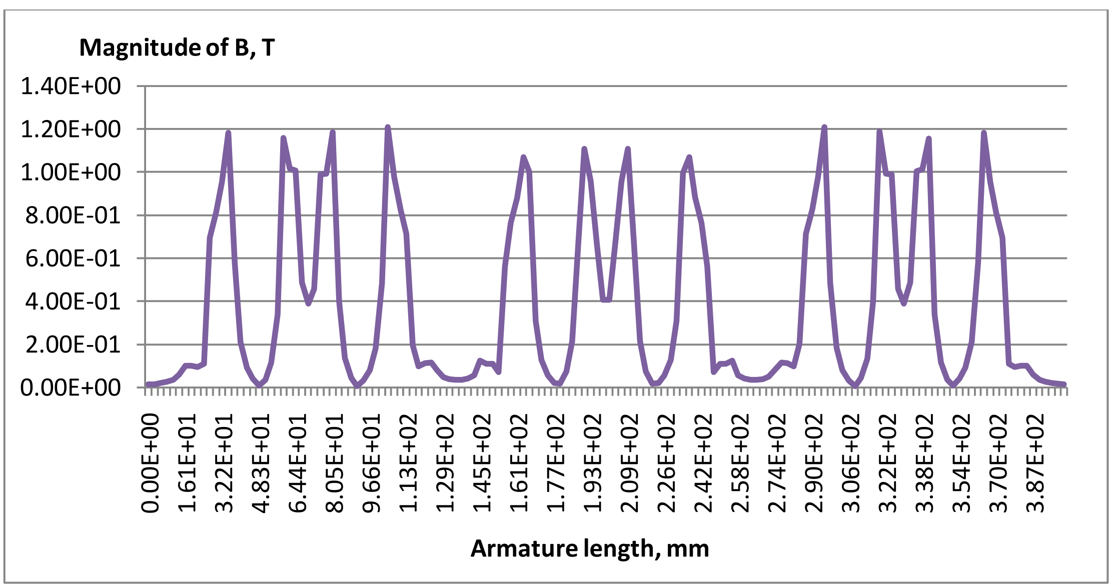

Figure 20 Magnitude of air-gap magnetic flux density

The design parameter of the machine has been optimised in terms of the ratio of radially magnetised magnet's length, T_{mr} over pole's length, T_p. The optimum $\frac{T_{mr}}{T_p}$ ratio is determined by analysing the efficiency of the machine. The analysis of the machine output power is done as per phase. That means the first phase of the machine only is analysed using finite element method (single phase of the motor is shown in Figure 21). This is because in three phase system, the total output power of the machine is three times the power of single phase machine. 2.5A current is supplied to the machine at the frequency of 50Hz while the number of turns of the coil is set to 1680 turns. The result of the simulation is shown in Table 2 and Figure 22.

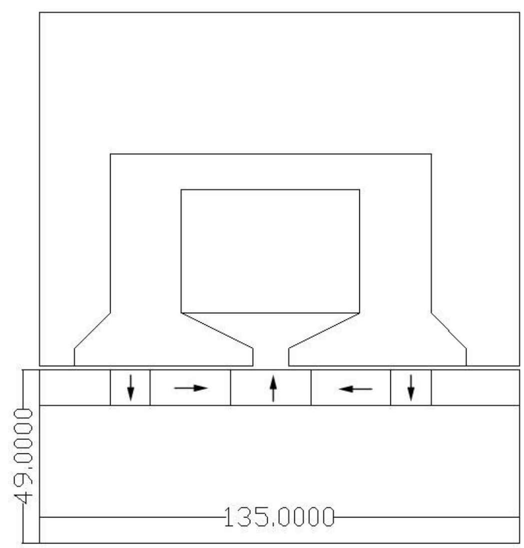

Figure 21 Single phase air-cored quasi-hallbach magnetised machine with rectangular magnet

Table 2 Comparison of machine's efficiency with varying T_{mr}/T_p

T_{mr}/T_p	T_{mr} (mm)	T_p (mm)	P_{in} (W)	P_{loss} (W)	P_{out} (W)	Efficiency,η (%)
0.4	18	45	1358.93	295.72	1063.20	78.24
0.45	20.25	45	1363.75	296.10	1067.65	78.29
0.5	22.5	45	1354.68	259.02	1095.66	80.88
0.55	24.75	45	1358.22	295.59	1062.63	78.24
0.6	27	45	1365.19	296.35	1068.84	78.29

