DESIGN AND MODELLING OF A LINEAR GENERATOR FOR WAVE ENERGY CONVERSIONS

By

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FINAL PROJECT REPORT

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

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CERTIFICATION OF APPROVAL

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Approved:

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Dr. Taib B Ibrahim
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

September 2013

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.

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Villasini Velautham

ABSTRACT

The positive development in science and technology nowadays has allowed us to harness energy from renewable sources. Much attention is given to wave energy as it holds enormous amount of untapped energy and it has a great potential in electricity generation these days. There are several methods in harnessing energy from wave such as oscillating water column, overtopping device, hinged contour device and floating buoy technologies. Existing linear generators used in Wave Energy Converters (WEC) are in large scale. This phenomenon has been limiting some end- users like fishermen from benefiting from this. Therefore, an inexpensive, small-scaled, mobile and efficient power producing system is needed. In this report, the Wave Energy Converter (WEC) that is used is the floating buoy method where the buoy is attached to the rope and a linear generator installed at the sea bed. A linear generator with the permanent magnet, tubular orientation, and iron-cored stator is proposed to be installed to the floating buoy WEC. The magnets have been used as the moving part where two new shapes of magnet were introduced; i.e. triangular shape and trapezium shape. The models have been simulated and analyzed using finite element software Ansoft Maxwell. The open-flux, air gap flux and back EMF distributions were investigated for two different designs. The results obtained were further analyzed where the design is further optimized for continuous improvement to achieve the best configuration of the linear generator.

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CHAPTER 1

INTRODUCTION

1.0 Project Background

The positive development in science and technology nowadays has allowed us to harness energy from renewable sources. The focus on generating electricity from renewable sources is once again an important area of research with global attention being drawn to climate change and the rising level of CO2 [1]. Therefore, much attention is paid to wave energy nowadays. Using waves as a source of renewable energy has became crucial after the oil crisis in 1970's. Figure 1.1 shows the renewable energy consumption around the world.

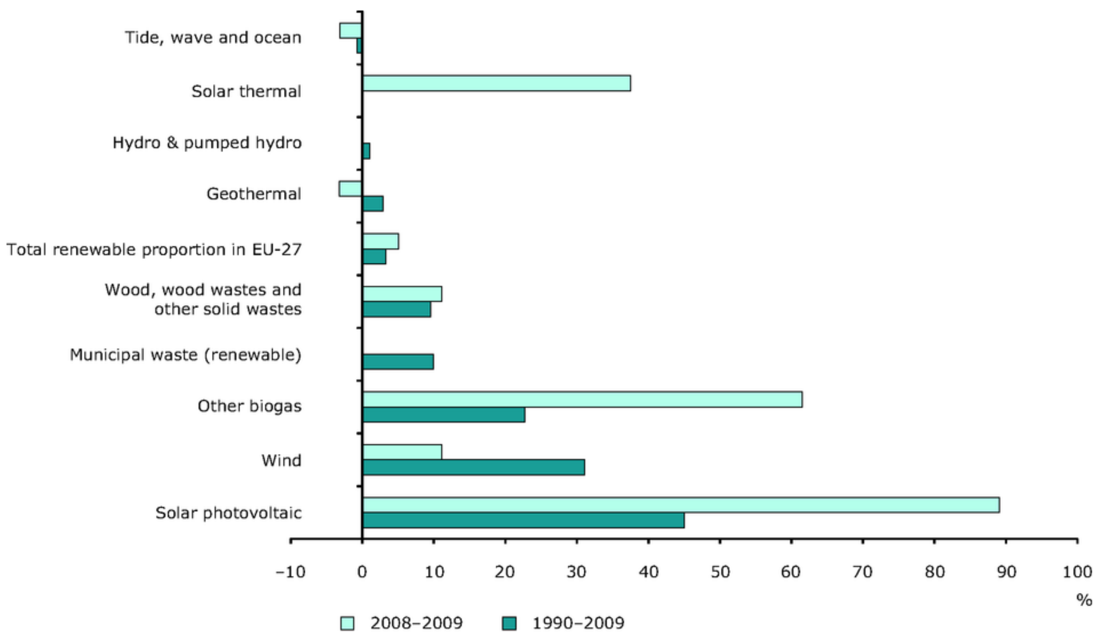


Figure 1.1: Average annual growth rates of renewable energy in electricity consumption (EU-27) for 1990-2009 and 2008-2009(EEA, 2012) [1].

Whenever a wind passes over the surface of sea, waves are generated. When the waves propagate slower than wind speed just above the waves, there is a definite energy transfer from the wind to the waves.

Air pressure differences between the upwind and the lee side of a wave crest as well as friction on the water surface by wind, will make the water to go into the shear stress causes the growth of the waves as shown in Figure 1.2. Wave energy is believed to hold a great potential for extracting energy from as ocean waves are huge and they have largely untapped energy resource.

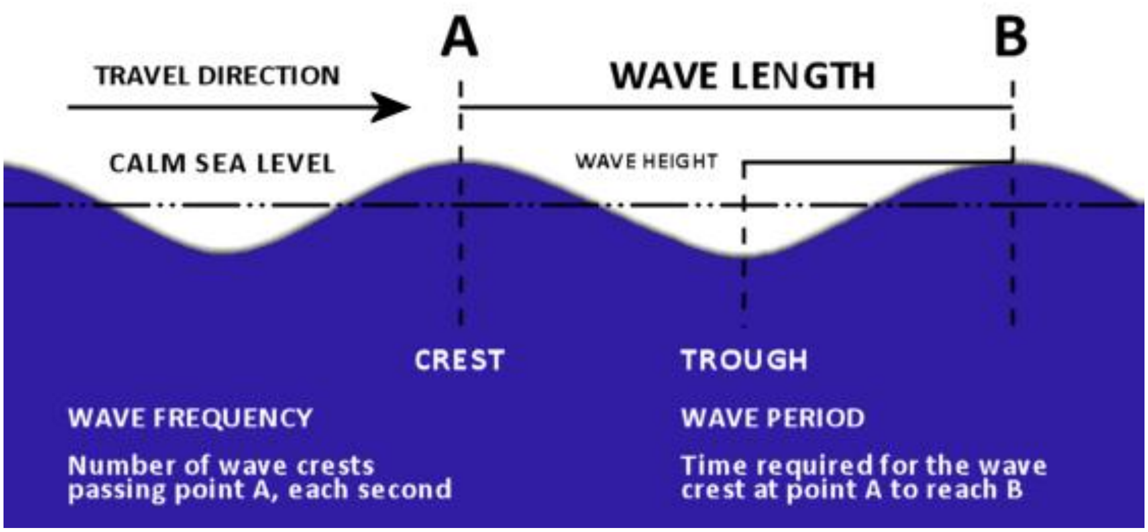


Figure 1.2: Wave forming [2].

The wave park idea which was suggested by a team from Oregon State University is highlighted where the linear generator is installed in seabed which is attached to a rope. This rope will be attached to a buoy which is floating on the surface of the sea. Therefore, when the buoy moves according to the waves, the rope attached to it also moves and a moving coil, moving core or moving magnet within the generator will generate electricity. Figure 1.3 shows the Oregon State University Conceptual Park that has been developed by Oregon State University.

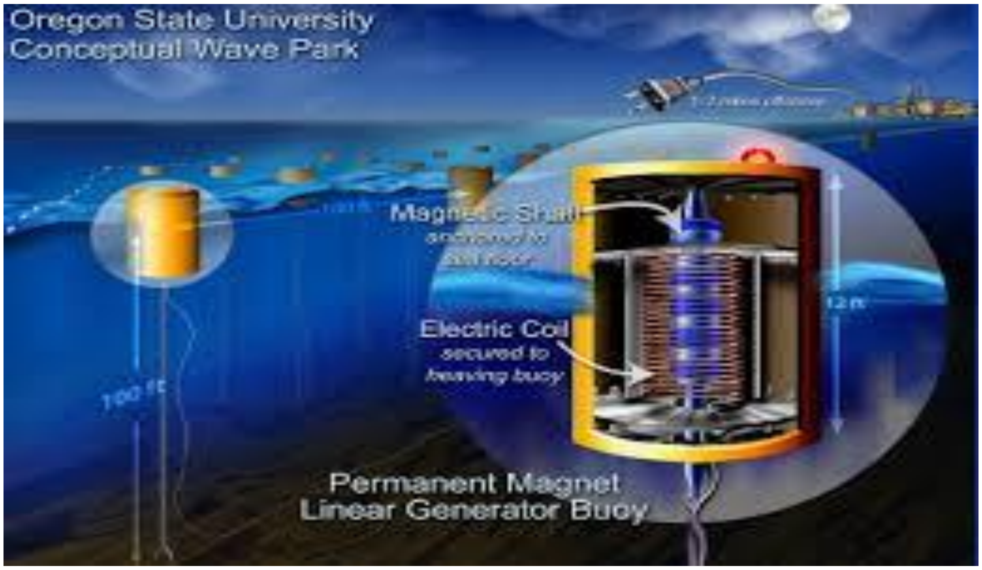


Figure 1.3: Oregon State University Conceptual Park [2].

1.1 Problem Statement

Existing linear generators used in Wave Energy Converters (WEC) are in large scale as shown in Figure 1.4. This phenomenon has been limiting some end-users like fishermen outdoor activities users benefiting from this. Therefore a small scaled, mobile, high efficiency and low-cost linear generators are crucial in a WEC to produce a single phase power output of 1kW. This can be beneficial to the fishermen for outdoor activities.

Figure 1.4: Oscillating water column (OWC) [2].

1.2 Objective& Scope of study

The main objective of this project is to propose a design of the linear generator to be used in a Wave Energy Converters (WEC) which can be beneficial for the fishermen and outdoor activities. In addition to this, the other sub-objectives are:

i. To conduct literature review on existing WEC Technologies in order to choose the most suitable design.

ii. To propose new designs of a linear generator which is efficient, low cost, mobile and small in size to allow the fishermen to benefit from it.

iii. To simulate and optimize the proposed design by using finite element method using ANSYS software.

1.3 Project Relevancy

This project acquires the knowledge and application of electrical and electronics field of study especially in designing a linear generator that is practical and efficient enough to be used in a wave energy conversion system. The knowledge in using the finite element software, Ansoft Maxwell is also crucial to simulate the proposed designs and to analyze the design against the investigated parameters such as air-gap flux distribution, back EMF and open flux distribution. Through this project which involves a lot of engineering disciplines, it is definitely relevant to meet the purpose of this final year project.

a. Feasibility of the project

The project will be conducted in two semesters which include three major phases which will be designing, simulation and optimization of the linear generator. In the first semester, focus will be more on proposing new designs of the linear generator and simulating the design using finite element software. The following semester will be focused primarily on enhancing or optimizing the design to obtain the best outcome of the linear generator. The objective is to design a linear generator that can generate electricity to for other suitable components in a fishermen’s boat. Finite element software, Ansoft Maxwell which is Finite element software will be used to simulate the design against parameters like air-gap flux distribution, back EMF distribution and open-flux distribution. This software is available as one of the university facility and this makes project feasible to be completed within the time frame.

b. Scope of research

Table 1.5: Scope of research planned for Semester 1 and 2

Semester	Scope of activities
Semester 1	1. Identifying on which WEC to choose 2. Choosing machine type : permanent magnet, DC machine, induction machine or synchronous machine 3. Identifying generator type to be used: rotary or linear on the WEC 4. Choosing between a tubular type or planar 5. Choosing between air-cored or iron cored linear generator 6. Choosing among three conditions: magnet moving, coil moving or core moving 7. Choosing the best permanent magnet configuration to enhance the design: radial, axial and Hallbach 8. Two designs with two different shapes of magnet will be proposed
Semester 2	1. The proposed design is analysed using finite element analysis 2. Design is analyzed against three parameters air-gap flux distribution, open-flux distribution and back EMF. 3. In order to be more efficient, the design is further optimized to achieve the best configuration

CHAPTER 2

LITERATURE REVIEW

2.0 Introduction

In the process of designing linear generator for wave energy conversions, literature reviews of past studies and researches need to be done in order to produce a good design. First the evolution of wave energy will be studied. Then, different types of linear generator will be studied thoroughly and compared to select the best possible alternative to be used for wave energy conversions. Various design configurations of the selected linear generator will be studied focusing in obtaining higher output power.

