Wave Energy Linear Motor/Generator

by

Muhammad Hadfiz Bin Mohd

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

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Universiti Teknologi PETRONAS
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Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Electrical & Electronics Engineering Programme
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Approved by,

____
(A.P. Dr. Mohd Noh Karsiti)

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June 2008

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.

MUHAMMAD HADFIZ BIN MOHD

ABSTRACT

This project reports on how to generate electricity from ocean wave by using permanent magnet linear generator. The objectives of this project are to design and build a small scale linear generator powered by ocean wave energy that able to generate at least 1 kW of electricity. It is not easy to harness wave energy and convert it into electricity in large amounts. So, the studies for this project include finding information and knowledge related to the topic besides developing skill through enquiry and literature review. Linear electric generators are linear motion electromagnetic devices that transform short stroke oscillatory motion mechanical energy into electrical energy. The linear generator in this project consists of a stator and a translator as its major part. In linear generator, electrical power is generated simply by forced relative movement of linear generator to its stator. The linear generator will oscillates with the wave up and down to cut electromagnetic flux inside the stator. Thus, the cuts of magnetic flux will result as electricity. To become a successful project, several things need to be reviewed like literature review on linear generator, design and development of the generator, experiment of prototype before gaining result and correct data. By varying the frequency of the wave energy, the cuts of magnetic flux depends on the cycle movement and the speed of the translator into the stator. Then, the line voltage and line current was measured to calculate the total output power that has been generating by linear generator. The results show that the output voltage and hence not unexpectedly, the output power, depends to a large extent on the translator speeds. As a result, the wave energy linear generator only generates a small amount of output power that not achieves the objective of this project.

ACKNOWLEDGEMENT

Most of the equipments for this project was provided by the Linear Generator (LG) Team Research under Universiti Teknologi PETRONAS.

All praises go to Allah, our sustainer, without whose grace and guidance, no effort could be attain success. I would like to convey my gratitude to my supervisor, A.P. Dr. Mohd Noh Karsiti for his invaluable assistance and technical guidance. Special thanks is due to the leader of the Linear Generator (LG) project, A.P. Dr. Abdul Rashid, for having given me the opportunity to be part of his Final Year Project (FYP) team and the trust such that I am able to undertake this project to achieve the objectives.

To all project members from the mechanical department, I can never thank them enough, for the achievements of this project would not have been possible without their effort and commitment: Nur Azura Kamaruzzaman and Mohd Fadhli. Special thanks to Mr. Razali from LG team members, who help and support had been tremendous and consequential to this project.

The assistances of lecturers and technicians from the Electrical & Electronics Engineering Department, Mechanical Engineering Department and Civil Engineering Department, is greatly appreciated. To all fellow postgraduates and undergraduate students, friends and family members, I am deeply grateful for all the help and support that they have given me.

To my parent, without their love and advice I could not have been the person I am today, I thank them from the very bottom of my heart.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1

INTRODUCTION

1.1 Background of Study

The free-piston term is most commonly used to distinguish a linear engine from a rotating crankshaft engine. The piston is 'free' because its motion is not restricted by the position of a rotating crankshaft, as known from conventional engines, but only determined by the interaction between the gas and load forces acting upon it [1, 4, 5, 6].

Linear electric generators are linear motion electromagnetic devices that transform short stroke oscillatory motion mechanical energy into electrical energy. The linear generator in this project consists of a stator and a translator. The stator is built from silicon steel lamination and cooper coils. The translator is built from permanent magnets and aluminum alloy shaft. The permanent magnet creates the flux required to generate the voltage in the coils [1, 4, 5, 6].

1.2 Problem Statement

The free piston linear engine is made as platform to convert mechanical to electrical energy through a particular arrangement with a linear generator. The linear electric generator produces electricity directly from linearly reciprocating motion of a single moving assembly of one or more piston connected to a linear shaft [1].

A tubular linear electric generator includes a stator and a translator. The translator that positioned inside the stator hole to move linearly back and forth relative to the stator to generate a current in the coils. This project shows the electromagnetic induction process of the linear generator produces the electricity by using the ocean wave energy.

1.3 Objectives and scope of study

The objectives of this study are to:-

- Study in detail the movements, and produce of electric current in the linear motor/linear generator
- To design and build a small scale linear generator powered by ocean wave energy that able to generate at least 1 kW of electricity

The scopes of study are:-

- Finding information and knowledge related principle of Linear Motor/Linear Generator
- Design a permanent magnet linear motor/linear generator prototype that required control, and produce electricity from ocean wave energy

CHAPTER 2

LITERATURE REVIEW/THEORY

2.1 Literature Review

To provide for the force to reciprocate the piston assembly, the LG will be operated as a brushless, permanent magnet linear motor. Essentially, current is injected into the stator coils which will then create a magnetic field whose strength is proportionate to the level of the injected current as showed in Figure 2.1.

The resultant magnetic field due to the coils being energized with electrical current will interact with the existing magnetic field of the permanent magnet on the translator shaft, creating a mechanical force as a product of the interaction which will be able to push on the translator shaft in certain linear direction and with a certain magnitude depending on the relative position of the permanent magnets with respect to the fixed stator coils.

The relative position of the permanent magnets with respect to the stator coils is critical to the production of the motoring force and starting strategy for LG, due to non-uniform magnetic fields both the permanent magnets and the armature current. The effect is that the interaction between these two fields which give rise to the motoring force will be different in magnitude and direction positions along the translator assembly [1, 4, 5].

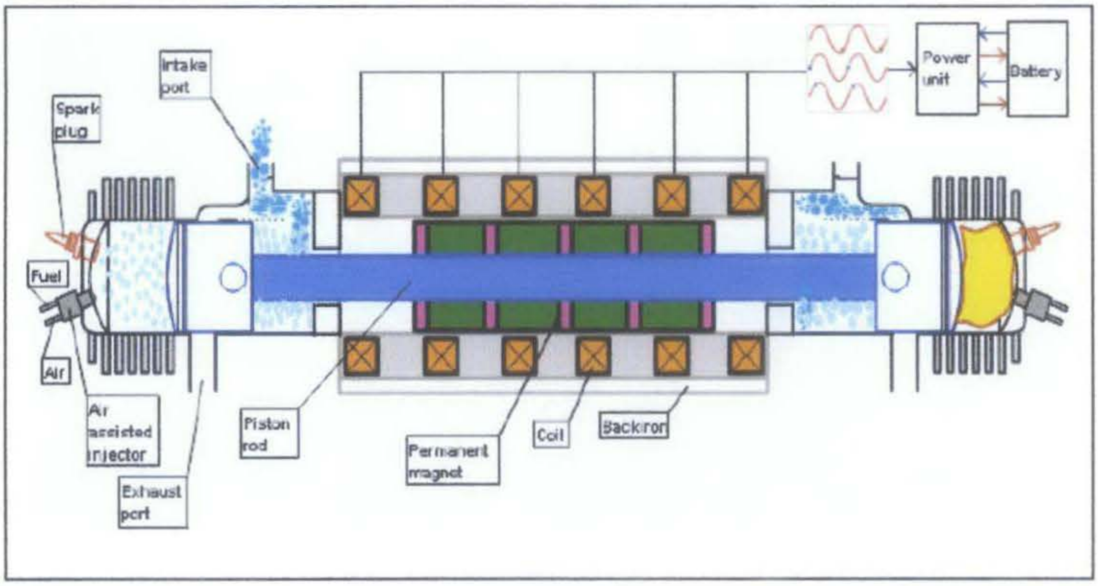

Figure 2.1: Linear Motor/Generator in Free Piston LG [5]

2.1.1 Principle of Linear Motor/Linear Generator

A simple linear motor consists of a current source, a moveable wire and a magnetic field is shown in Figure 2.2. Assuming that the current is flowing around the loop as indicated, and the magnetic field is shown going into the page, the effect of the force on the moveable wire will be to move the moveable wire to the right. This simple concept is how a linear motor operates, a current in moved through a wire where the direction of current flow is perpendicular to the magnetic field. The result is a force applied to the wire that makes it move. The force is dependent on the direction and magnitude of the current, the direction and magnitude of the magnetic field, and the angle between the current and the magnetic field vectors.

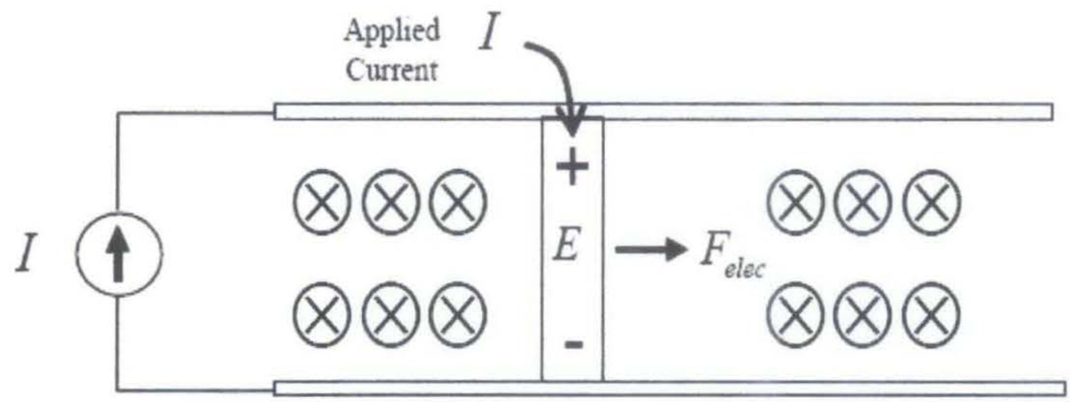

Figure 2.2: Basic Principle of Linear Motor [7]

From the description of a linear motor given above, a force can be generated on current carrying wire in a magnetic field. The **Lorentz Force Law** indicates that a constant current perpendicular to a uniform magnetic field will result in constant force on that wire. If wire is free to move, the constant force would result in constant acceleration. Constant acceleration would eventually result in physically impossible speeds. Refer to **Appendix A** for Lorentz Force Law.

$$F = ILxB$$

where: **F** = forces, measured in Newton's
I = current in wire, measured in amperes
B = magnetic field, measured in Teslas
× = vector cross-product
L = length of wire, measured in meters, vector direction along wire, aligned with positive current

It turn out that changing the magnetic flux flowing through the area defined by a closed loop of wire produces a current in the closed loop of wire. **Faraday's Law** below described this result. It is concept behind electric generator, that current is generated by changing the area of a closed loop of wire in a magnetic field.

Faraday's Law states that changing area of a conductor loop in magnetic field result in a current. This simply means that the ***induced electromagnetic force (EMF)*** is proportional to the rate of change of the magnetic flux through a coil. Hence an induced voltage is present which is given. Refer to **Appendix B** for Faraday's Law.

$$E_{induced} = (v x B) L$$

where:	$E_{induced}$	= electric field
	L	= length and direction of the moveable wire
	v	= velocity of the moveable wire
	B	= magnetic field

The above equation indicates that the induced voltage is dependent on the velocity of the wire, the magnitude and direction of the magnetic field and length and direction of the wire in the magnetic field [7].