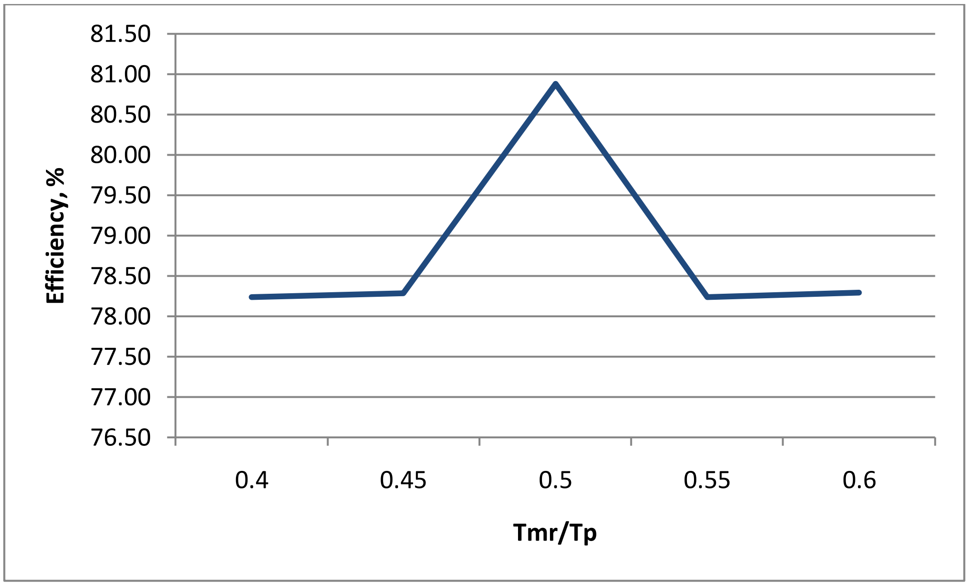

Figure 22 The graph of machine's efficiency versus T_{mr}/T_p.

4.3 Finite Element Analysis of Air-cored Quasi-Halbach Magnetised Machine with Trapezoidal Magnet

Figure 23 and 24 show the magnetic flux distribution for the air-cored quasi-hallbach magnetised machine with trapezoidal magnets when the armature is at initial position (z=0mm) and at the maximum stroke position (z=14mm). In both cases, the frequency is set to zero and no load is applied to the motor.. From the figure below, the magnetic flux is almost symmetry at both tooth of the iron core. This shows that the configuration of the permanent magnet is correct.