2.1 Wave energy

Wave energy is a renewable energy where the energy can be harnessed from the waves. Waves get their energy from wind passing over the surface of sea [2].

2.1.1 The wave energy conversion process

The basic principle in wave energy conversion is that a device which can effectively generate waves can also be used to effectively absorb waves [3], [4]. If wave energy is needed to transport to a suitable form one place to another, Wave Energy Converters (WEC) is needed where it can fulfill the demand. Despite considering seawater desalination [5], the most practical way to harness wave energy is by converting it into electricity and injecting it to the utility grid [6]. From there, it will be made available to the users.

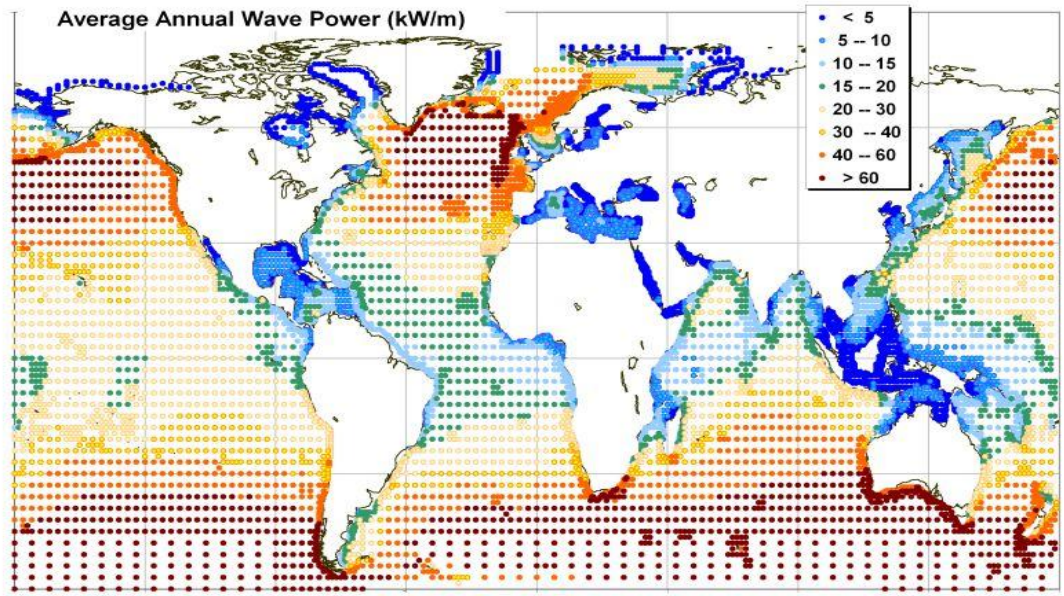


Figure 2.1: Average annual wave power measured in kW per meter [7].

2.2 Classification of WECs

Even though there are more than 1000 wave energy conversion techniques have been discovered around the world, WECs are generally categorized by type and location [1]. According to Vermaak, 2012, the basic operating principles of the three main categories are considered by way of examples.

a) Oscillating Water Column (OWC)

An OWC consists of a chamber with an opening to the sea below the waterline. As waves approach the device, water is forced to feed into the chamber. Thus, pressure is applied on the air inside the chamber. The trapped high pressured air will escape to atmosphere through turbine [1]. Figure 2.2 shows an Oscillating Water Column (OWC) using a Wells Turbine to convert wave energy to electricity.

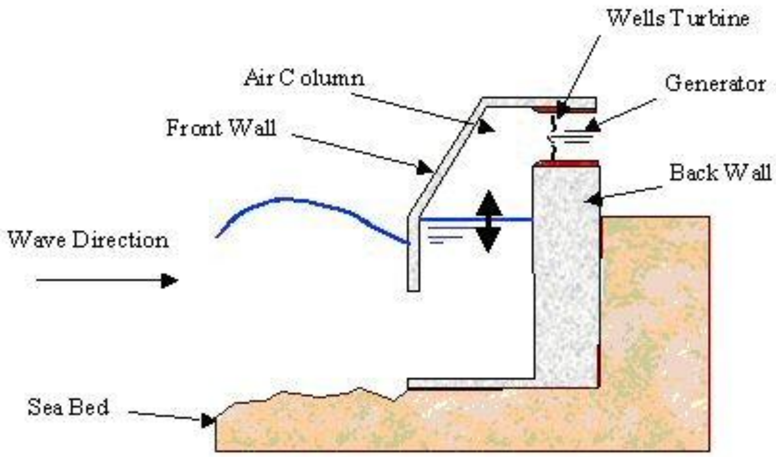


Figure 2.2: Oscillating water column (OWC) [8].

b) Overtopping devices

Sea water is captured by an overtopping device in a reservoir above the sea level [1]. Overtopping devices collect water in a reservoir and thereby convert wave energy to potential energy [9]. Figure 2.3 shows an Overtopping device using a reservoir to turn the turbine.

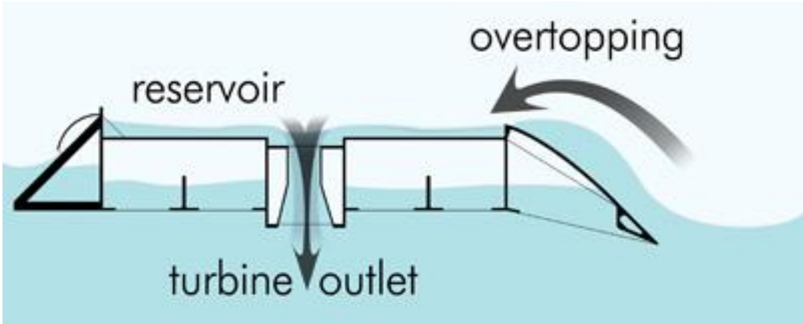


Figure 2.3: Overtopping system [10].

c) Hinged Contour device (HCD)

Cylindrical units are connected by hinges. These units will move according to the wave when the wave passes through it. These hinges will generate the power. The Pelamis is one of the examples of HCD and is shown in Figure 2.4. [11][12].

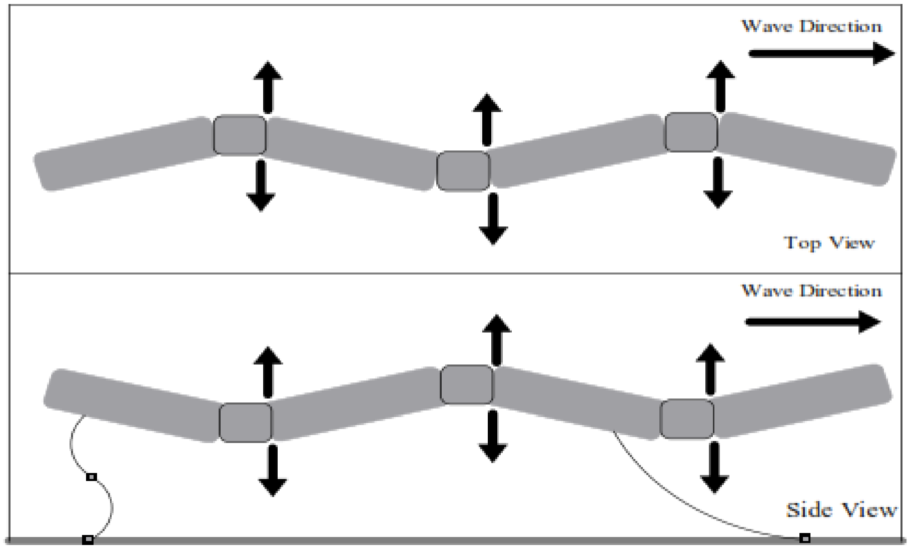


Figure 2.4: Pelamis System [13]

d) Buoy Technology Wave Energy Conversion (BTWEC)

   BTWEC is used to harvest energy from all the directions at one point and also called as point absorber. It is an offshore device located near the ocean surface [13]. According to H. Khalid et al. [13], the BTWEC can be classified into two main categories namely submerged and floating buoy technologies as shown in Figure 2.5.

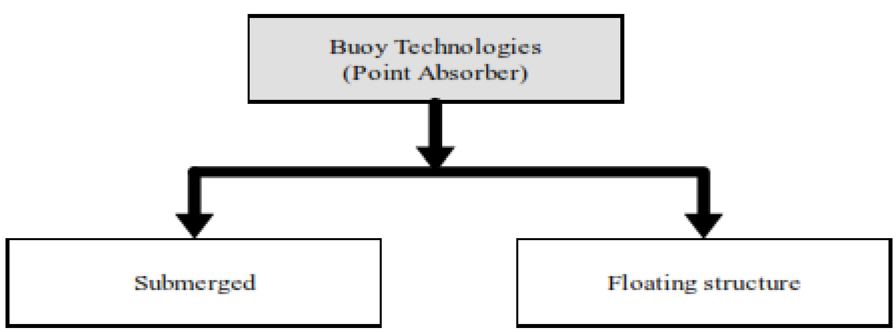
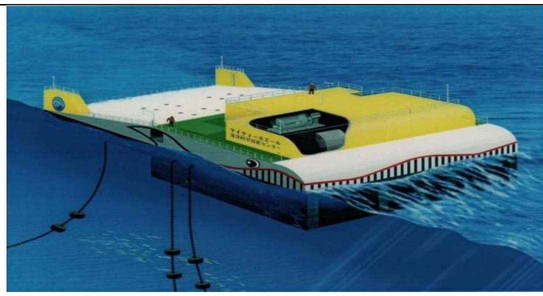
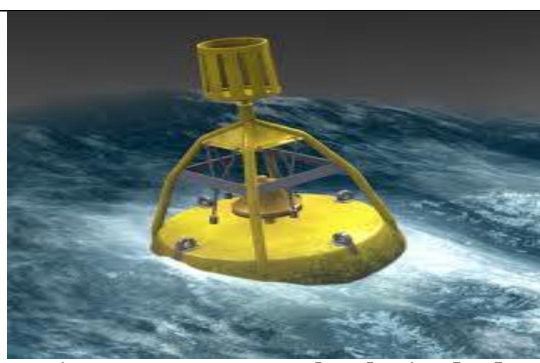


Figure 2.5: Buoy technologies [13]2.3 Comparison between the types of WECs

Table 2.2 shows the comparison between the Wave Energy Conversions (WEC) to show the distinct differences.

Table 2.2: Comparison between the types WECs

WEC TYPE	ADVANTAGE	DISADVANTAGE
 **Figure 2.6: OWC [15]**	Simple, robust and easy to be build on land	High initial building cost Can be an eyes sore as the landscape changes
 **Figure 2.7: Overtopping device [16]**	Not dependant of resonance with the waves; therefore constructed very large [16].	Controlling the output and stabilizing might be an issue due to the floating structure to optimize power output [16].
 **Figure 2.9: Buoy technologies [17]**	Can be used in a small scale, mobile or portable, low-cost and the power take-off method is simpler.	Lower power output compared to other technologies

Since this linear generator will be designed for fishermen to benefit from it, the most suitable WEC that can be used is the Buoy Technologies Wave Energy Converter Technologies. To be specified, Floating Buoy Technologies (FBT) will be used to achieve the objective. Since the design of the linear generator has to compromise with small scale factor, mobile, low-cost and high efficiency and low-cost, this method or technique has been identified as the best. Figure 2.10 shows the floating buoy system with the linear generator. There are several solutions for placing the linear generator WEC components and Figure 2.11 is showing the example of placement.