2.1.2 Linear Synchronous Motor

A linear synchronous motor (LSM) is a linear motor in which the mechanical motion is in synchronism with the magnetic field. The thrust (propulsion force) can be generated as an action of:

- traveling magnetic field produced by a polyphase winding and an array of magnetic poles N, S,...N, S or a variable reluctance ferromagnetic rail (AC armature windings)
- traveling magnetic field produced by electronically switched DC windings and an array of magnetic poles N, S,...N, S or a variable reluctance ferromagnetic rail (linear stepping or switched reluctance motors)

The part producing the traveling magnetic field is called the armature or forcer. The part which provides the DC magnetic flux or variable reluctance is called the field excitation system. AC polyphase synchronous motors are motors with DC electromagnetic excitation. Replacement of DC electromagnetic by permanent magnets (PM) is common. PM brushless LSM can be divided into two groups:

- PM LSM with no position feedback, where the input current waveform is sinusoidal and produces a traveling magnetic field
- PM DC linear brushless motor (LBM) with position feedback, in which the input rectangular or trapezoidal current waveform is precisely synchronized with the speed and position of the moving part

In the case of LSM operating on the principle of the traveling magnetic field, the **speed (V)** of the moving part

$$V = V_s = 2fr = \frac{w}{\Pi} r$$

is equal to the **synchronous speed (Vs)** of the traveling magnetic field and depends only on the **input frequency (f)** (angular input frequency w = 2πf) and **pole field (r)**. It does not depend on the number of poles 2p. There are many topologies of LSM, which can be classified according to whether they are planar or cylindrical, single sided or double sided, slotted or slotless, iron-cored or air-cored and transverse flux or longitudinal flux. PM in the reaction rail is one of the excitation systems that operate on the principle of the traveling magnetic field [2].

2.1.3 Linear generator

The operation of linear generator (LG) is reversible process of linear motor that converts mechanical energy into electrical energy. Linear generator operates on the basis of **Faraday's Law** of ***electromagnetic induction***, according to which:

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

That is, a **voltage (*e*)** is induced in a coil if its **flux linkage (λ)** varies with **time *t*** [3]. This project will concentrate to one of the categories of the LG which is moving permanent magnet type. Whereas numerous configuration of moving permanent magnet LG are feasible, two topologies are shown in Figure 2.3and Figure 2.4. The first figure (Figure 2.3) has multiple magnets, whereas the second (Figure 2.4) has a single moving permanent magnet. Clearly, there is no difference in their principle of operation. For discussion and analysis, consider the LG with a single moving permanent magnet of Figure 2.4. Refer to **Appendix C** for details of symbol.

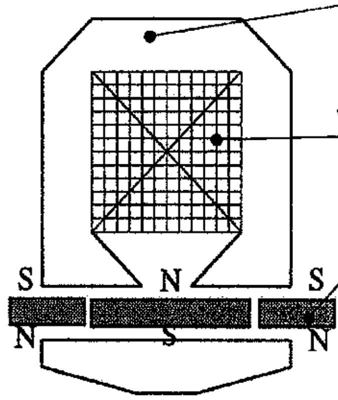

Figure 2.3: Multiple Moving Magnets [3]

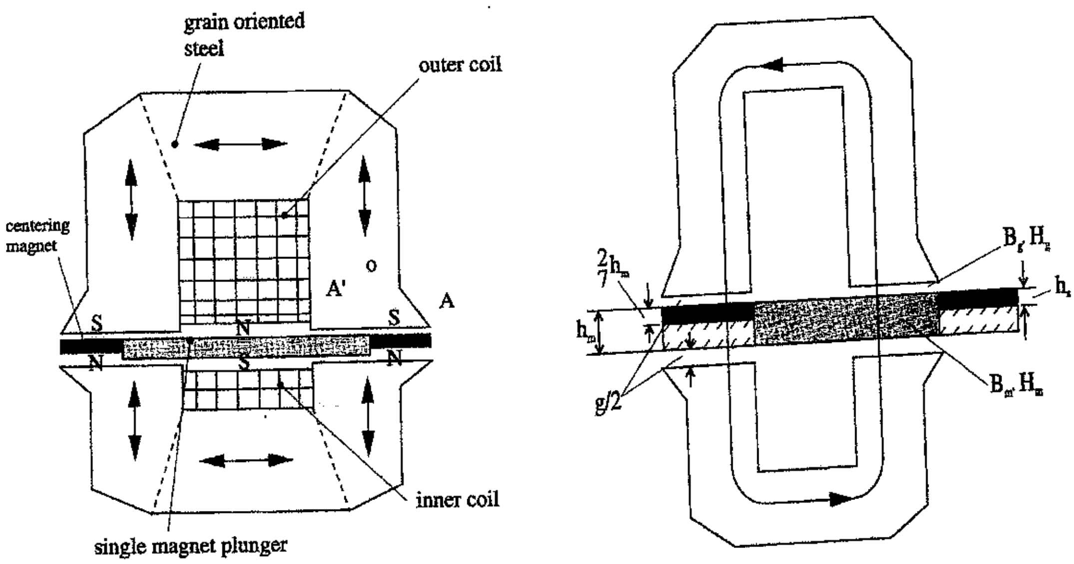

Figure 2.4: Single Moving Magnet [3]

The first step in the analysis and design of a permanent magnet LG is the determination of the air gap field produced by the magnet. Neglecting saturation and leakage, for the magnet position shown in Figure 2.4, we have;

$$B_m = B_g = \mu_0 H_g \quad (1)$$

Neglecting the reluctance of the core, **Ampere's Law** yields;

$$k_s H_g (2g) + H_m h_m + H_m h_s = 0$$

Assuming rare-earth magnets, their demagnetization characteristic can be written;

$$B_m = B_r + \mu_{rc} H_m (2)$$

Combining (1) through (2) yields;

$$B_m = B_r \left[1 + \frac{\mu_{rc}}{\mu_0} \left(\frac{2k_s g}{h_m + h_s} \right) \right]^{-1}$$

Having determined the maximum air gap flux density, the **induced EMF, E**;

$$E = 4.44 f B_m A_g N$$

where:

- f = frequency of motion (moving magnet)
- A_g = surface area of the magnet, m^2
- N = total number of turns on the stator
- B_m = maximum air gap flux density, T

In order to know the generator performance characteristic, all the parameters of the PMLG must be identified. **The magnetizing inductance, L_m** is given by:

$$L_m = \frac{\mu_0 \pi D_m N^2 l_s}{2 k_s g_m}$$

where:

- D_m = mean diameter of the windings, m
- l_s = stroke length, m
- g_m = magnetic air gap, m

Referring to the symbols shown in Figure 2.5, the leakage inductance is given by:

$$L_\sigma = \mu_0 N_i^2 \left(\frac{h_{si}}{3b_{si}} + \frac{h_s}{b_{si}} \right) \Pi D_i + \mu_0 N_0^2 \frac{h_{so}}{3b_{so}} \Pi D_0$$

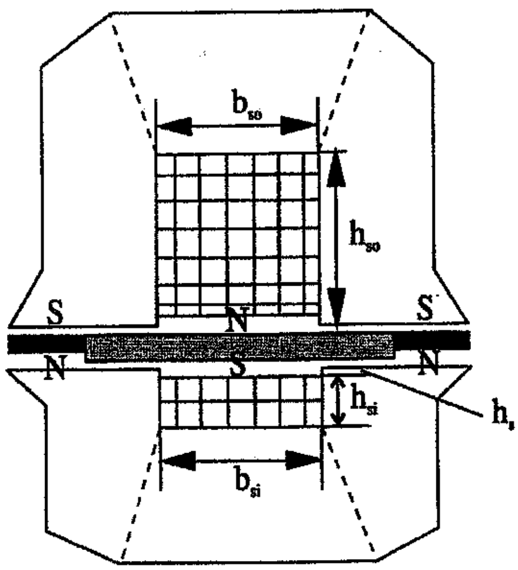

Figure 2.5: Linear Generator Dimension [3]

Finally, the **synchronous inductance, L_s** becomes

$$L_s = L_m + L_b$$

Since;

$$\boxed{N = N_i + N_0} \quad \boxed{A_g = \Pi D_m l_s}$$

Rewrite the **induced EMF, E**:

$$E = 4.44 \Pi f (N_i + N_0) B_m D_m l_s$$

2.1.3 Linear Generator of Oregon State University

Oregon State University has taken the first steps towards generating power from waves. They have built a buoy system capable of capturing the ocean's power in the form of offshore swells, and converting it into electricity. One system bobs two miles offshore and is called the permanent magnet linear generator buoy is shown in Figure 2.6. Inside the buoy, an electric coil wraps around a magnetic shaft, which is attached to the sea floor. The coil is secured to the buoy, and it bobs up and down with the swells while the shaft stays in a fixed place. This movement generates electricity. Each buoy could potentially produce 250 kilowatts of power, according to researchers, and the technology could be scaled up or down to suit the needs of the people on shore. Researchers estimate it would only take about 200 of these buoys to provide enough electricity to run the business district of downtown Portland. Parametric dimensions of generator were shown in Table 2.1 [12].

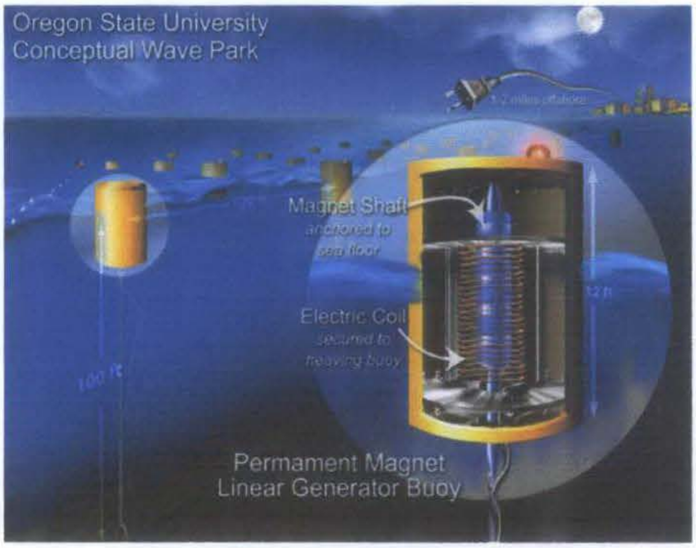

Figure 2.6: Permanent Magnet Linear Generator Buoy [12]

Table 2.1: Parametric Dimensions of Generator

Total thickness of magnet pair	0.02 m
Magnet external diameter	0.045 m
Magnet internal diameter	0.020 m
Steel spacer thickness	0.02 m
Total translator length	0.32 m
Number of stator poles	4
Height of coil section	0.02 m
Radial width of coil section	0.006 m
Air gap clearance	0.0006 m

Electric parameter of the generator is shown in Table 2.2 and wave tank test for the permanent magnet linear generator buoy is shown in Table 2.3 [12].

Table 2.2: Electrical Parameters of the Generator

▪ Rated voltage	25 V
▪ Rated current	3 A
▪ Rated power output	50 W
▪ Number of phases	2

Table 2.3: Wave Tank Test

Load (ohm)	**Wave height (m)**	**Wave period (s)**	**Peak voltage (V)**	**Peak current (A)**	**Peak power (W)**
5	1.37	3	20	1.4	25
2	1.37	3	16	1.6	18
10	1.37	3	19	1.2	12
5	0.98	3	12	0.6	6
5	1.21	3	10	0.5	5
5	0.66	3	9	0.5	5
2	0.98	3	6	0.7	4
5	0.98	2	10	0.5	3.6
2	0.82	6	2.4	0.1	0.2
10	0.98	3	20	0	0
No load	0.98	3	20	0	0

CHAPTER 3

METHODOLOGY/PROJECT WORK

3.1 Methodology

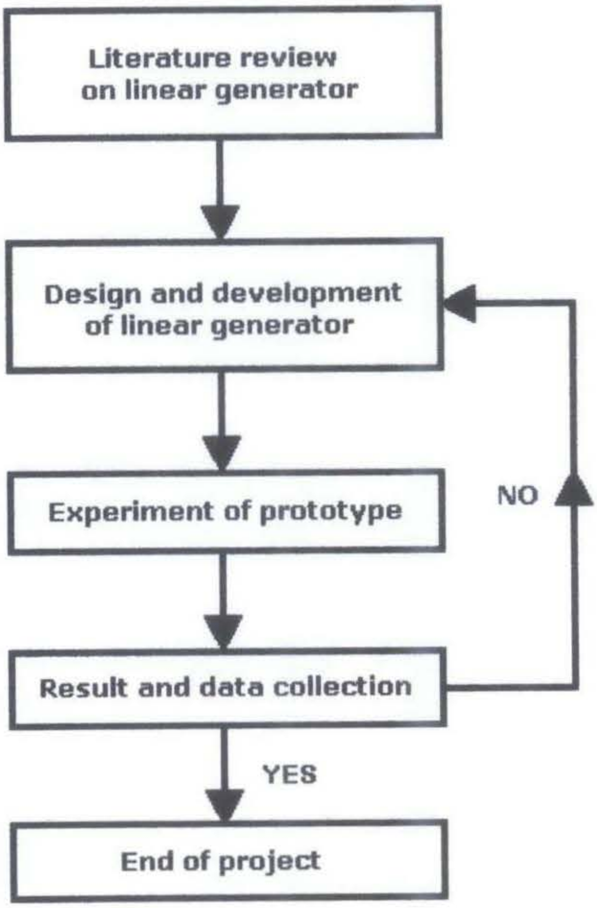

Figure 3.1: Process Flow Chart

3.1.1 Literature review on linear generator (LG)

At the beginning of the semester after the title selection was done, literature review process was conducted. Literature review is very essential in doing this project since all relevant information regarding this project was gathered and studied during this period. The internet is the biggest and easiest source of information. Nevertheless, some literatures were also gathered from books that can be found in the library and also the post graduate thesis regarding the free-piston linear generator.