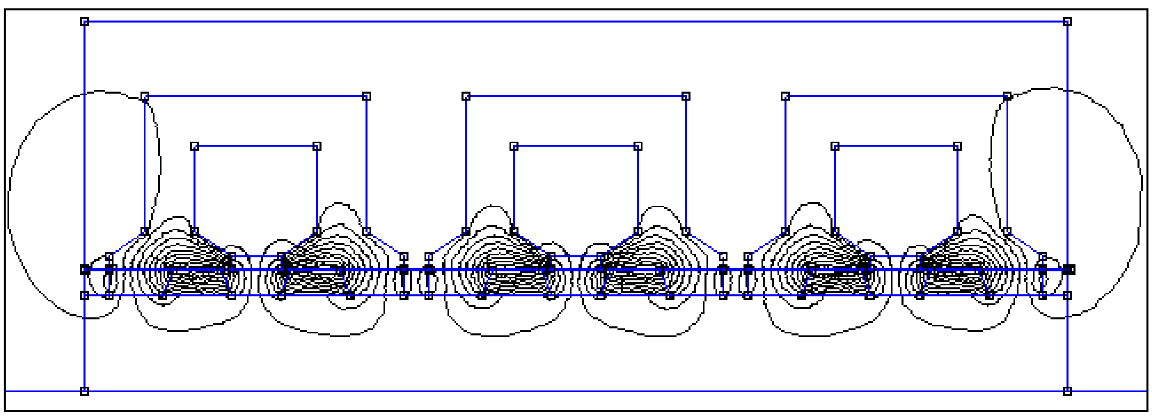

Figure 23 Magnetic flux distributions at initial position, z=0mm

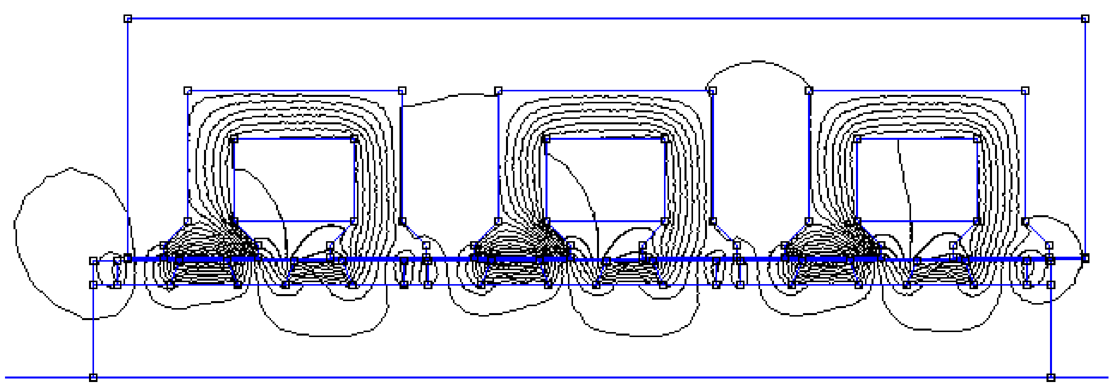

Figure 24 Magnetic flux distributions at maximum stroke position, z=14mm

Figure 25 shows the graph of magnitude of air-gap magnetic flux density versus the length of the machine. The maximum magnitude of magnetic flux density is about 1.27T. It is higher than the maximum magnitude of magnetic flux density of air-cored quasi-Halbach magnetised generator with rectangular magnet which is 1.20T. Therefore, trapezoidal quasi-hallbach magnet increases the magnetic flux density at the air gap.

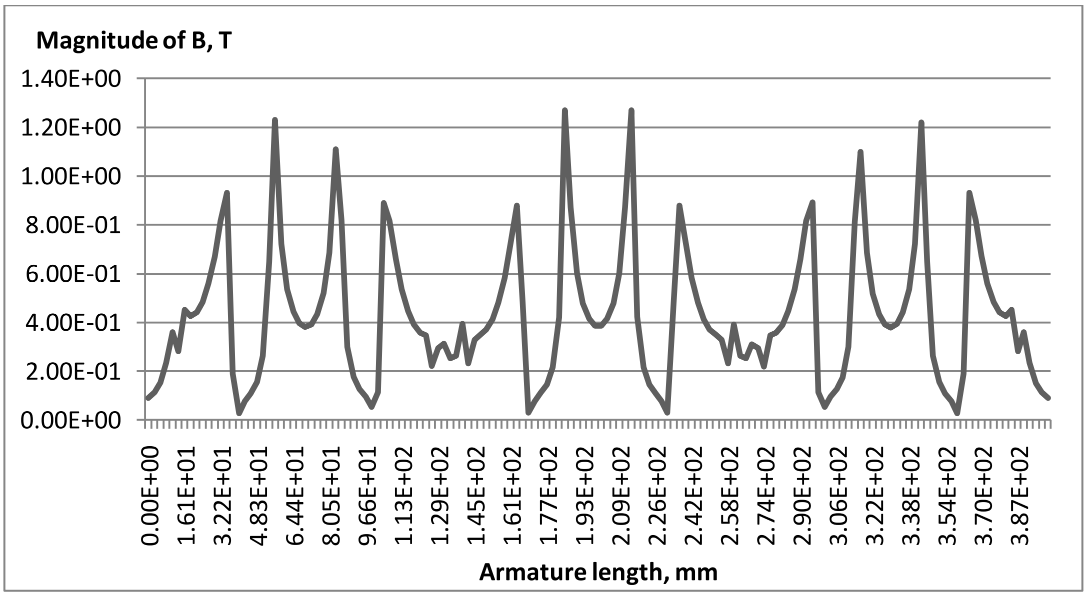

Figure 25 Magnitude of magnetic flux density at the air gap

CHAPTER 5
CONCLUSION AND RECOMMENDATION

5.1 Conclusion

Literature review on various linear machine topologies has been done and the topologies can be grouped into three groups which are moving-coil, moving-iron and moving-magnet machine. Based on that information, moving-magnet topology has been selected for designing two designs of long stroke linear permanent magnet machine which are air-cored quasi-hallbach magnetised machine with rectangular magnet and air-cored quasi-hallbach magnetised machine with trapezoidal magnet. Finite element analysis has been conducted on both machines and optimisation of the t_{mr}/t_p has been done to air-cored quasi-hallbach magnetised machine with rectangular magnet. Therefore, air-cored quasi-hallbach magnetised machine with rectangular magnet can be further developed for generating electricity from the ocean wave.