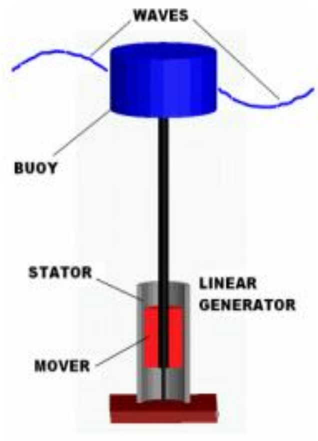


Figure 2.10: Floating buoy system with the linear generator [18]

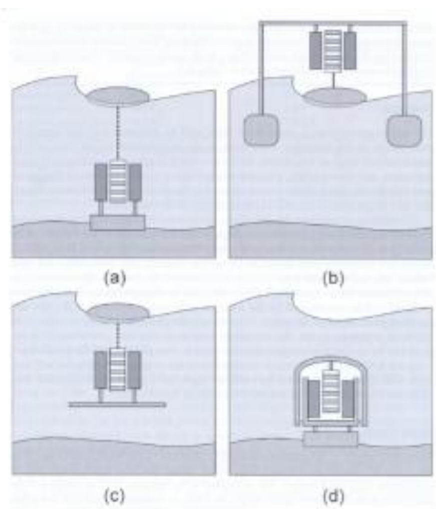


Figure 2.11: Various solutions for placing the linear generator WEC components [19]

2.4 Linear generator vs. rotary generator

As shown in Figure 2.12, the power take-off method from WEC technology, linear electrical generator is the best attached with the Floating Buoy Technologies (FBT) as it is simpler to construct. Simpler also means low-cost. Therefore a linear generator will be the best for FBT system. The design of linear generator will be discussed further.

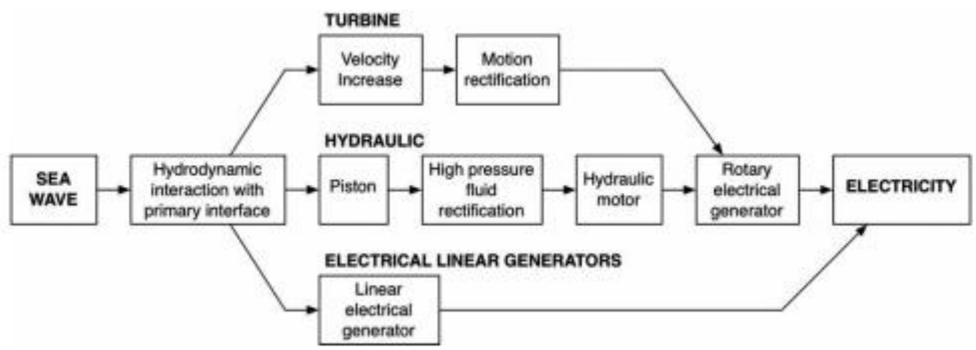


Figure 2.12: Power take off mechanisms using linear and rotary electrical generator [1].

2.5 Linear generator type

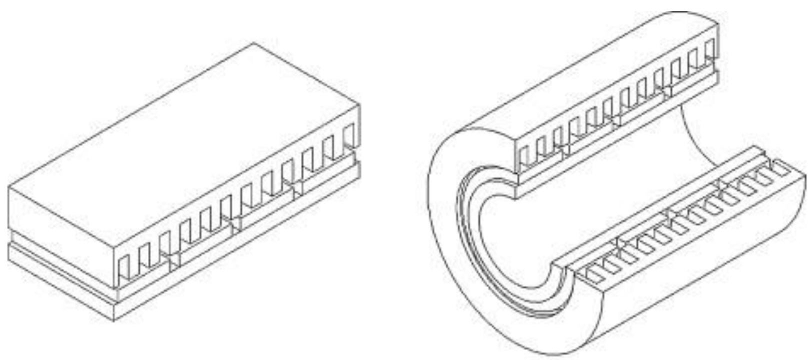
Linear generator is a device that converts mechanical energy to electrical energy and it moves or slides along one direction which can be x-axis or y-axis. There are many types of linear generator that can be used for wave energy conversions such as induction generator, synchronous generator, direct current generator, and permanent magnet generator. Each type of generator has its own advantages and drawbacks. In order to show a distinct comparison between the generators, Table 2.2 is tabulated in term of performance and feasibility for wave energy conversion.

Table 2.2: Comparison between the types of generators

Linear generator type	**Advantage/Disadvantage**
Induction generator	Advantage: simple structure, high reliability, strong, no brushes needed, suitable for high circumferential speed of the generator. Disadvantage: poor starting torque, need high starting current, lagging power factor.
Synchronous Generator	Advantage: high efficiency at low speed, adjustable power factor, can operate at any speed. Disadvantage: collector rings and brushes required, speed variable is unable, starting torque is zero, needs DC excitation from external source.
DC Generator	Advantage: high starting torque, rapid acceleration and deceleration, cheap, suitable for heavy jobs. Disadvantage: needs regular maintenance, require load before start-up.
Permanent Magnet Generator	Advantage: electricity is not required to magnetize, higher power and torque density, suitable for low load application Disadvantage: magnet installation is expensive, weight increases with size, high cogging torque

2.6 Tubular vs. Planar linear generators

An outcome of high performances at low speed and a simple structure, implying a high reliability is essential for a linear generator to be compatible with WEC. According to Oprea et. al [19] advanced bearing system is needed in non-tubular structures to compensate the high magnetic forces in the normal direction. Figure 2.13 shows the planar and tubular type permanent magnet machine.



(a) Planar linear PM machine (b) Tubular linear PM machine

Figure 2.13: Linear machines. [20]

Permanent magnet mover (slider), coil-wounded stator and windings are the main components of Tubular-type linear generator. There are three windings used and the Fill Factor is assumed to be near to 0.8. The slider of the machines is moved at 0.5m/s square wave, furthermore the slider consists of hollowed shaft and iron spacers which separates permanent magnet.

The core and the spacers are considered to be realized by using pure iron with nonlinear B-H curve. Magnetic flux paths are produced by iron poles while ring magnets on cylindrical mover are axially magnetized. Usually hallbach array magnets or radial magnets are mostly used in such machines. Table 2.3 shows the advantage and possible applications of a tubular type of a linear generator.

Table 2.3: Advantages of a tubular type of a linear generator

Advantages	1. Leakage is small due to its symmetric structure than that of the flat type one. 2. Shaft used is cylindrical so it's very convenient to connect with rod of engine piston. 3. Similarly it has less copper losses because the amount of coil is less and there is no end coil used [1]-[2]. 4. More efficient and reliable
Application	Can be best used in wave energy conversion

2.7 Air core vs. Iron core stator

Iron core stators are usually high cost, heavy and additional resources is required to install, stabilize and maintain. Iron core also suffers from cogging torque which is a resulting torque from the interaction between the permanent magnet of the rotor and stator slots of the permanent magnet. This torque is also knows as no-current torque. Cogging torque is an undesirable component for the operation of iron-core electric generators. It is especially prominent at lower speeds where windings on either the rotor or stator become worn or defective, highly skilled technicians are-required to conduct repair or maintenance. The heavy weight and unwieldiness of conventional iron-core stators also often require the use of machinery or teams of technicians to conduct even routine maintenance.

Therefore, the iron-cored stator generators disadvantages can be tackled using slotted stator topology. In addition, these air-cored machines suffer from large attractive forces between the two PM rotors and normally require a relatively large number of PM magnets to operate due to the fact that they have a relatively larger air gap between the rotors and stator. Since the linear generator that is needed to design will be operating at low speed, light weight, low cost. The iron-cored stator will be the best option.

2.8 Stator topology: Slotted

The PM Linear generators can be designed as single or multiple air-gaps with slotted or slotless designs or even totally ironless armature.

Table 2.8: Advantages and disadvantages of slotted design stators

Advantage	Stator topology	Disadvantage
Powerful Can be used in high power applications Inexpensive Easier to clean Robust Low noise	SLOTTED	Cogging torque is present due to steel shaft with permanent magnets Losses are high Damping losses are high

For wave energy conversions, it is for low power generating scale; therefore, the slotted topology will be used to propose the design of the linear generator.

In terms of delivering power, conventional slotted motors used to enjoy the advantage over slotless types, due (as noted) to the proximity of iron and magnets and the reduced air gap. Eliminating the teeth and using stronger magnets both serve to maximize the strength of the electromagnetic field for optimum power output. Rare-earth magnets, along with the fact that fewer coils, or "turns," of the wire are required in slotless motors, also help contribute to low electrical resistance, low winding inductance, low static friction, and high thermal efficiency in slotless motor types. One more important difference between slotless and slotted designs is the rotor diameter. Slotless motors have a larger rotor diameter than slotted construction for the same outside motor diameter and will generate a higher inertia, as well as accommodating more magnet material for greater torque.

2.9 Selection of moving part

The magnet volume needed to generate the field of a moving coil machine is much greater than moving magnet generator which produce same output and efficiency. Since magnets are by far the most expensive constituent of either type, moving coil applications are applicable for price insensitive applications. Advantage of the moving coil type is absence of radial forces, open circuit axial forces, and torques on the moving coil. Such effects are very important in linear machines. Radial forces can overwhelm gas bearings or even oil bearings and lead to lossy operation or failure. Moving iron was rotationally unstable in its air gap. If tilted, it tended to tilt further and close the gap, acting like a negative torsion spring with such a high spring constant that it defeated all attempts at stabilization by better initial alignment and greater mechanical rigidity. Moving magnet gives more efficiency. In this design, the linear generator will be have the magnet moving instead of coil or core moving based on practical concerns.

2.10 Magnet configuration

In this design, Hallbach type magnet configuration will be used. Figure 2.15 shows the radial, axial and Hallbach type of magnet configuration.

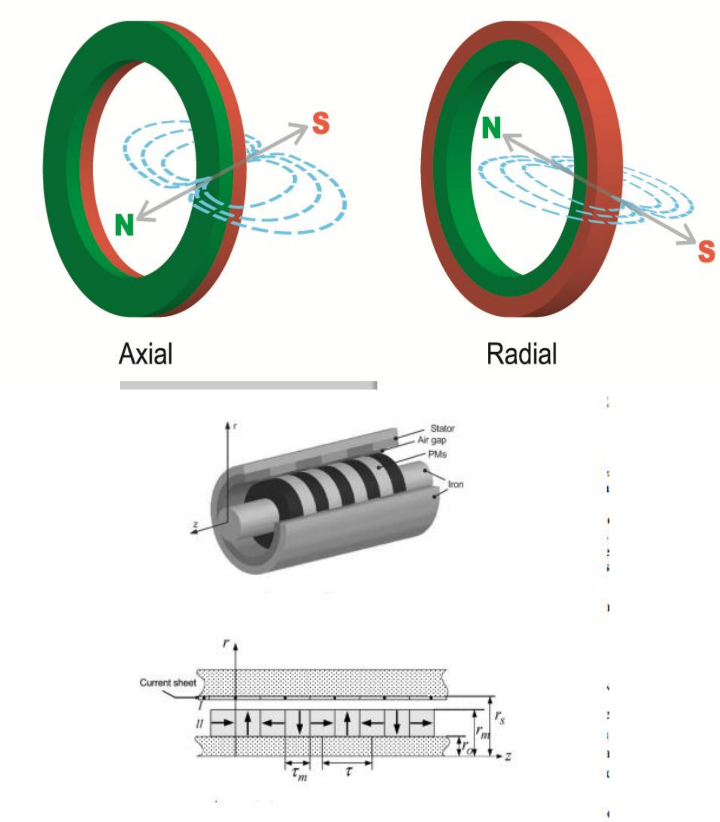


Figure 2.15: Radial, Axial and Hallbach type of magnet arrangement [20]

2.11 Conclusion

In this chapter, the design criterion of the linear generators has been discussed and analyzed in detail to select the best topology. The design will be produced according to the selected parameters as shown in Figure 2.16. Figure 2.16 shows the selected parameters (highlighted in yellow) that will be used in the linear generator design. In next chapter the design is proposed and dimensions of the linear generators are discussed.