3.1.2 Design and development of ocean wave linear generator

The device consists of a linear generator with its translator and stator, a floater and a spring. A steel framework is use to support the linear generator during the experiment. A spring is use as connection between the linear generator and the framework which functions to support the oscillating movement. Below the linear generator is a floater functions as a base to capture the movement of wave. The permanent magnet on the translator creates the flux required to generate the voltage in the coils. As the translator of the linear generator oscillates up and down, it will cut the magnetic flux in the stator and produce the induced voltage. The generated electricity will be measure by using voltmeter. Meanwhile, the waveform of the induced voltage will be capture by using the oscilloscope.

3.1.3 Experiment of prototype

After the designing and development of prototype was done, it will be tested in a wave energy tank. Several experiments will be conducted to ensure a good result. At this time, some modification might be needed to get the expected result.

3.1.4 Result and data collection

The results from all experiment will be recorded and compared. The best result will be chosen as the result of the project.

3.2 Project Activities

3.2.1 Design and Development of Linear Generator (LG)

Description:

The particular LG used in this project (designed and built by the ***Universiti Malaya* LG Project Team**) is a 3-phase permanent magnet brushless LG, with the following basic design:

- Stationary coil: 3-phase, Y connected (4 wire including neutral), 4-coil
- Moving magnet:7-pole permanent magnet carried by the translator
- Iron-cored stator

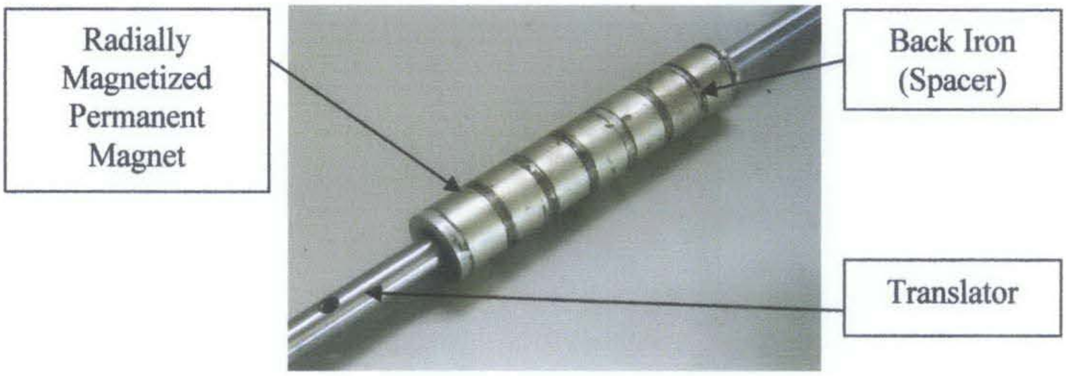

Figure 3.2: Moving Magnet (translator)

The design relates to the field of linear generator, in which the current is generated in the generator coils by the movement of the translator constructed by permanent magnets with respect to a stator constructed of a core and coils. The tubular translator is built from permanent magnets and aluminum alloy shaft as shown in Figure 3.2. The permanent magnet arrangement is constructed of seven **Radially Magnetized Permanent Magnets (RMPM)** and six back irons (spacer) that arranged alternately in series along the shaft and the translator is one stroke longer than the stator. The permanent magnets are mounted in the shaft to give the magnetic field source for the generator. Refer to **Appendix D** for dimension of linear generator.

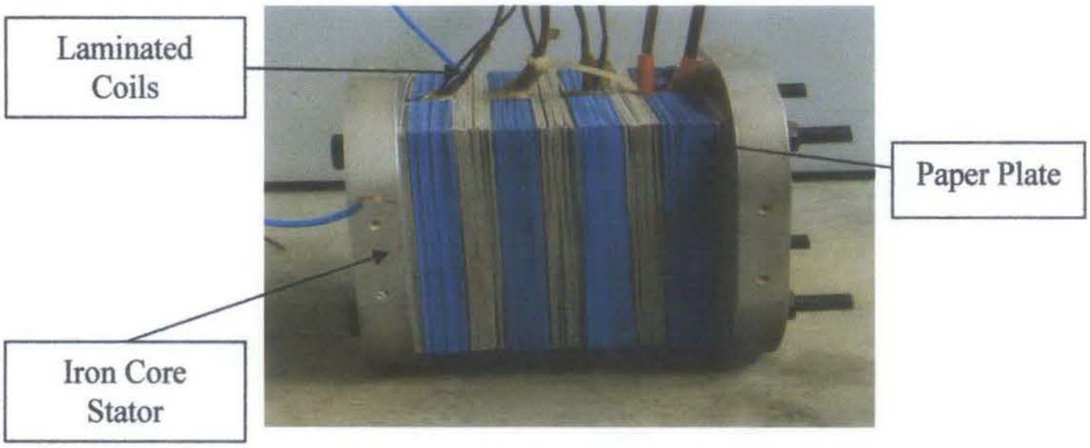

Figure 3.3: Iron Core Stator and Laminated Coils

The stator includes a laminated core where 4 coils that located in the stator slot in the same distance as shown in Figure 3.3. Only 3 coils are been used based on the star connection. The core is constructed of silicon steel laminations stacked axially. All lamination have the same outer diameter. However, some laminations have bigger inner diameter to form the core slots where coils are located and others have smaller diameter to form core teeth. Spiral of lamination core provide the flux return path through generator. Refer to **Appendix E** for dimension of translator, stator and coil.

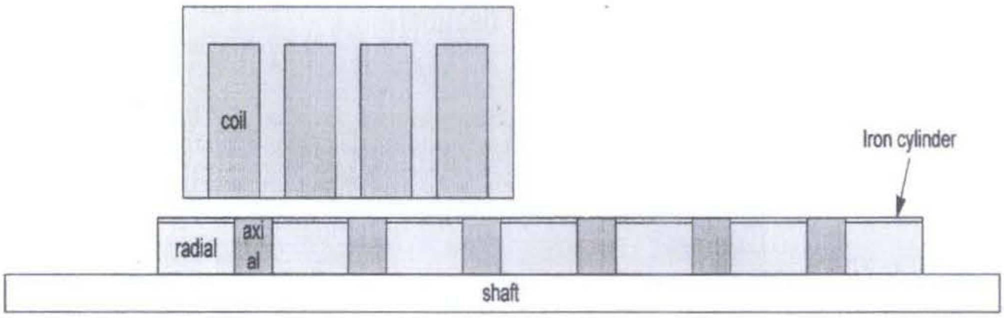

Figure 3.4: Cross Section of Linear Generator

The translator is one stroke longer than the stator as shown in Figure 3.4. A long translator linear generator that consist some sets of permanent magnet can activate all coils. It gave a significant improvement in the generator output power.

3.2.2 Change steel plate with paper

Description:

The cogging force became a big issue. The generator could not be moved easily due to the interactive force between permanent magnet and stator teeth. The magnet pack usually stuck at the steel plate in the stator when move in up and down motion. To solve this problem, the steel plate in the stator is replaced with paper as shown in Figure 3.5. Refer to **Appendix F** for dimension of paper plate.

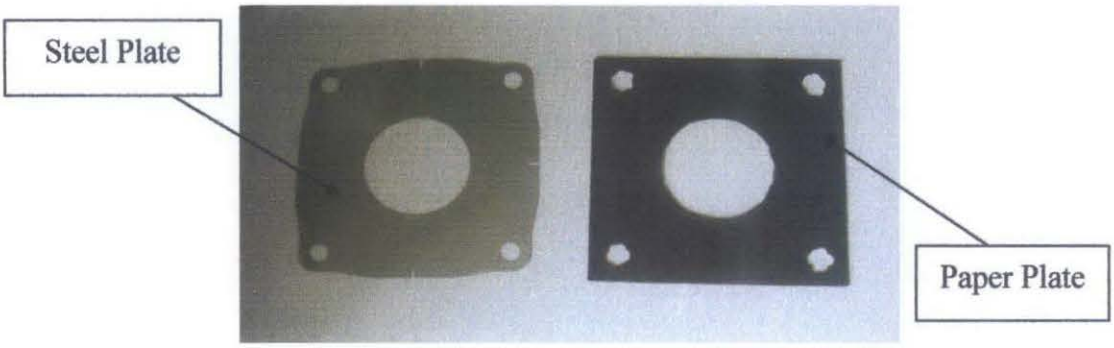

Figure 3.5: Steel Plate to Paper Plate

3.2.3 Spring selection

Description:

A spring is a flexible elastic object used to store mechanical energy as shown is Figure 3.6. Springs are usually made out of hardened steel. In classical physics, a spring can be seen as a device that stores potential energy by straining the bonds between the atoms of an elastic material. Hooke's law of elasticity states that the extension of an elastic rod (its distended length minus its relaxed length) is linearly proportional to its tension, the force used to stretch it. Similarly, the contraction (negative extension) is proportional to the compression (negative tension) [13]. These apply the equation:

$$F = kx$$

where: x = distance the spring is elongated by

F = restoring force exerted by the spring

k = spring constant or force constant of the spring

From the data collected:

- Mass of magnet = 6 kg
- Length of spring before stretch = 20.5 cm
- Length of spring after stretch = 30 cm
- Force = mass x gravitational acceleration
  = 6 kg (9.81 ms^{-2})
  = 58.86 N
- Spring displacement, x = 9.5 cm = 0.095 m
- Spring constant, k = F/x = 58.86/0.095
  = 619.58 kgs^{-2}

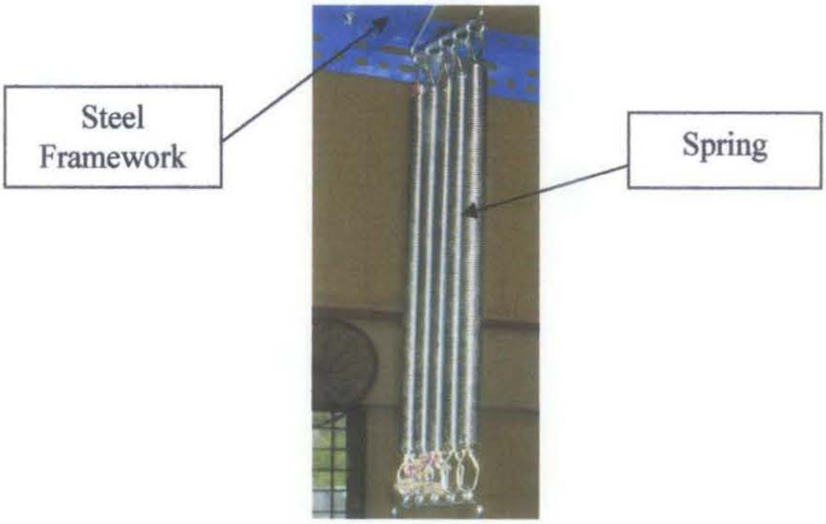

Figure 3.6: Spring

3.2.4 Preparation of steel framework

Description:

Mechanical structures have been design and build by mechanical team members. Steel framework functions as stand to hold the linear generator during the operation as shown in Figure 3.7. The height of the framework is designed high enough to apply motion of the generator without reaching the water. Refer to **Appendix G** for the dimension of steel framework.