5.2 Recommendation

Base on the findings, further optimisation of the design will be focused on these parameters which are:

i. radius of the air-cored
ii. height of the permanent magnet

Besides that, further analysis will be carried out using analytical model to validate the finite element analysis result.

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APPENDICES

APPENDIX I - Planned Milestone for the First Semester of Final Year Project

No.	Detail/ Week	1	2	3	4	5	6	7	8	9		10	11	12	13	14	15
1	Selection of Project Topic	■									Mid-semester Break						
2	Preliminary Research Work Feasibility study of tidal wave generating system (tidal power, cost, energy policies and environmental effects)		■	■	■												
3	Submission of Preliminary Report				●												
4	Seminar 1					■	■	■									
5	Project Work i. Literature review of current linear machine topologies					■	■	■									
6	Submission of Progress Report								●								
7	Seminar 2								■	■		■	■	■			
8	Project work continues i. Identify factors that reduce machine efficiency ii. Proposed new topology iii. Analysis of magnetic flux distribution								■	■		■	■	■			
9	Submission of Interim Report Final Draft														●		
10	Submission of Interim Report															●	
11	Oral Presentation																●

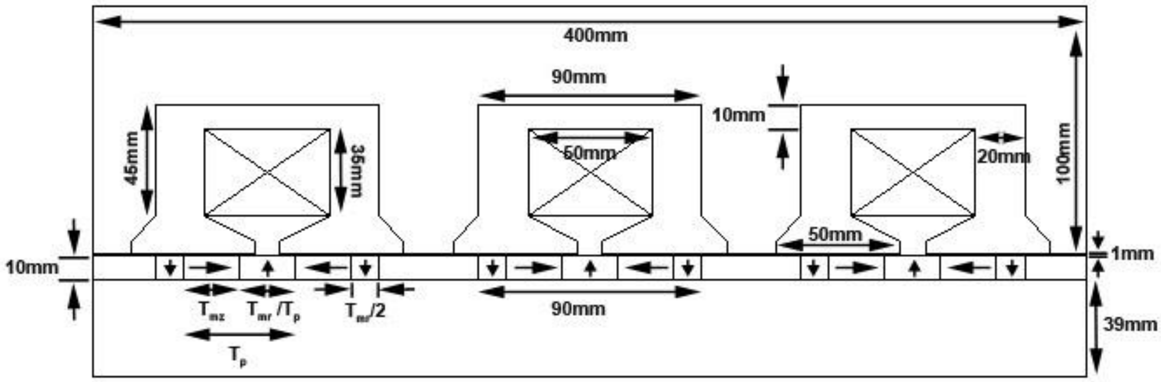
■ Process
● Suggested Milestone

APPENDIX II - Planned Milestone for the Second Semester of Final Year Project

No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14	19	20	21
1	Project Work Continue Learn using FEMM Refine the design geometry of the linear machine	■	■	■					Mid-semester Break										
2	Submission of Progress Report 1				●														
3	Project Work Continue Finite element analysis of the proposed design				■	■	■	■											
4	Submission of Progress Report 2									●									
5	Project work continue i. Optimise the design parameter of the machine									■	■	■	■	■	■	■			
6	Poster Exhibition											●							
7	Submission of draft report														●				
8	Submission of Dissertation (soft bound)															●			
9	Oral Presentation																●		
10	Submission of Project Dissertation (Hard Bound)																		●

■ Progress
● Suggested Milestone

APPENDIX III – Dimension Of Air-Cored Quasi-Halbach Magnetised Generator With Rectangular Magnets



APPENDIX IV – Dimension Of Air-Cored Quasi-Halbach Magnetised Generator With Trapezoidal Magnets