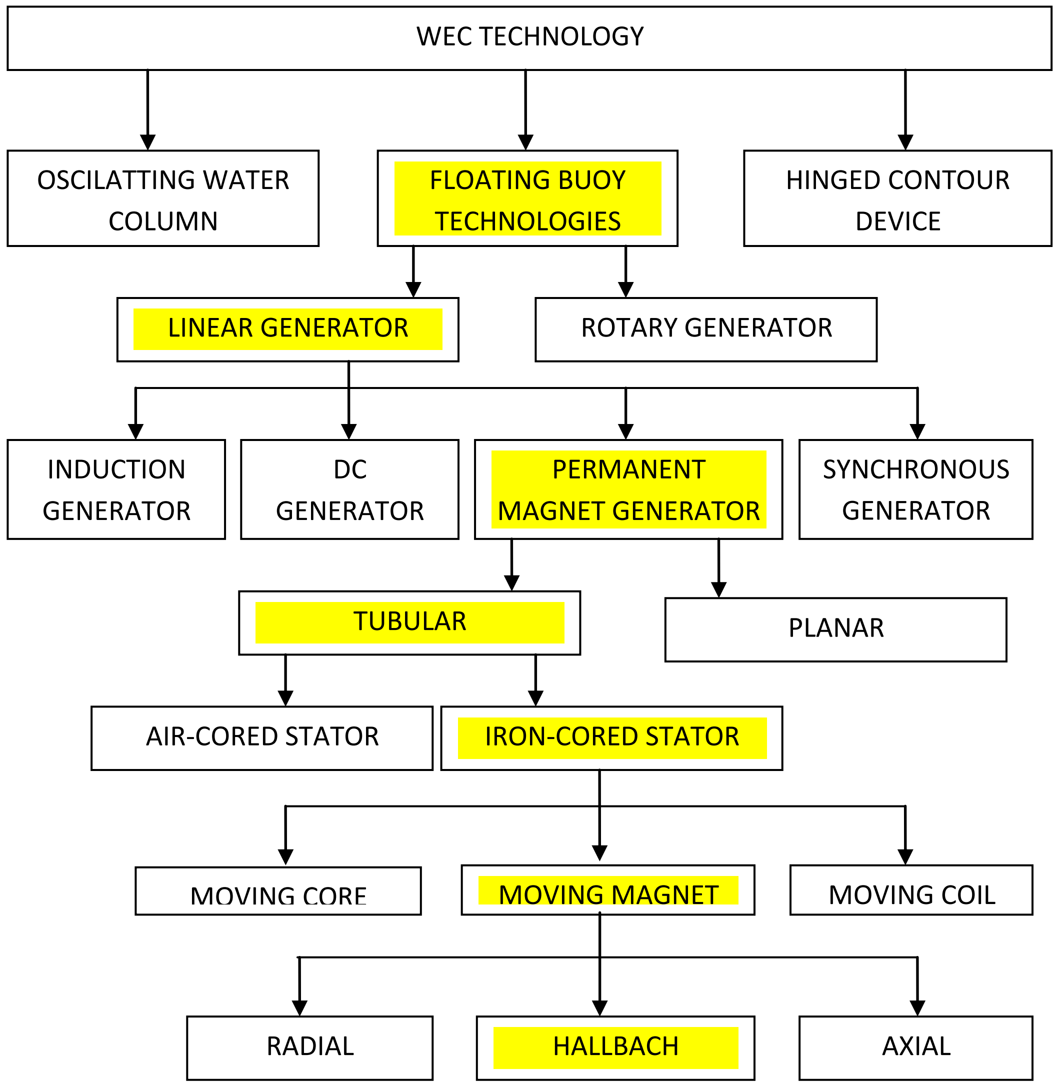


Figure 2.16: Selection design criteria on designing linear generator

CHAPTER 3

METHODOLOGY

3.0 Introduction

Achieving the objectives of this project within allocated time is crucial. Therefore a proper planning and scheduling is needed to complete the tasks within the timeframe. A good planning and scheduling will greatly influence the outcome of the project. In this chapter the research methodology will be discussed. The process flow and the tools required will also be discussed.

3.1 Research Methodology

In order to achieve the main objective of this project as stated earlier, the other sub-objectives need to be accomplished and analyzed well .For the first sub-objective which is to conduct a literature review on linear generator , a well structured literature review on selected suitable papers is done, focusing on the permanent magnet arrangement. Furthermore, the affecting parameters of a permanent magnet generator will be also paid attention to propose the best design.

Next, is to conduct a structured literature review on wave energy on the selected review papers to determine the current technology in Wave Energy Converter (WEC) Technology. The literature review will be focused mainly on the working principle of the existing types of converters and reviewing the advantages and disadvantages of each technology.

Following that, the proposed design model will be simulated using finite element software which is readily available in the lab. The results will be analyzed further to discuss on its performance and efficiency. The design will be compared against three parameters which are air-gap flux distribution, open-flux distribution and back EMF distribution. Finally, for the last sub-objective, the proposed design will be modified further after analyzing the result to further optimize the design configuration and will be analyzed again using the same method of finite element analysis.

3.2 Process Flow

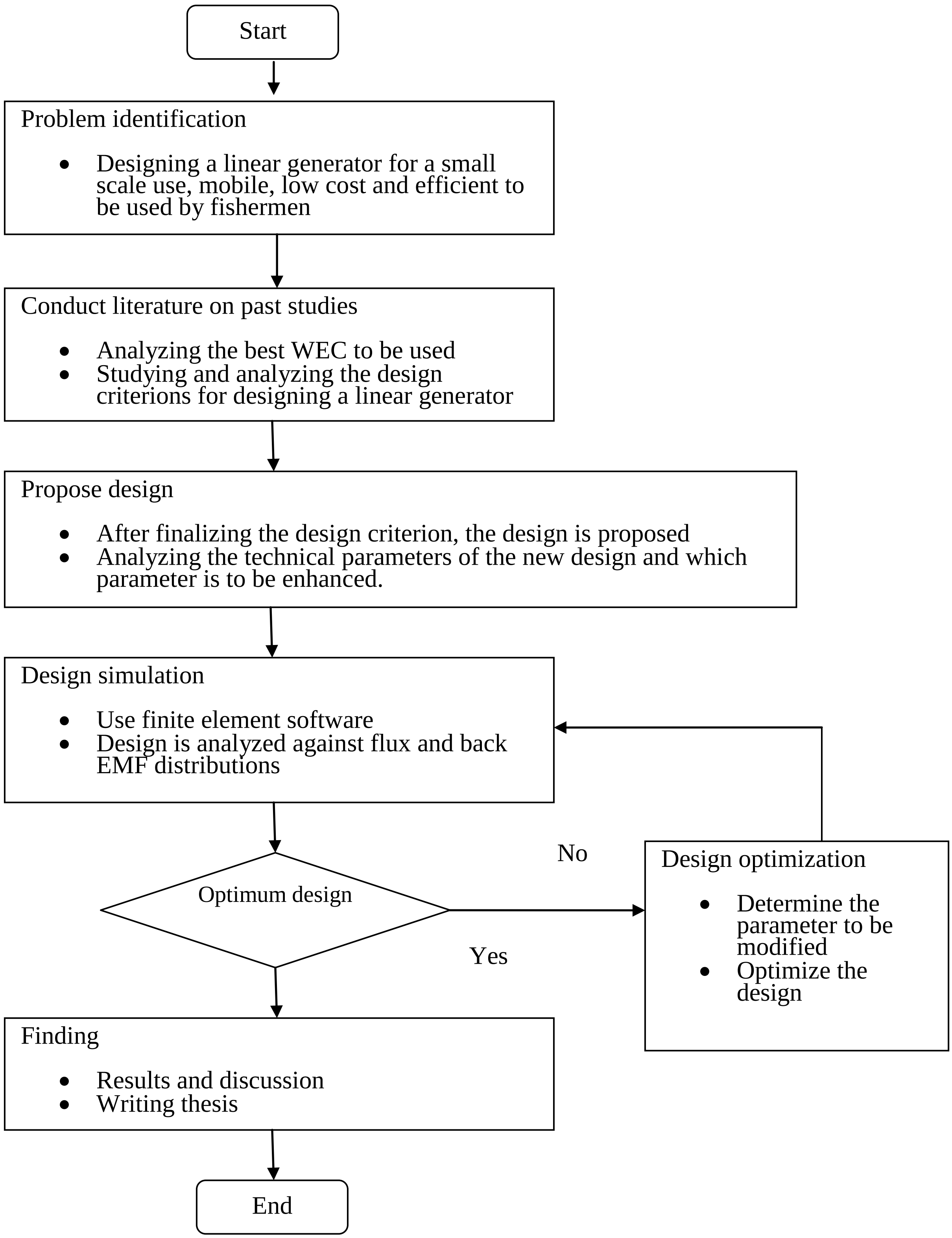


Figure 3.1: Project flow process3.3

Gantt Chart

Project Title: NOVEL DESIGN ON LINEAR GENERATOR FOR WAVE ENERGY CONVERSION											
Project Tasks	**Project**										
	2013										
	Jan	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*	*Sept*	*Oct*	*Nov*
Project Title Selection											
Planning & research phase											
Literature review											
Design and simulation phase											
Proposing design, simulating and analyzing											
Optimization of design phase											
Optimization of design if it's necessary											
Presentation phase											
Submission of Progress Report											
Pre-EDX											
Submission of Draft Report											
Submission of Dissertation											
Submission of Technical Paper											
Oral Presentation											
Submission of Project Dissertation											

3.4 Tool

Tool used to complete this project are listed in Table 3.1

Table 3.1: Tools used in completion this project

No	Software	Function
1.	AutoCAD	To design the linear generator of the model
2.	Ansoft Maxwell	To simulate and analyse the proposed design model
3.	Microsoft Excel	To tabulate result and findings
4.	Microsoft Word	To write the report

3.4.1 AutoCAD

AutoCAD is common and widely used software used by engineers and designers in fieldwork. The software can be used to design 2D and 3D design, modeling and architectural drawing. AutoCAD has a user-friendly interface that exhibits design a drawing model from a simple design to complex design. The AutoCAD drawing can be easily exported to Ansoft Maxwell for further analysis of the design. Therefore, AutoCAD is known as one of the most powerful tool for the design engineers.

3.4.2 Ansoft Maxwell

Ansoft Maxwell is a simulation driven product development software. This software predicts or anticipates how a design would function in a real world once it is being produced. Organizations usually use this software very confidentially to test the design against tested parameters to avoid creating wrong design.

CHAPTER 4

PROPOSED DESIGN

4.0 Introduction

Based on the literature review discussed in Chapter 2, the design criterions were finalized and there are many factors that can affect the performance of the linear generator. In this chapter the proposing two new shapes for Hallbach permanent magnet arrangement is introduced.

4.1 Design consideration

The primary objective of this project is to propose a new design of linear generator which is efficient, low cost, mobile and small in size which can generate electricity to allow the fishermen to benefit from it. Therefore some initial design considerations are crucial to justify the whole design. Before proposing the design, the design needed to be easy in manufacturing and produce god back EMF values. It has to be easy for manufacturing because complex designs may give a better result but the cost of manufacturing will be possible problem. Since the linear generator is for fishermen to benefit from, cheap cost is a very important parameter to be considered. Therefore, only a simple and easy manufacturing process is important in maintaining the cost. Back electromotive force (EMF) is a force produced to show the output of a generator. For back EMF considerations, higher back EMF means higher efficiency of the system.