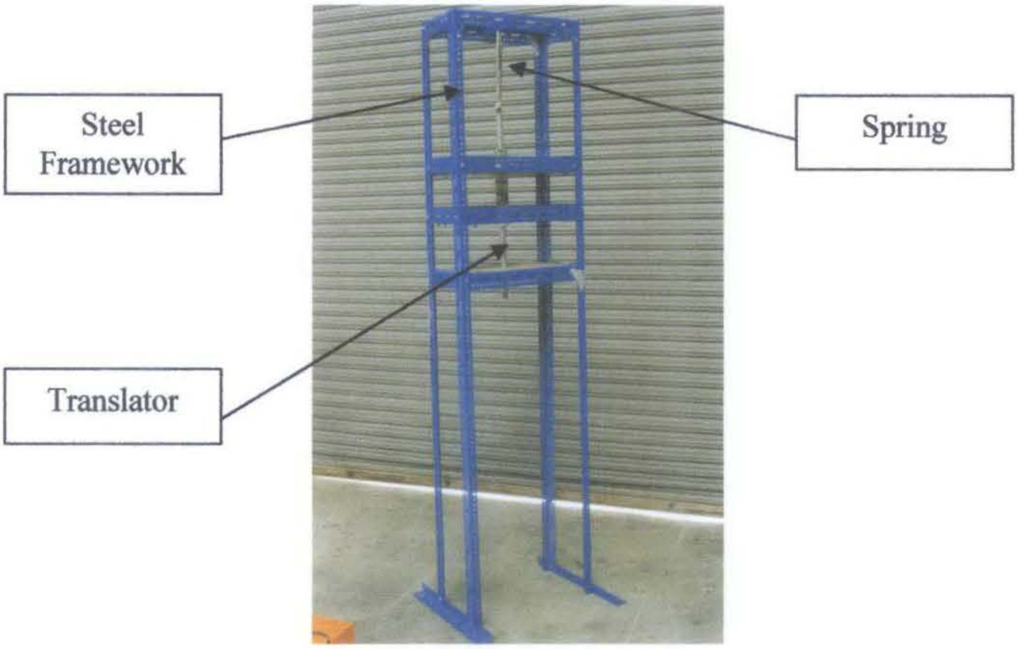

Figure 3.7: Steel Framework

3.2.5 Research on wave energy tank

Description:

Wave energy tank is a tank that used wave generator to create waves of various types. This accessory unit is used to help obtain information on the behavior of waves in the offshore area as well as in coastal protection. The rotational speed of the drive motor can be sleeplessly varied, corresponding to wave frequency. Furthermore, the stroke also can be sleeplessly adjusted, causing a change in the wave height (amplitude). So, the waves can be changed in frequency and amplitude. The wave energy tank dimension is shown in Figure 3.8.

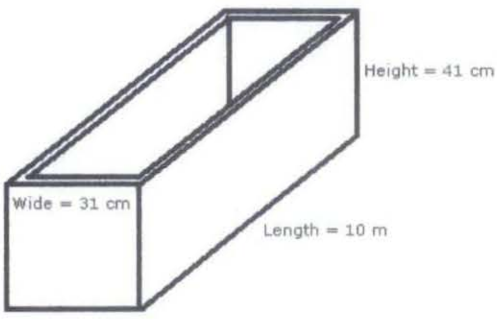

Figure 3.8: Wave Energy Tank Dimension

Figure 3.9: Wave Energy Tank

The framework that holds the linear generator was placed on the wave tank as shown in the Figure 3.9. The linear generator was positioned at the area that the wave occurs in the smooth and constant waveform. The framework has been adjusted to put the floater precisely on the surface of the water. This is because; to make sure that the linear generator was powered by the wave energy from the surface of the wave. Thus, the oscillation of the linear generator perfectly showed the output power result from surface wave energy.

3.2.6 Linear Generator Connection

Description:

The winding for each phase has two output leads (for a total of six in a three-phase system). If we examine an actual three phase machine, we will see only three leads coming out. This is because they are connected inside the generator. The two possible configurations are delta and star connection is shown in Figure 3.10.

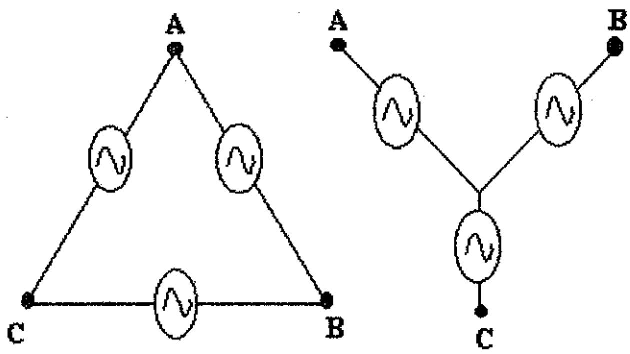

Figure 3.10: Delta and Star connection

- **Phase Voltage (V_{phase})** : The induced potential across any single phase; measured inside the machine casing.
- **Phase Current (I_{phase})** : The current passing through any single phase; measured inside the machine casing.
- **Line Voltage (V_{line})** : The potential across any pair of wires (A-B, B-C, C-A); measured outside the machine casing.
- **Line Current (I_{line})** : The current passing through any one of the three output cables (A, B, or C); measured outside the machine casing.

For this project, the connection is star connection. The equations are:

$$V_{line} = V_{phase} x\sqrt{3}$$

$$I_{line} = I_{phase}$$

To calculate the power output for the three phase system, the equations are:

$$AP = \sqrt{3} x V_{line} x I_{line}$$

$$TP = APxpf$$

where:
AP : Apparent Power
TP : Reactive Power
pf : Power Factor

Connection Diagram:

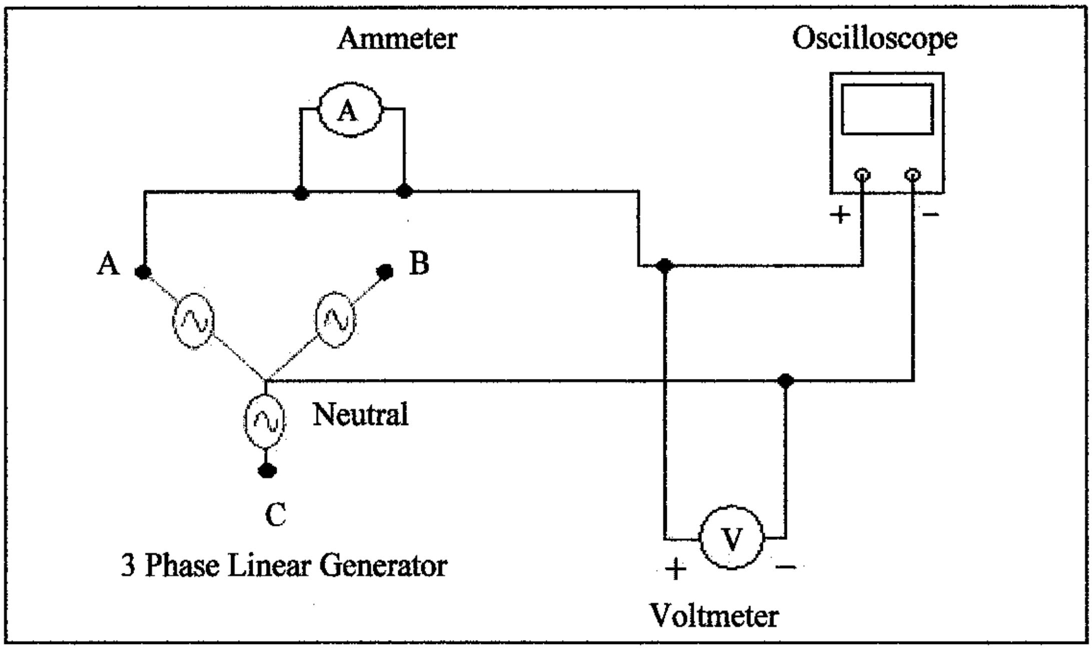

Figure 3.11: One Phase Connection

The induced voltage and current is measured on the one phase of the star connection as showed in Figure 3.11. The output line voltage from movement up and down of linear generator is measure using the voltmeter and the waveform of the line voltage will be identified using the oscilloscope. The line current is measured by using the ammeter. From the formula of three phase star connection, the power output of the linear generator can be calculated.

3.3 Wave Energy Linear Generator Prototype

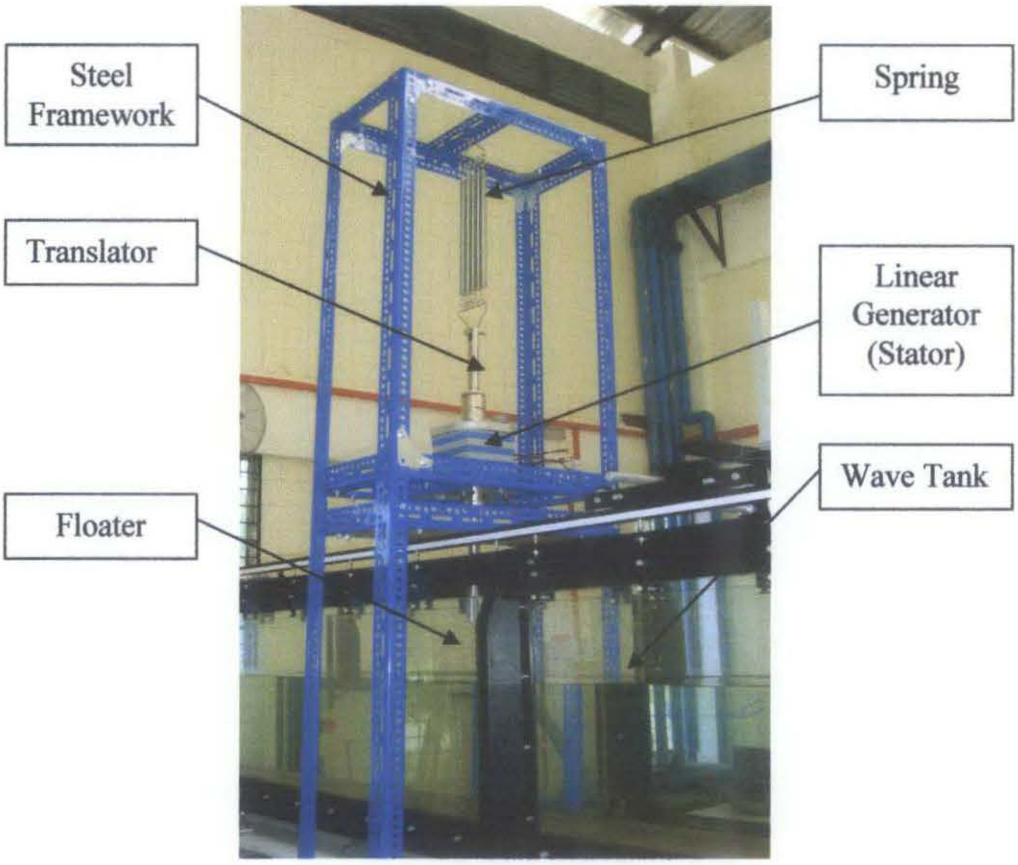

Figure 3.12: Linear Generator on the Wave Energy Tank

The assembly of the all components of the wave energy linear generator prototype on the wave energy tank was shown in Figure 3.12. The steel framework is functioning to hold the linear generator on the wave tank. Then, the framework was adjusted to put the floater that was attached at the end of the shaft of the translator on the surface of the water. The floater is used to capture the movement of the wave. The upper end of the translator was connected with spring that will support the oscillation motion of the linear generator. The translator was positioned at the middle hole of the stator because the oscillation of the translator into the stator can produce friction. The friction can affect the output power result for the linear generator.