4.2 Proposed design

In considering the design of linear generator, the design has to be simple and efficient, two new designs have been proposed such that these two new linear generators should has capable in generating electricity. The designs were modeled using Ansoft Maxwell software employing the actual dimensions of the model design.

Figure 4.1 and 4.2 show two different shapes of the permanent magnet arrangement of the proposed linear generator. The magnets arrangement used were Hallbach magnet arrangement. For both magnets, the material used was Neodymium (NdFeB). The moving part and unmoving part of the system is separated by air gap. The moving magnet part is seen as the translator where the translator will be attached to a rope. This rope will be further attached to a buoy floating on the surface of the sea. A major advantage of using a permanent magnet machine is its simplicity which does not require complicated installation and quite light for low load application.

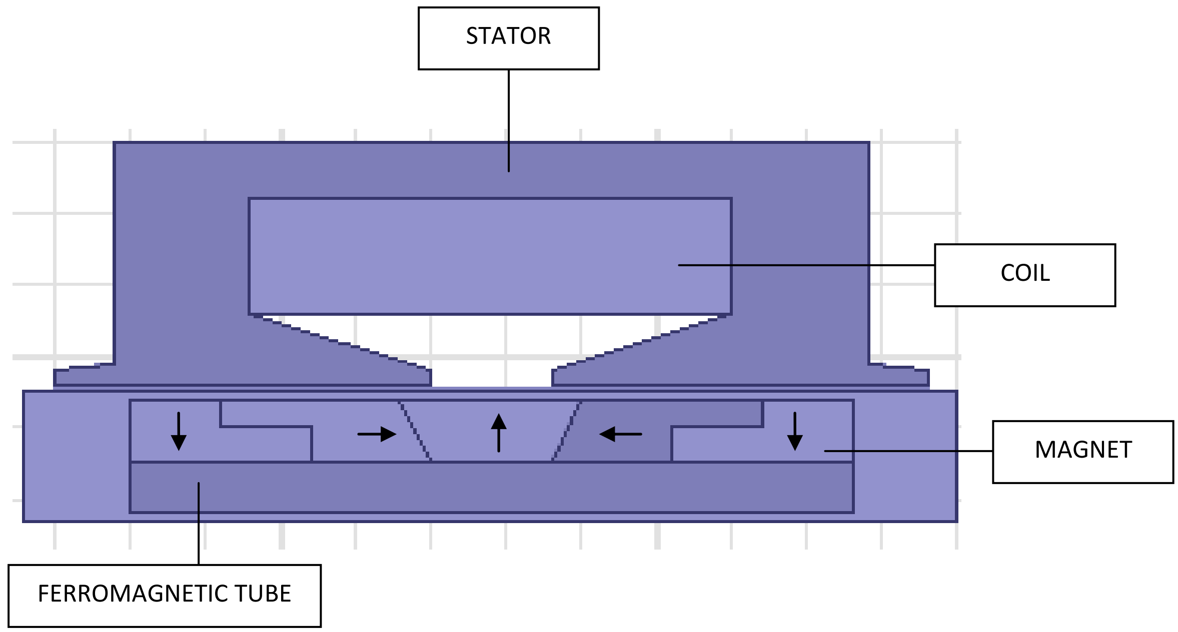


Figure 4.1: Proposed design A

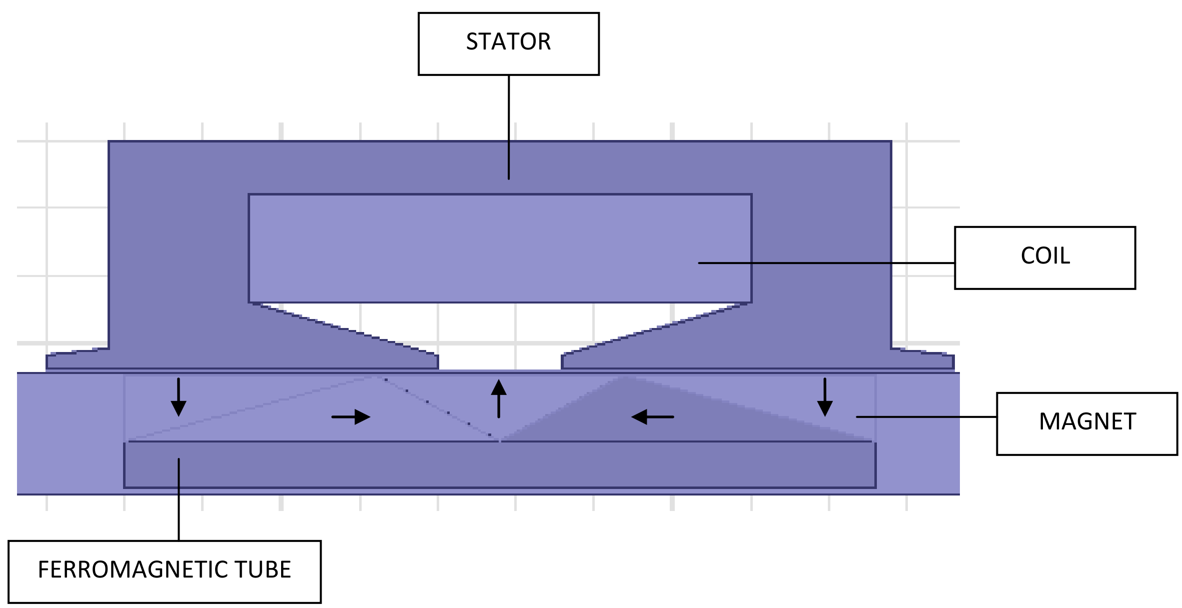


Figure 4.2: Proposed design B

The magnets are laminated with iron core to reduce the eddy current in the linear generator. A set of copper coil is fitted into the stator tooth of the generator to serve the purpose of producing electricity. Design A and B are having the same design parameters except for the shapes of permanent magnet arrangement that is introduced. Table 4.2 shows the tabulated design for both linear generators. Following that table is Table 4.3 showing the magnet parameters that is used for the proposed design.

Table 4.2: Design parameter for the proposed design

Parameters	Dimension (mm)
Stator outer diameter	50
Air gap	0.5
Permanent magnet thickness	5
Stator tooth length	17.5
Stator tooth width	25
Number of coil turns	500

Table 4.3: Permanent magnet parameters for the proposed design

Permanent magnet parameters	Value
Relative permeability, Mu	1.05
Bulk conductivity	625000siemens/meter
Remanence value, Br	1.029 Tesla

4.3 Conclusion

The design parameter shown was used to model the design using Ansoft Maxwell software. The design simulation will be further discussed in next chapter. Then the number of coil turns and air-gap distance is further adjusted and discussed in Chapter 6 to find the best configuration design of the linear generator.

CHAPTER 5

RESULT AND DISCUSSION

5.0 Introduction

In this chapter the simulation of the proposed design will be discussed. The focus here is to obtain and study the flux distribution as well as the back EMF of the linear generators.

5.1 Simulation Result

5.1.1 Open Flux Distribution

From the meshed part of the model, the simulations of the modeled designs were conducted to study the characteristic of flux distribution. To ensure no interference from the coil, the model is being simulated in static condition with 0A current from the coil. The vector directions for flux distribution need to be correct before we analysis with movement of the models. The result for Design A and B is shown in Figure 5.1 and 5.2 respectively when z – axis is set to 0 mm.

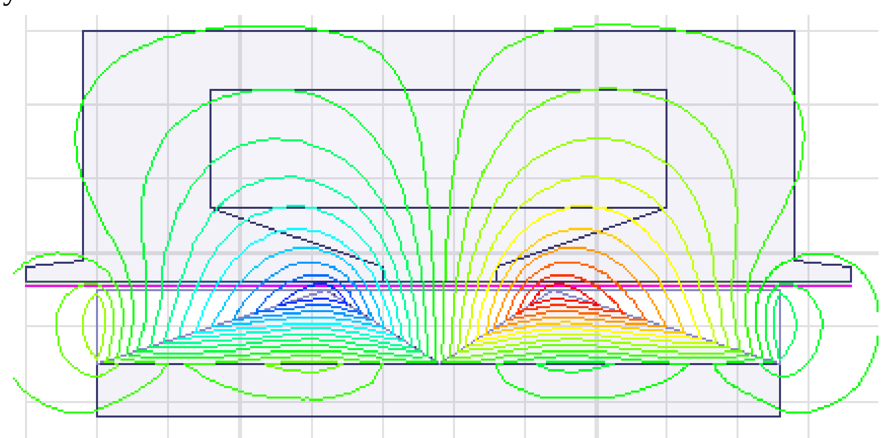


Figure 5.1: Open-flux distribution of proposed design A for z = 0

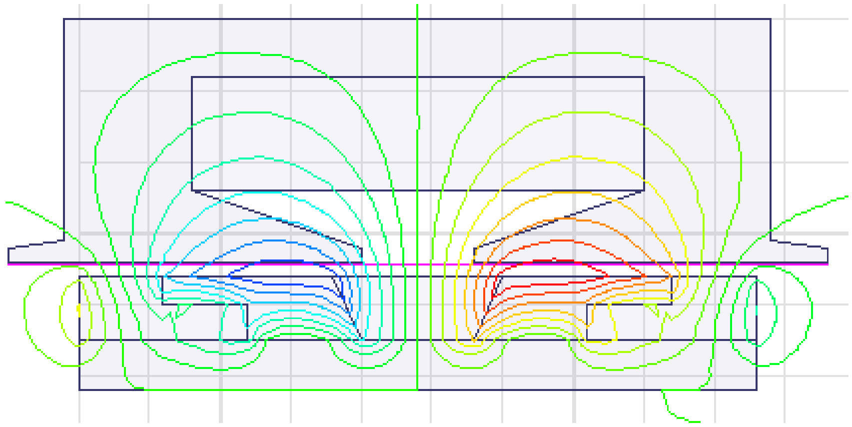


Figure 5.2: Open-flux distribution of proposed design B for z = 0

The flux distribution characteristic is proven to be right as the flux is flowing from the center part of the magnet to two sides of the other magnet (left and right) fulfilling the conditions of Hallbach array. A complete flux loop can be seen on both sides of the slot. This shows a balanced flux distribution flowing to the stator. With the presence of laminated iron at the magnet is used to reduce Eddy current. Figure 5.3 and 5.4 shows the flux distribution when z - axis is set to 11.0 mm.

After confirming the right flux distribution, the linear movement of the linear generator is carried out. Motion band is assigned to the magnet as discussed in previous chapter. The parameter chosen is set to move the translator from -6.75 mm to 6.75 mm. The velocity of the translator is set as 1 meter per second. The flux distribution of the design models will be further analyzed at air- gap.