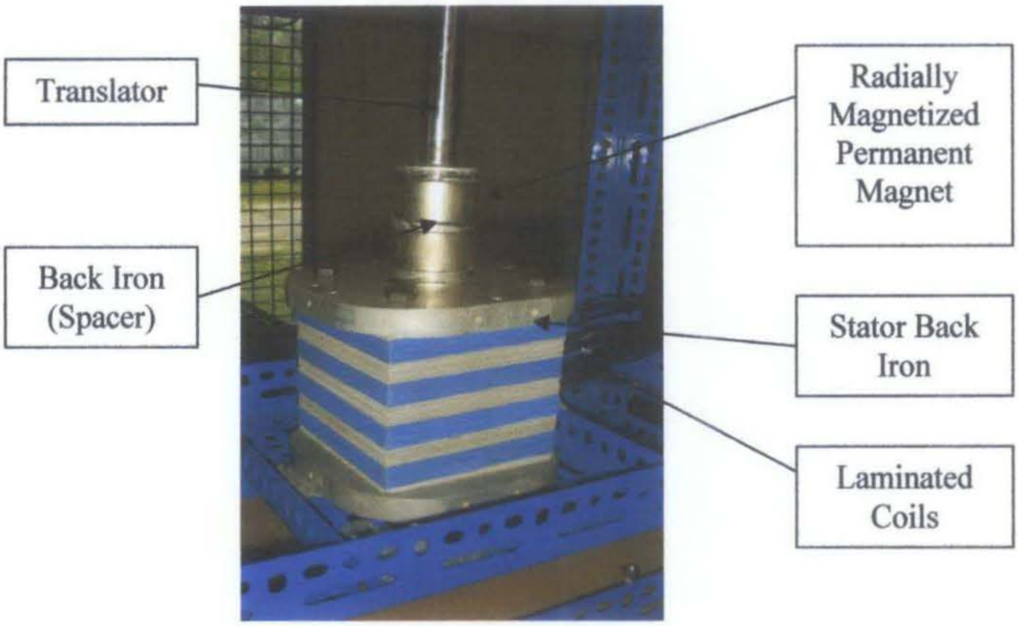

Figure 3.13: Linear Generator on the Steel Framework

The translator is one stroke longer than the stator as shown in Figure 3.13. A long translator linear generator was chosen for the prototype because through the cycle of oscillation inside the stator, the translator can activate all coils. Means that, all the laminated coils in stator and permanent magnet on the translator was energized by cuts the magnetic flux and produce the output power. The flux linkage due to the permanent magnet depends on the pole pitch and the displacement. The maximum flux linkage occurs when the axis of the coil is aligned with that of the permanent magnet pole. Under these conditions, we have maximum EMF at peak linear speed. By using the spiral of electrical laminated coils, it can provide the flux return path through the generator. The laminated coils were divided into 3 phases, Phase A, Phase B and Phase C. Based on line voltage and line current, measurement could be done by connect the laminated coils of the linear generator with the measuring equipment using the star connection.

CHAPTER 4

RESULT AND DISCUSSION

4.1 Result

This linear generator model is designed to generate at least 1 kW of electricity from ocean waves. To build this model, various aspects need to be counted such as the spring selection for the linear generator to move up and down and linear generator components itself. In spring selection, the displacement of the spring must be obtained correctly in order to have constant movement while generating the electricity. So, the forced exerted by the linear generator should be counted correctly in order to select the best value of spring stiffness constant.

For the linear generator itself, the steel plate in the armature of the generator need to be change into paper plate. This is because the magnet pack usually stuck at the steel plate in the armature when move in up and down motion. To solve this problem, the steel plate in the armature is replaced with paper but this changing is afraid may cause some reduce in efficiency of the power produce.

Furthermore, to obtain smooth movement of linear generator, the height of the framework must be adjust suitable to the length of the linear generator. Steel framework functions as stand to hold the linear generator during the operation. The height of the framework must be designed high enough to apply motion of the generator without reaching the water.

For generator circuit connections, there are two possible configurations to obtain three phase connection which are Delta and Star connection. For this generator, we use Star connection because for a given amount of line voltage and line current, the star generator has a larger current while a delta connected machine has a smaller phase current. Unfortunately, because of this more power is lost inside the generator in the form of heat for star connection than delta connection. Beside that manufacturing and rewinding of a star connected machine is easier due to the less complex connections of the windings. If one phase of a star connected machine opens up, two of the three output voltages will go to zero volts. This occurrence does not allow a selection of which loads to remove. Two thirds of the loads on that generator will lose power.

After completed all of the requirements, the experiment of the project can be done in wave energy tank. Wave energy tank is a tank that use wave generator to create waves for the experiment of linear generator. Through this we will get the amount of power generated by the system.

4.1.1 Experiment using Wave Energy Tank

An experiment had been conducted to test the linear generator. Certain amount of wave frequency had been selected to see the output from the linear generator. The wave increment also had been measured for each wave frequency. Below are the results of the experiment:

Table 4.1: Wave Increment for certain Wave Frequency

Wave Frequency[Hz]	Wave Increment[cm]
0	0.0
10	2.5
20	4.0
30	7.0
40	12.0
50	13.5
60	15.0
70	9.0
80	7.0
90	5.5

Table 4.2: Line Voltage for One Phase

Wave Frequency[Hz]	Line Voltage [mV]		
	Minimum	Maximum	Average
30	9.73	27.50	13.20
40	9.66	44.19	14.73
50	11.92	36.07	21.12
60	11.90	54.16	27.20
70	15.5	33.8	21.66
80	10.69	18.78	13.20
90	10.00	18.78	11.63

Table 4.3: Apparent Power Calculation for One Phase

Wave Frequency [Hz]	Average Line Voltage [mV]	Line Current (I) [mA]	Apparent Power, $AP = V_{line} \times I_{line}[10^{-6}$ W]
30	13.20	1.111	14.67
40	14.73	1.113	16.39
50	21.12	1.116	23.57
60	27.20	1.118	30.41
70	21.66	1.114	24.13
80	13.20	1.111	14.67
90	11.63	1.110	12.91

Table 4.4: Total Apparent Power Generated by Linear Generator

Wave Frequency[Hz]	Total Apparent Power, $AP = \sqrt{3} \times V_{line} \times I_{line}$ [10^{-6} W]
30	25.41
40	28.39
50	40.82
60	52.67
70	41.79
80	25.41
90	22.36

4.1.2 Graph of Experiment

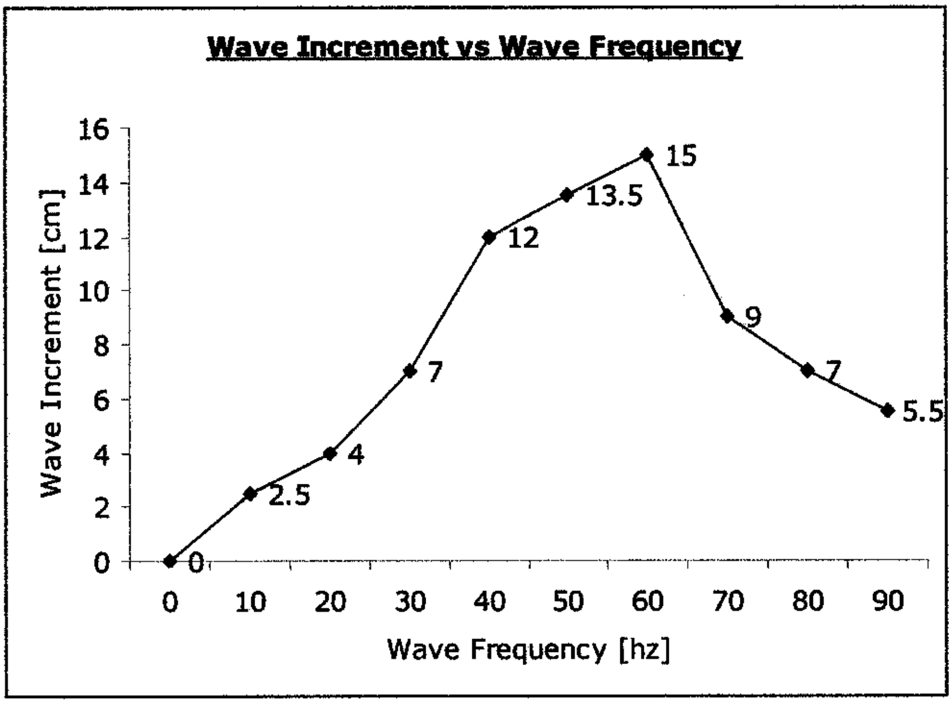

Figure 4.1: Wave Increment vs. Wave Frequency

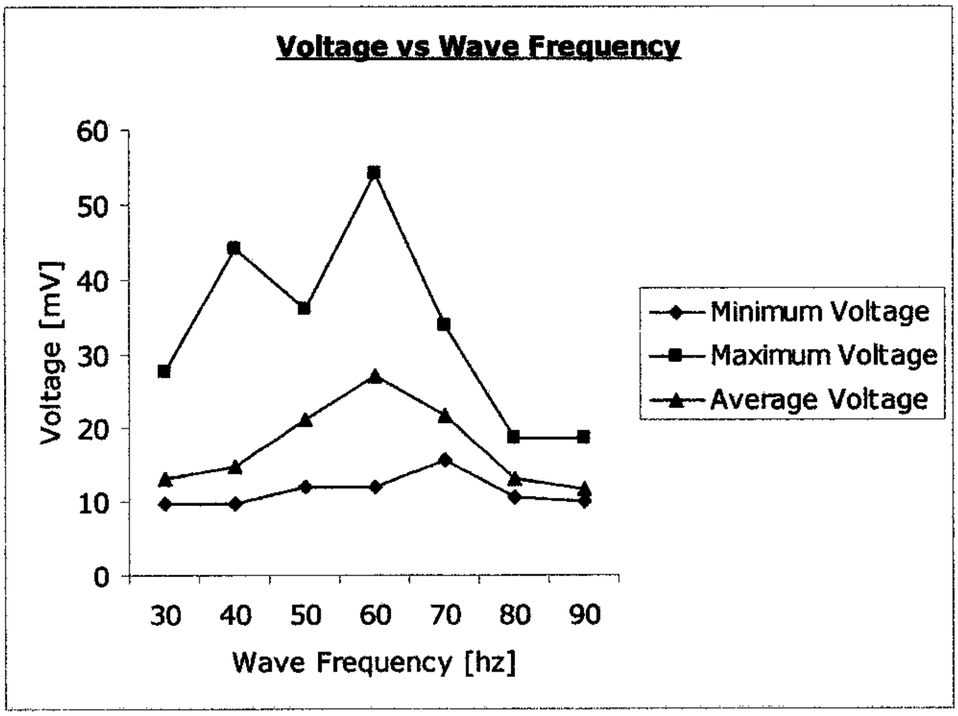

Figure 4.2: Line Voltage vs. Wave Frequency

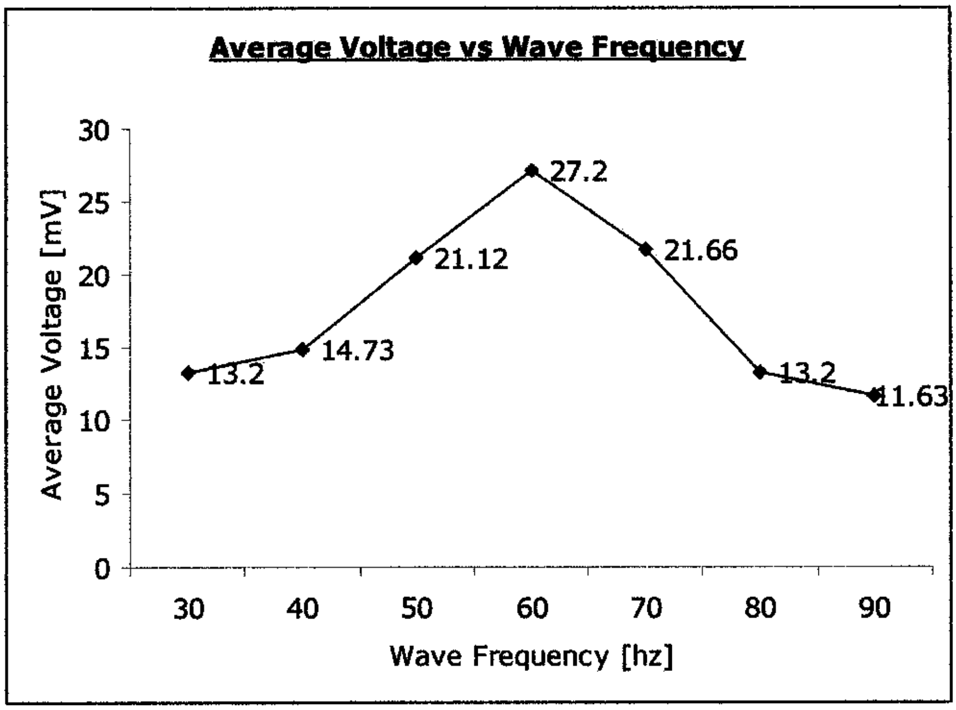

Figure 4.3: Average Line Voltage vs. Wave Frequency

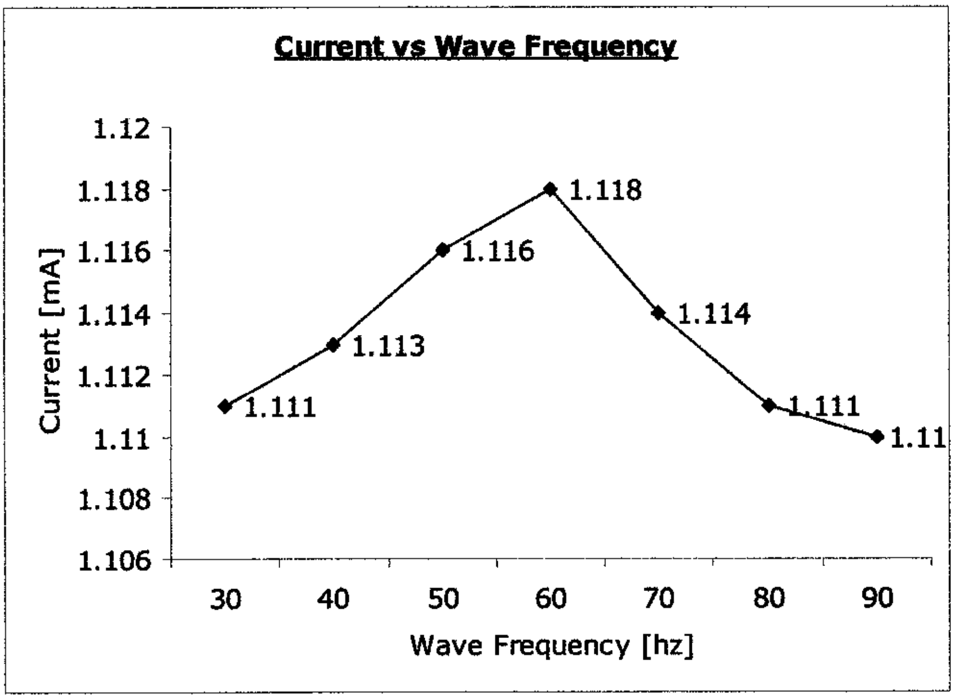

Figure 4.4: Line Current vs. Wave Frequency

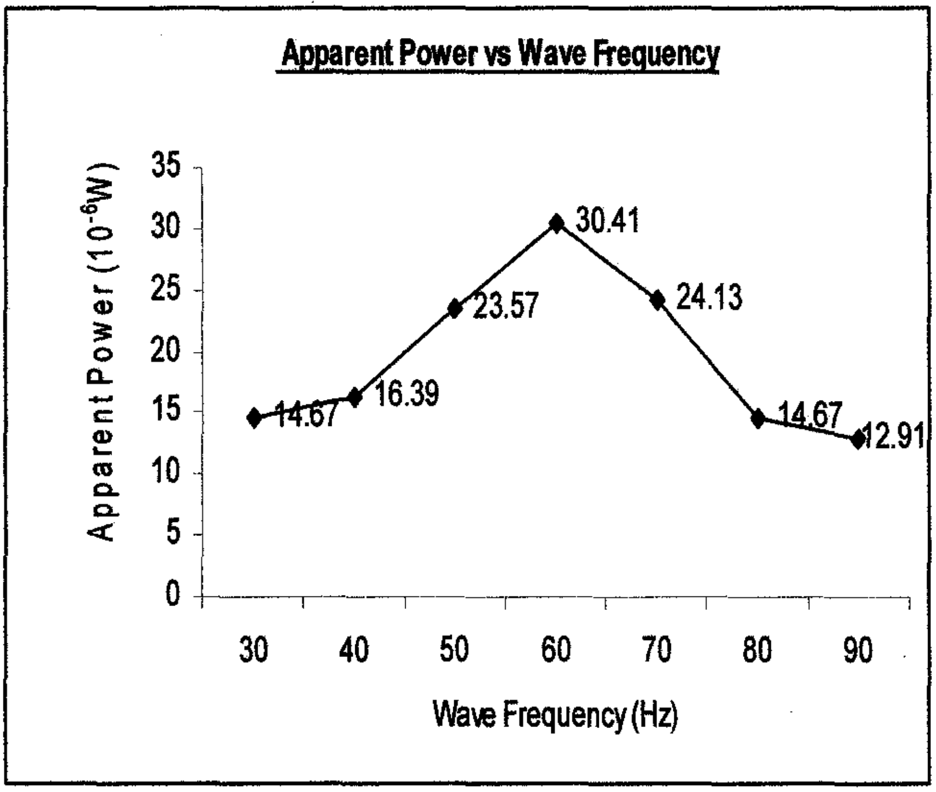

Figure 4.5: Apparent Power vs. Wave Frequency

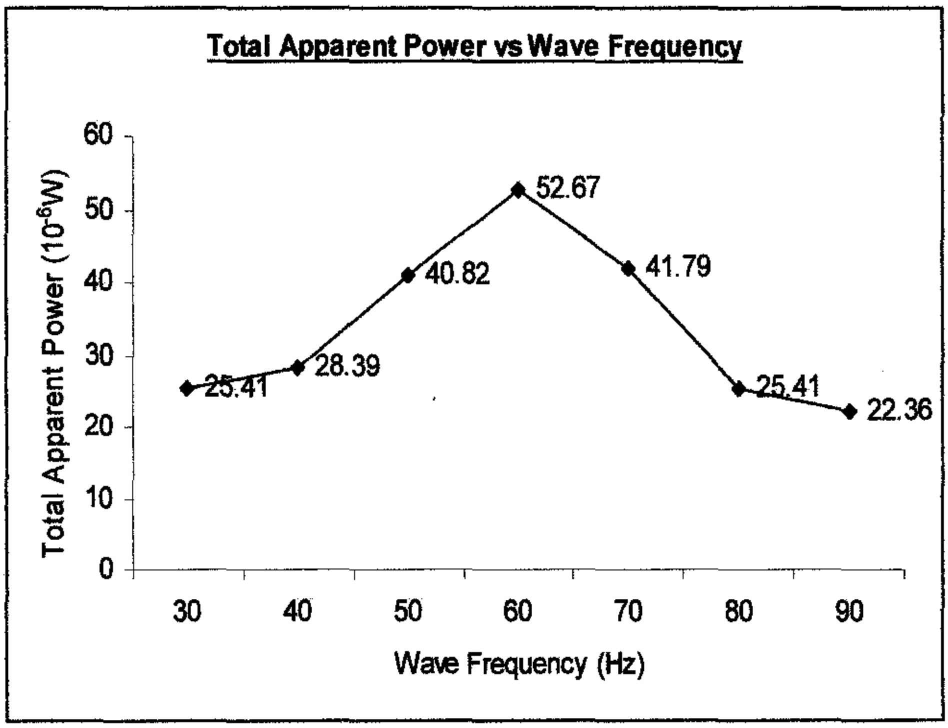

Figure 4.6: Total Apparent Power vs. Wave Frequency

4.1.3 Line Voltage Waveform

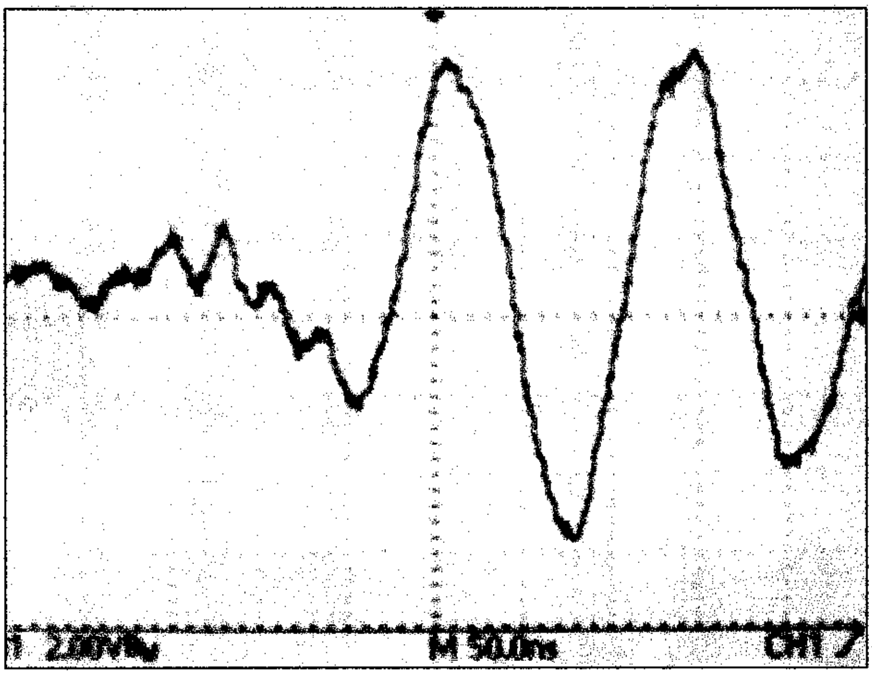

Figure 4.7: 30 Hz Wave Frequency

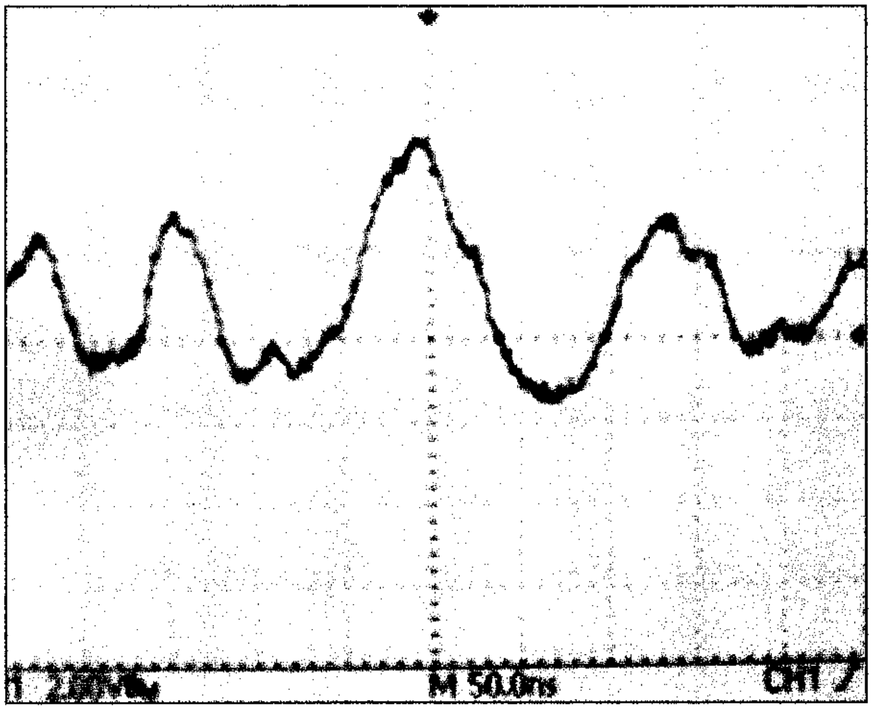

Figure 4.8: 40 Hz Wave Frequency