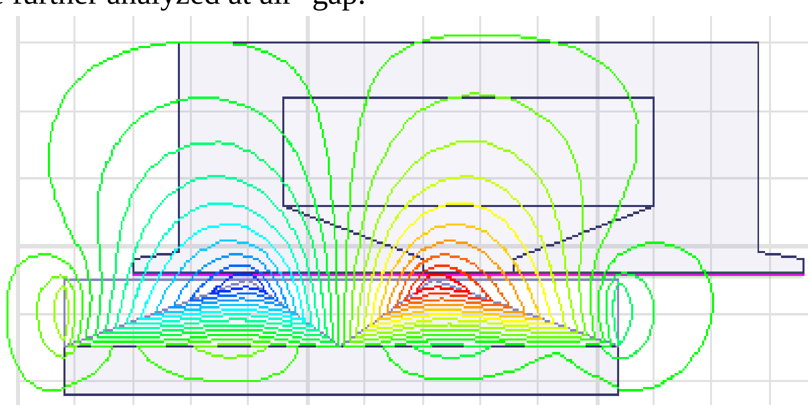


Figure 5.3: Open-flux distribution of proposed design A for z = 11 mm

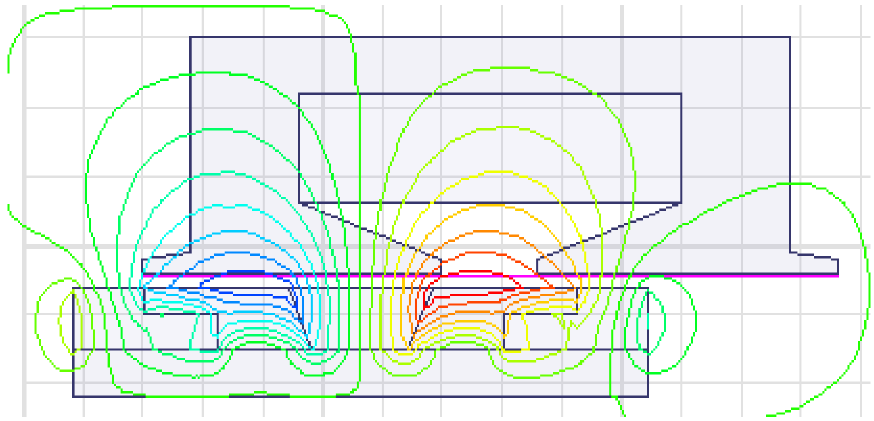


Figure 5.4: Open-flux distribution of proposed design B for z = 11 mm

5.1.2 Air Gap Flux Density

Based on the flux distribution obtained from the simulation, the models were further tested for for the plot of air gap flux density using the same finite element software. Flux density defines as how intense or how many flux lines are there in a given unit area. Measurement of flux density is represented by the closeness of the flux lines in the diagram. More flux line intensity produces higher flux density. Usually, higher flux density is seen at the magnet poles.

In order to measure flux density of the air gap between the magnets and stator, one straight line was drawn between those parts. The straight line drawn along the magnets and stator and were positioned exactly in the centre of the air gap to get the average measurement of the air gap flux density. The winding coil is set to be 0A to avoid interference resulting from the induced flux of the current-carrying winding coil. The graph plots were being traced at the initial position at 0mm where the magnet attached to translator is about to move. At this point, the stator tooth is completely facing the magnet pole where the flows of flux into the stator tooth at its maximum.
Figure 5.3 and 5.4 plot the distribution of flux density along the air gap for both proposed design.

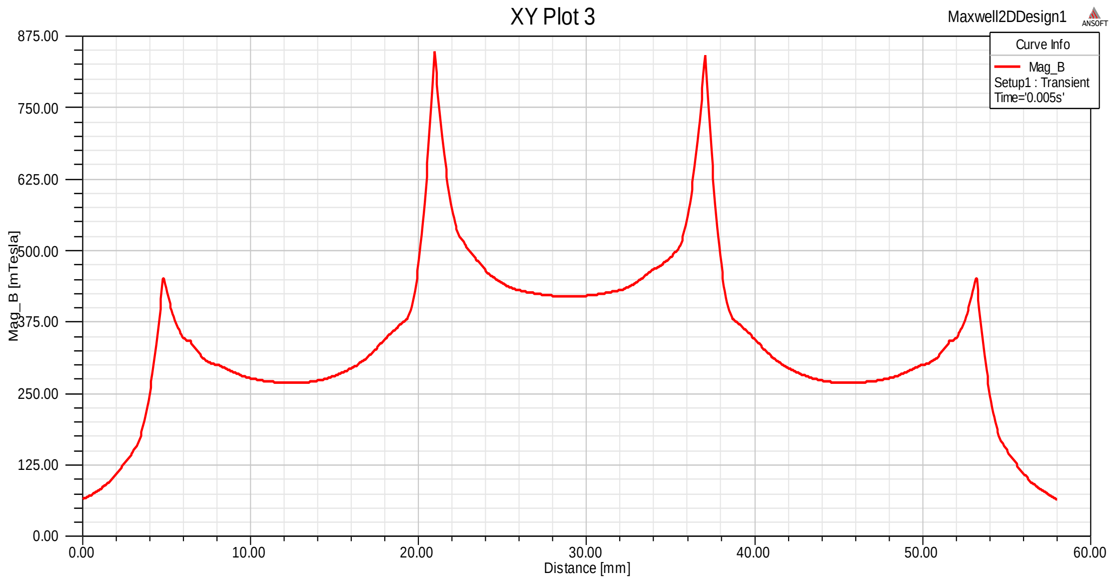


Figure 5.5: Air-gap flux distribution of proposed design A

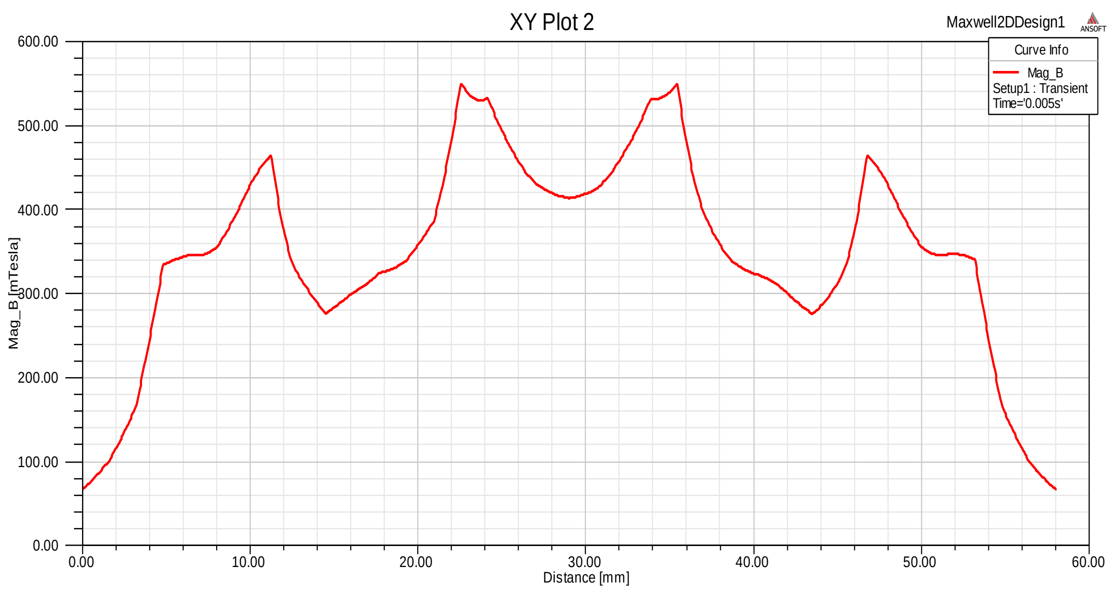


Figure 5.6: Air-gap flux distribution of proposed design B

In analyzing the trend of air gap flux density of both designs, the graph represents the flow of flux into the stator tooth. Flux density usually increases when it magnet approaches the stator tooth as the magnetic flux tends to flow into a medium such as iron which has good magnetic conductor properties as compared to air. Investigating further, the drop in flux density shown in both proposed design's graphs indicates the region in between the stator tooth where the distribution line is at least when the translator starts to move.

Observing both graphs of the proposed design A and B, the magnetic flux density produced form Design A is 0.43 Tesla and Design B produces 0.42 Tesla at the stator side. Analyzing this, the flow of magnetic flux into the stator, we can confirm that there is possibility in generating electricity in these two proposed design.

5.1.3 Back EMF

For this part of analyzing, winding coils need to be introduced to the simulation. For the initial stage of simulation for back EMF distribution results, the number of winding copper wire is set to be 500 turns of coil. The current for both winding is set to be 0A.

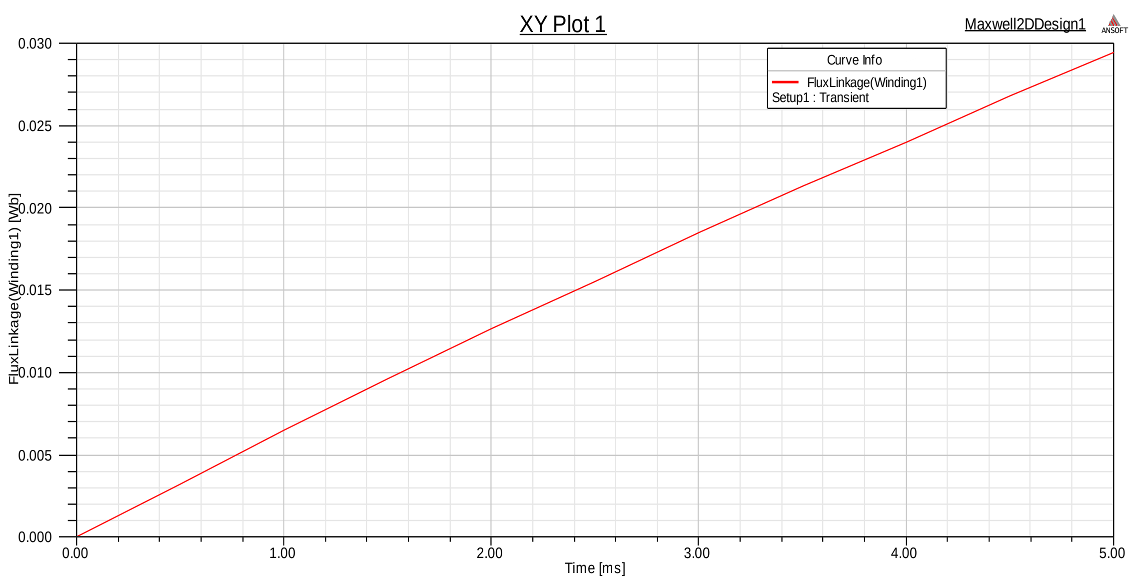


Figure 5.7: Flux linkage of winding for proposed design A

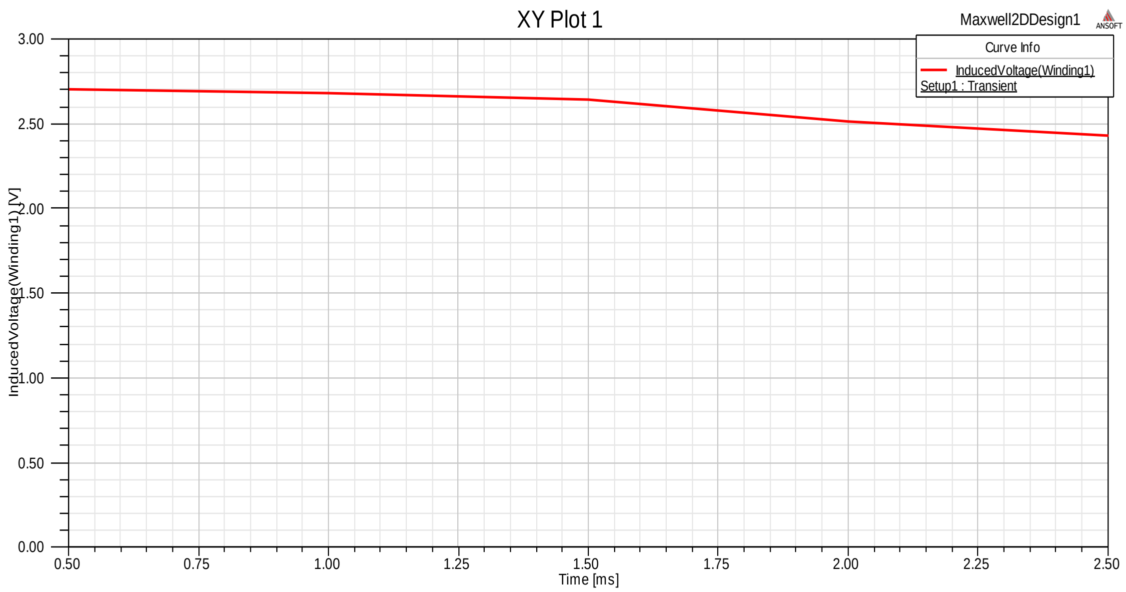


Figure 5.8: Induced voltage of proposed design A

Figure 5.5 and 5.6 shows the flux linkage as well as induced voltage of the winding resulted from the simulation for Design A. Flux linkage is defined as the amount of magnetic flux threading the coil, multiplied by the number of coil turns. The flux linkage across the coil is affected by the number of coil turns as well as the strength of the magnetic field. It is observed that the voltage induced from stator winding is proportional with the flux linkage as the result of translator movement satisfying the following equations;

$$\lambda = \int v \, dt$$

$$v = \frac{d\lambda}{dt}$$

$$\lambda = \int B.dS$$

where λ is the flux linkage in Weber, *v* is the induced voltage and *B* is the flux density vector per area. From the graph plotted in Figure 5.6, the average induced voltage achieved in proposed Design A is 2.59 V. Meanwhile, Figure 5.7 and 5.8 shows the flux linkage and the induced voltage of the winding for proposed Design B. The induced voltage recorded for Design B is 2.14 V taken at average.