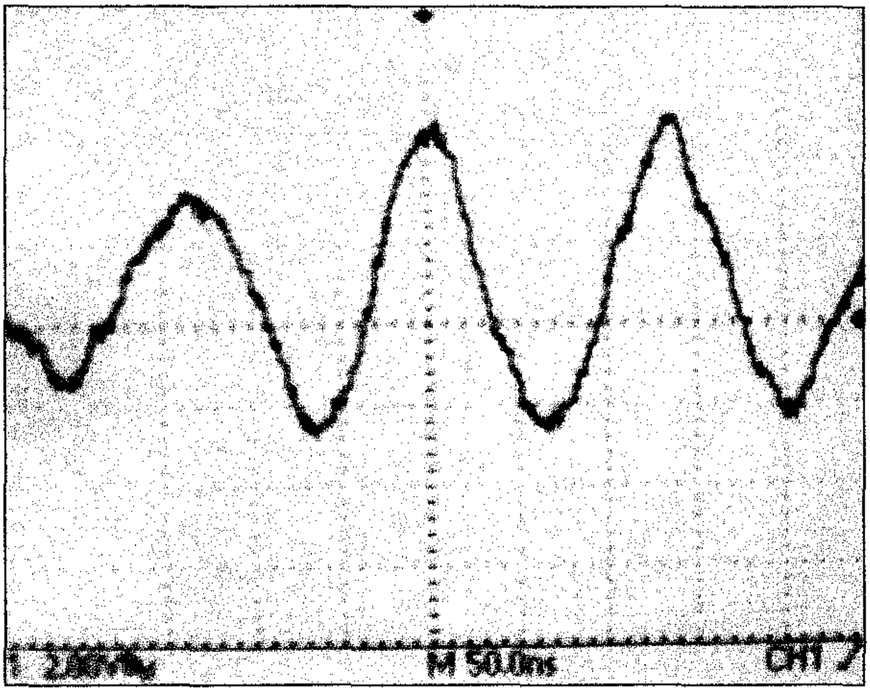

Figure 4.9: 50 Hz Wave Frequency

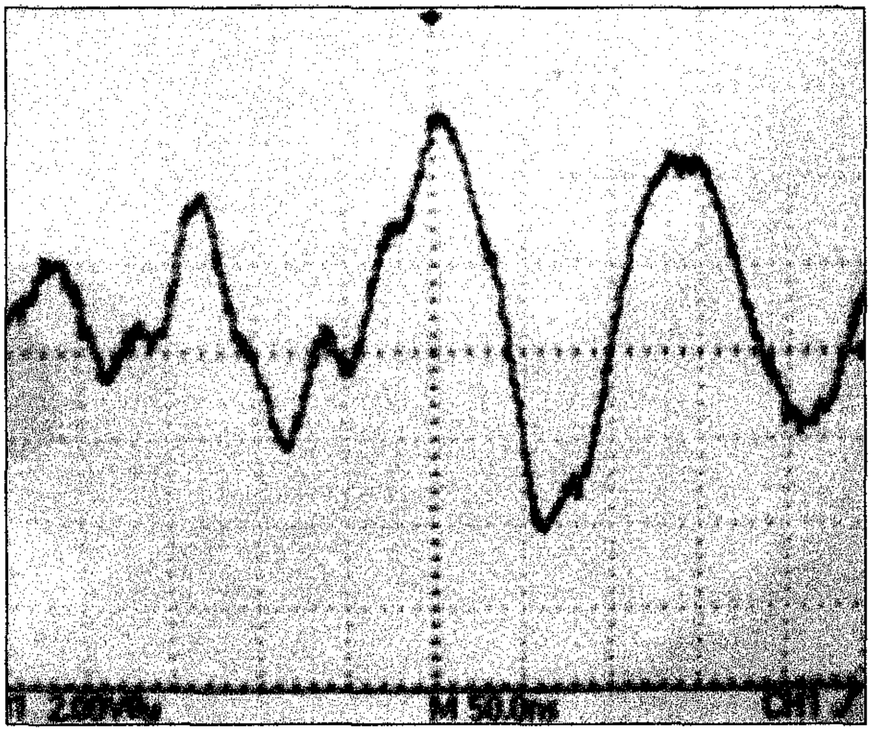

Figure 4.10: 60 Hz Wave Frequency

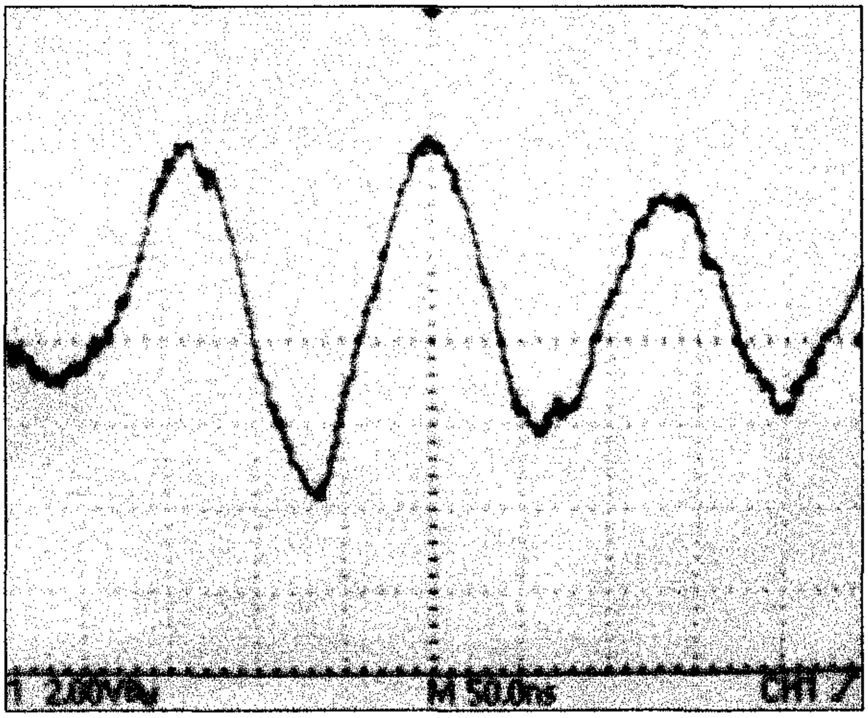

Figure 4.11: 70 Hz Wave Frequency

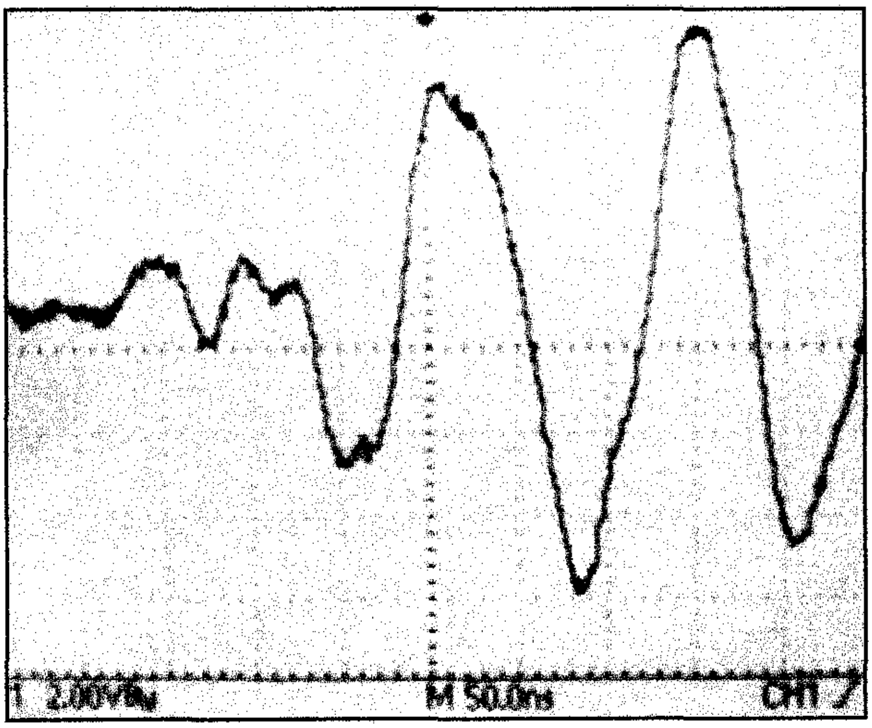

Figure 4.12: 80 Hz Wave Frequency

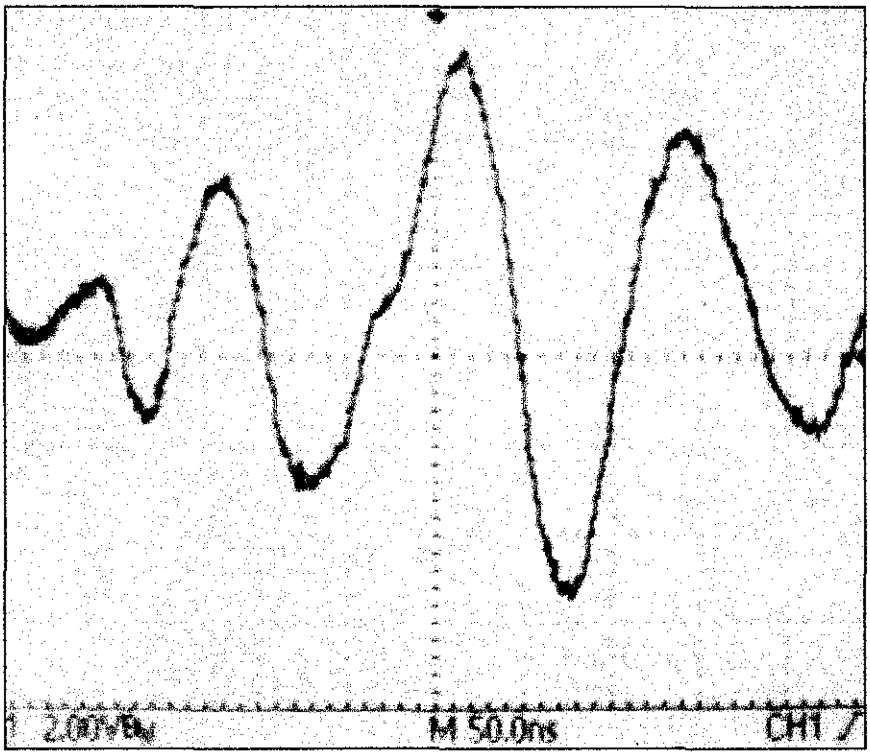

Figure 4.13: 90 Hz Wave Frequency

4.2 Discussion

From Table 4.1, the increments of wave from 10 Hz to 60 Hz were increasing. Following the theory, the increments should be decreasing as the frequency become larger. These errors occur because of the limited length of wave tank that limit the space for wave to be fully generated. From 60 Hz to 90 Hz, the wave was decrease proportionally to the higher frequency.