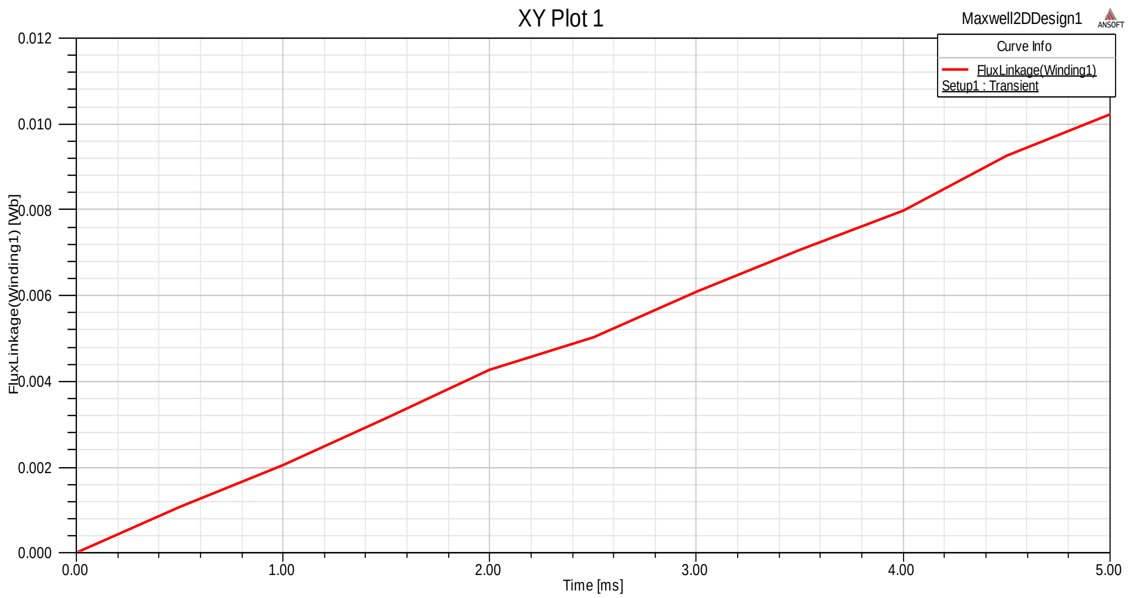


Figure 5.9: Flux linkage of winding for proposed design B

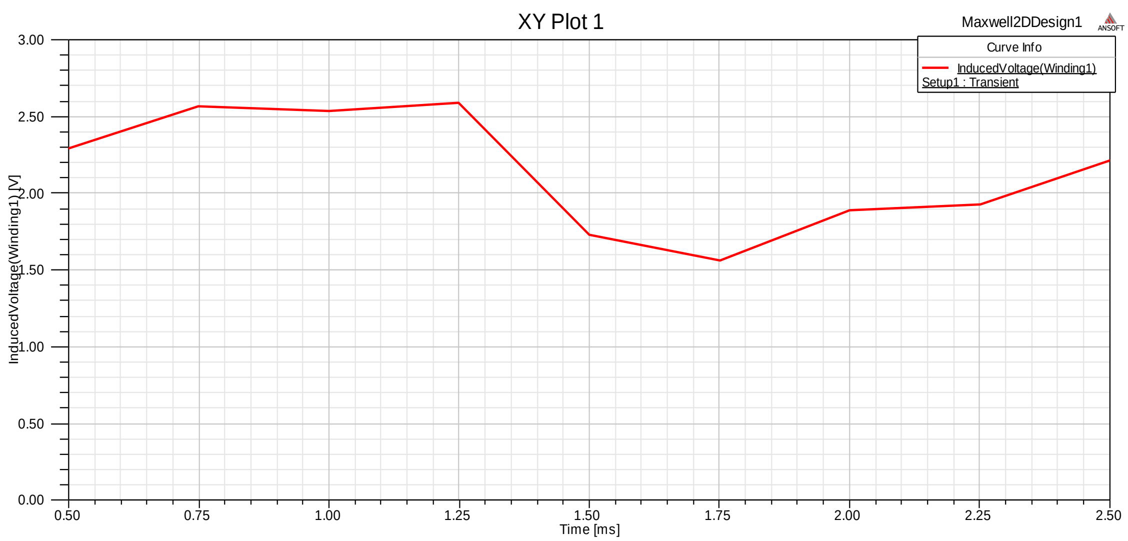


Figure 5.10: Induced voltage of proposed design B

The generated voltage for both designs are based on the open circuit voltage drop without any input current need to be connected to the load in order to calculate the power produced by this two generators of the proposed design.

5.14Flux Lines

Figure 5.11: Flux lines of proposed design A

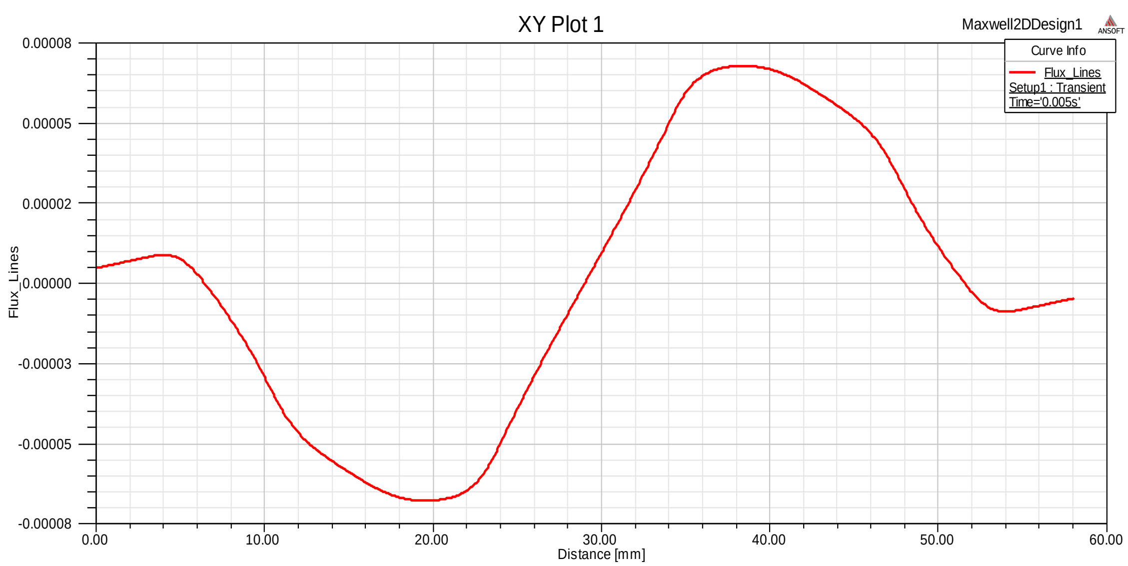


Figure 5.12: Flux lines of proposed design B

5.2 Performance analysis

After completing the simulation and performance analysis for both Design A and B in term of the flux distribution, air gap flux density as well as the back EMF of the linear generators, the simulation result obtained is analyzed to find the best design to proceed with optimization. The flux distributions for both designs are proven to be correct. From the observation of performance plot of Design A compared to Design B, Design A has recorded a higher Tesla value compared to Design B. The narrower tip shown in Figure 5.3 is because the narrow tooth tips. This will cause the flux collected is directed to the centre of stator tooth thus resulting in compressing the flux line in the middle area of the tooth.

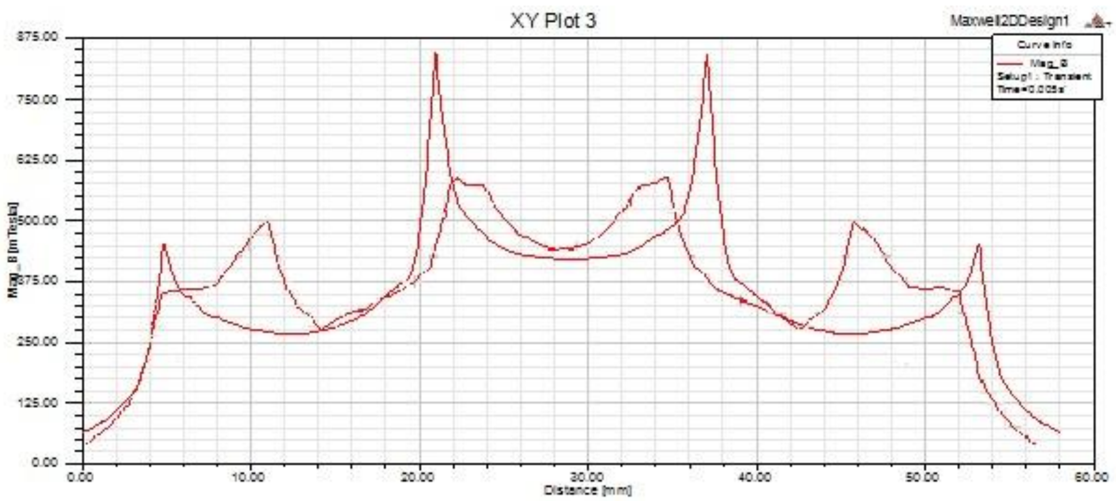


Figure 5.13: Air gap flux distribution comparison for Design A and B

The comparison between Design A and B can be seen clearly in Figure 5.13. Based on the performance plot of back EMF distribution, the proposed Design A has produced higher induced voltage compared to Design B. Therefore, Design A is selected as the best configuration and will be used for next stage which is optimization.

5.3 Optimization

After obtaining the simulation result for both designs, the designs will be further tested for its performance for better efficiency. This is also another process in achieving one of the objectives. The purpose of this optimization is to improve the model performance in terms of Back EMF. Some of the design parameters were changed in order to study the performance feedback of the linear generator. Here the linear generator A will be used to study the optimization criteria. Two types of design optimization will be conducted in this chapter which is number of coil turns variation and air-gap length variation.

5.4 Variation of Number of Coil Turns

5.4.1 Optimization design

The default design of the linear generator A has a number of coil turns of 500. In optimizing the design, the current design is varied with another three different variations of number of coil turns. The adjustments were done using Ansoft Maxwell without changing the other parameters of the generator. The simulations were done for 700, 900, and 1100 number of coil turns in the linear generator.

5.4.2 Optimization result

The simulation setting and procedure for all three variations are kept constant to avoid the repeatability error as well as to observe the outcome in detail. All the simulation results for each variation are plotted and layered together to see the differences clearly. Figure 5.14 shows the induced voltage for variation N1 (500), N2 (700), N3 (900) and N4 (1100).

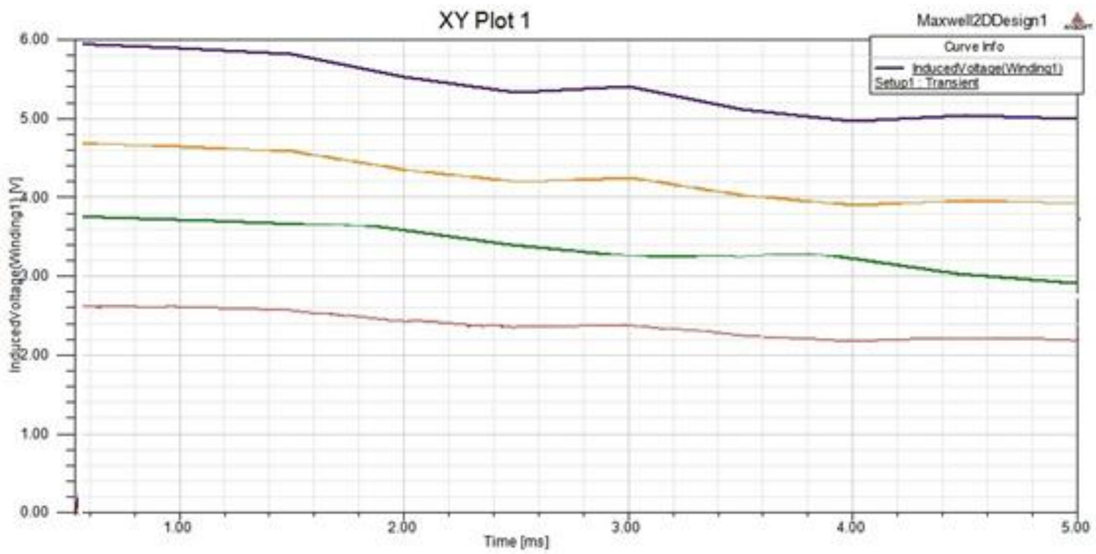


Figure 5.14: Induced voltage for variation N1 (purple), N2 (green), N3 (orange) and

N4 (blue)

Based from Figure 5.14, it can be concluded that the variation of N4 has the highest voltage induced. Based on rough observation on the graph, all the variations produce a similar trend in the plot but with different magnitudes. The design with number of coil turns of 1100 produces the highest voltage induced at the average of 5.8 V. This shows that the voltage induced by the generator rises with the increment of the number of coil turns. Therefore this design with number of coil turns of 1100 will be used for the next design optimization replacing the original proposed design.

5.5 Variation of Air-gap Length

5.5.1 Optimization design

Another adjustment made for this chapter in order to achieve the objective is the variation of air-gap length. In the current design, the air-gap length is fixed as 0.5 mm (default). The variations will be done for another two different lengths of air-gap which is 1.0 mm and 1.5 mm using the same method and design parameters to avoid interference of results.

5.5.2 Optimization result

The simulation setting and procedure for both variations are kept constant to avoid the repeatability error as well as to observe the outcome in detail. All the simulation results for each variation are plotted and layered together to see the differences clearly. Figure 6.2 shows the induced voltage for variation L1 (0.5 mm), L2 (1.0 mm) and L3 (1.5 mm).

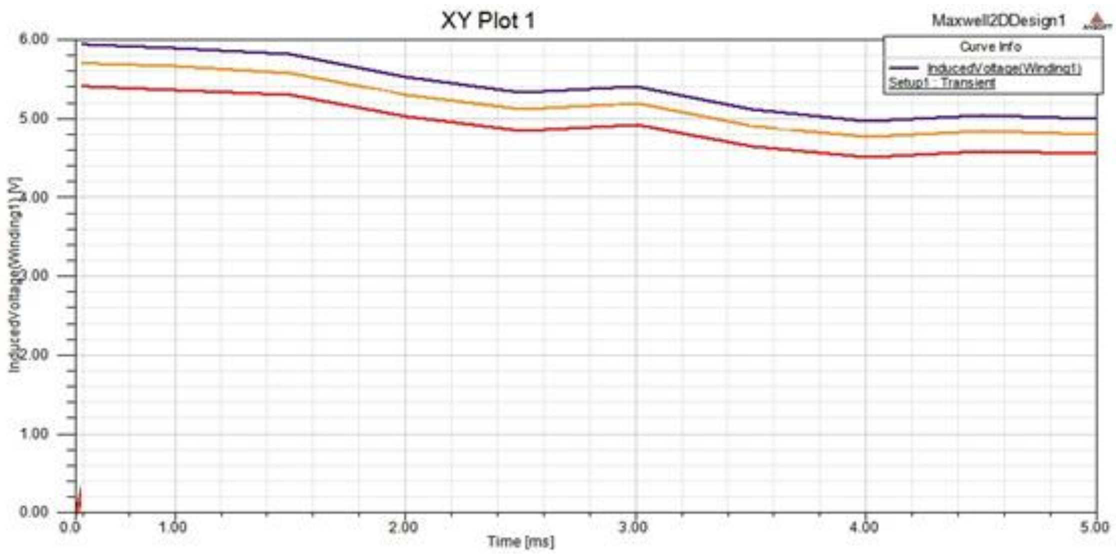


Figure 5.15: Induced voltage for variation L1 (blue), L2 (orange) and L3 (red)

Based on the figure above, it can be clearly seen that the air-gap length of 0.5 mm produces the highest Back EMF at the average of 5.8 V following with 1.0 mm with 5.43 V and 1.5 mm produces 5.17 V at an average value.. It can be clearly also observed that increment in air-gap length will produce lesser induced voltage. Therefore, the air-gap length for this design is maintained at 0.5 mm which was the initial design parameter.

Assuming the both generators are connected to a bulb with resistive value of 240 Ω, the generated power for both designs is calculated.

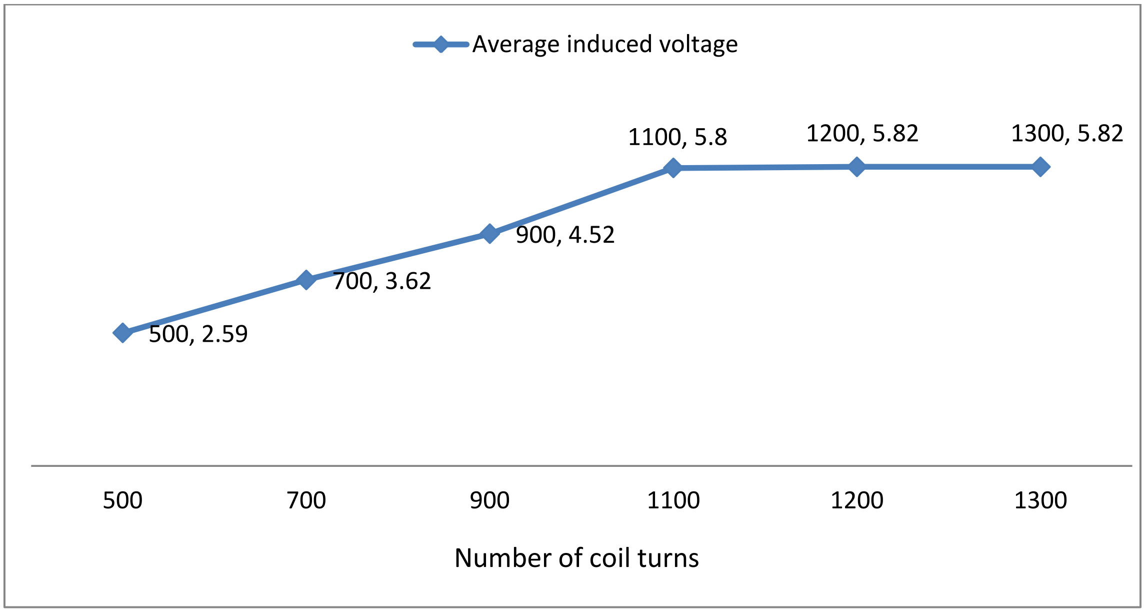


Figure 5.16: Performance plot for number of coil turns optimization

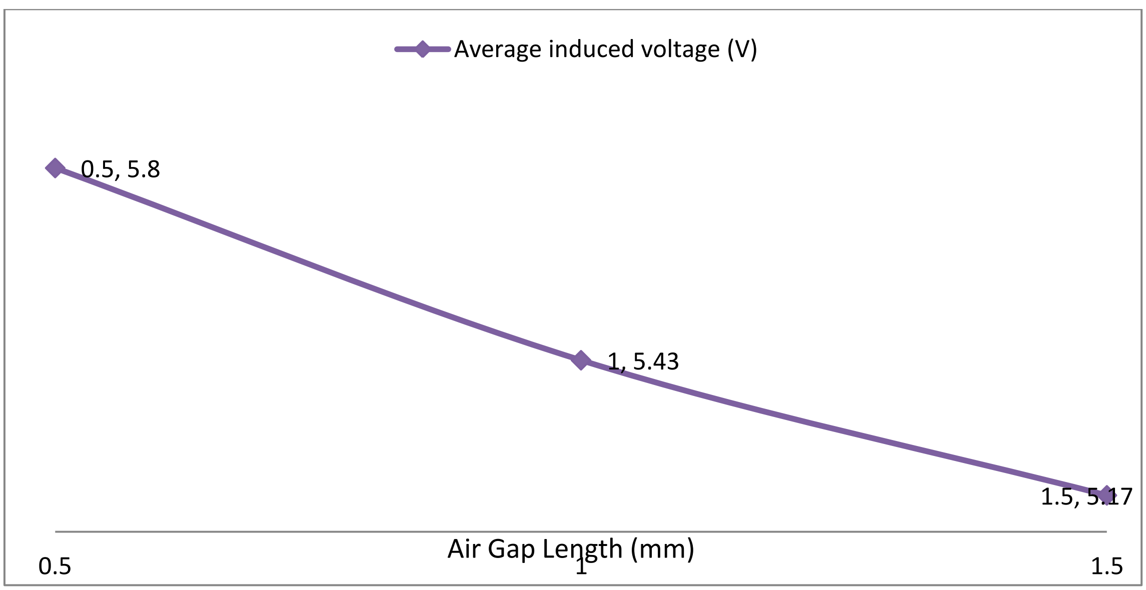


Figure 5.17: Performance plot for air gap length optimization

As shown in Figure 5.16, number of coil turns of 1100 has the highest average value of voltage induced. Figure 5.17 shows air gap length with 0.5 mm recorded the highest average value.

5.6 Conclusion

In this chapter the optimization stage has been performed for the selected design which is Design A. Two design optimizations had been performed to further improve the efficiency of the linear generator; variation of number of coil turns and variation of air-gap length. The simulation procedure and other dimensions were kept constant and the outcome for each variation is analyzed and studied thoroughly. Based on the simulation outcome which was focusing on the induced voltage of the model, the highest induced voltage was produced when the number of coil turns is kept at 1100 and air-gap length is at 0.5 mm. Therefore, this is selected as the final design after performing the optimization.

CHAPTER 6

CONCLUSION AND FUTURE WORK

6.0 Conclusion

The idea of using the specified criterion for the linear generator is achieved after a thorough study. Through this project a small scale wave energy converter will be used attached closely with a new design of linear generator to produce an efficient power output. The Floating Buoy Technologies will be used as the operating system where the designed new linear generator will be placed to benefit the fisherman so that it is small, mobile, inexpensive and efficient power delivery. The design parameters that have been finalized are PMLG tubular type, iron-cored stator, moving magnet and slotted topology with Hallbach magnet arrangement will be used to in this design. The magnets of two different shapes namely Design A and Design B of Hallbach magnet arrangement tested against three parameters which are EMF distribution, open-flux distribution and air-gap distribution. The simulation work and the analysis have been performed and the optimization of design is done in order to achieve the objective. After analyzing the performance of both designs, Design A of triangular shapes magnet were selected to optimize further in maximizing the efficiency of the linear generator. Two optimization developments were done to obtain the best performance; number of turns per coil optimization and air-gap length optimization with the optimum result of 1100 and 0.5 mm.

6.1 Future Work

The selected design can be further improved and optimized to maximize the performance of the linear generator. The design model has to be analyzed with the same finite element analysis to study the power generation and model efficiency to be compared with existing linear generators in market.

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