From Table 4.2, the output of line voltage was directly proportional to the increment of the wave height. The larger the wave height, the higher the line voltage produced. Since the wave height for 60 to 10 Hz was decreasing, it also cause the output of line voltage became smaller.

From Table 4.3 and 4.4, the apparent power produced for this experiment is small because of certain errors that occur during the experiment such as limited wave height, improper movement of the floater, permanent magnet condition is not so good and the changes of steel plate in the generator to the paper plate that result lower efficiency of the generator. So, the results can be improved if we minimized the errors.

From the Figure 4.7 until Figure 4.13, the motion of waveform of the line voltage is not stable and changing rapidly. When the translator is moved, the flux linkage is generated in the coil. Then, voltage is induced on the coils terminal. The oscillation of translator in the stator by using the wave energy is not constant and consequently producing high noise and harmonics in the line voltage waveform. Furthermore, the cutting of electromagnetic flux inside the stator winding not occurs in complete position and reduces the efficiency of the linear generator performance. Therefore, the waveform is not accurately describing the motion of the induced voltage in the linear generator. The voltage waveform depends on the speed characteristic of the translator motion.

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

5.1 Conclusion

The sinusoidal motions in this experiment describe the motion of the translator, not the ocean wave. A description of the translator motion should be based on force models including spring force, electromagnetic forces and gravity. The variations in the output voltage depend on the speed of the generator translators that cuts the magnetic flux in the armature and results in generating electricity. The results show that the load current and hence not unexpectedly, the output power, depends to a large extent on the translator speeds. Thus, the wave energy linear generator is unable to generate 1kW of electricity.

5.2 Recommendations

The result of this experiment can be improved if certain errors are minimized. For future works, another experiment will be done in the wave tank with some modification to minimize the errors. To get the more accurate result, auxiliary system (rectifier, DC converter, and inverter) should be use in the measuring part. It can produce smooth output voltage and current and reduce the noise and harmonics.

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APPENDICES

APPENDIX A

Lorentz Force Law

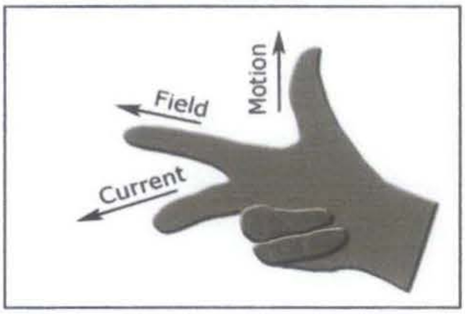
In physics, the Lorentz force is the force exerted on a charged particle in an electromagnetic field. The particle will experience a force due to electric field of $q\mathbf{E}$, and due to the magnetic field $q\mathbf{v} \times \mathbf{B}$. Combined they give the Lorentz force equation (or law):

$$\mathbf{F} = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}),$$

where

F is the force (in newtons)
E is the electric field (in volts per meter)
B is the magnetic field (in teslas)
q is the electric charge of the particle (in coulombs)
v is the instantaneous velocity of the particle (in meters per second)
× is the cross product.

Thus a positively charged particle will be accelerated in the *same* linear orientation as the **E** field, but will curve perpendicularly to both the instantaneous velocity vector **v** and the **B** field according to the right-hand rule (*i.e.*, if the thumb of the right hand points along **v** and the index finger along **B**, then the middle finger points along **F**).



Fleming's right hand rule (for generators) shows the direction of induced current flow when a conductor moves in a field. The right hand is held with the thumb, first finger and second finger mutually at right angles, as shown in the diagram.

- The Thumb represents the direction of Motion of the conductor.
- The First finger represents the direction of the Field.
- The Second finger represents the direction of the induced or generated Current (in the classical direction, from positive to negative).

APPENDIX B

Faraday's Law

Faraday's law of induction (more generally, the law of electromagnetic induction) states that the induced EMF (electromotive force) in a closed loop equals the negative of the time rate of change of magnetic flux through the loop. This simply means that the induced EMF is proportional to the rate of change of the magnetic flux through a coil.

In layman's terms, moving a conductor (such as a metal wire) through a magnetic field produces a voltage. The resulting voltage is directly proportional to the speed of movement: moving the conductor twice as fast produces twice the voltage. (The magnetic field, the direction of movement, and the voltage are all at right angles to each other. Whenever movement creates voltage, Fleming's right hand rule describes the direction of the voltage.)

The relation between the rates of change of the magnetic flux through the surface S enclosed by a contour C and the electric field along the contour:

$$\oint_C \mathbf{E} \cdot d\mathbf{l} = -\frac{d}{dt}\int_S \mathbf{B} \cdot d\mathbf{A}$$

where

> **E** is the electric field,
> **dl** is an infinitesimal element of the contour C,
> **B** is the magnetic field.

The directions of the contour C and of $d\mathbf{A}$ are assumed to be related by the right-hand rule. Equivalently, the differential form of Faraday's law is

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

which is one of the Maxwell equations.

In the case of an inductor coil where the electric wire makes N turns, the formula becomes:

$$\mathcal{E} = -N\frac{d\Phi_B}{dt}$$

where EMF is the induced electromotive force and $d\Phi/dt$ is the time-rate of change of magnetic flux Φ. The direction of the electromotive force (the negative sign in the above formula) was first given by Lenz's law.

APPENDIX C

Symbols

B_m = PM operation flux density, T

H_m = PM operation field intensity, A/m

g = air gap, m

k_s = saturation factor

B_r = residual flux density, T

μ_{rc} = PM recoil permeability, H/m

B_g = airgap flux density, T

H_g = airgap magnet field intensity,A/m

H_m = main magnet thickness,m

H_s = spring magnet thickness (being backed by iron core)

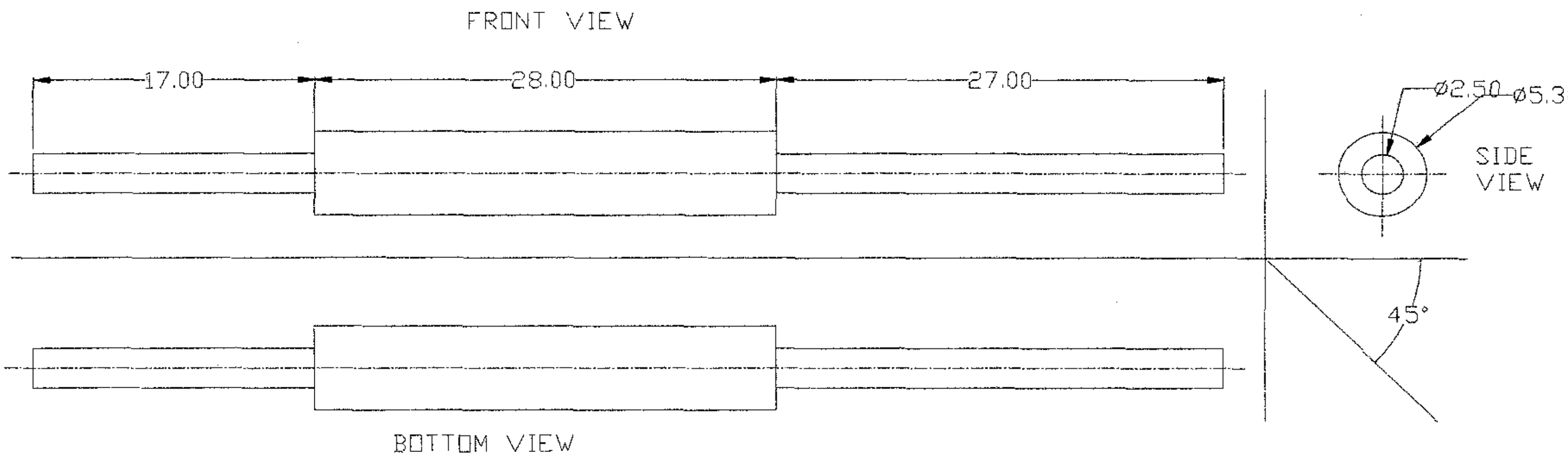
APPENDIX D

Linear Generator Dimension

ITEM	SPECIFICATION	UNIT
Shaft radius	2.5	cm
Magnet (axial and radial) inner radius	5.3	cm
Radial magnet length	3.5	cm
Radial magnet thickness	0.5	cm
Axial magnet length	2.0	cm
Axial magnet thickness	0.5	cm
Air Gap	0.2	cm
Stator back iron	8.5	cm
No. of turn per coil	312	turn

APPENDIX E

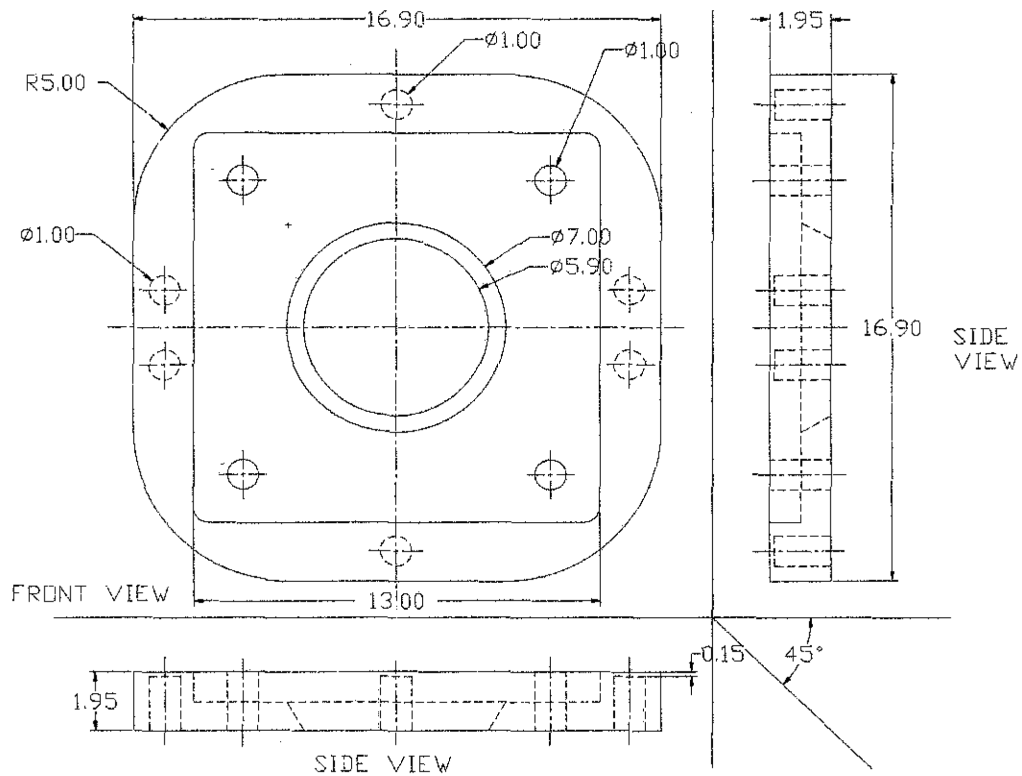
Dimension of Translator



Note: All dimensions are in centimeter unit **Scale: 1:1**

APPENDIX E

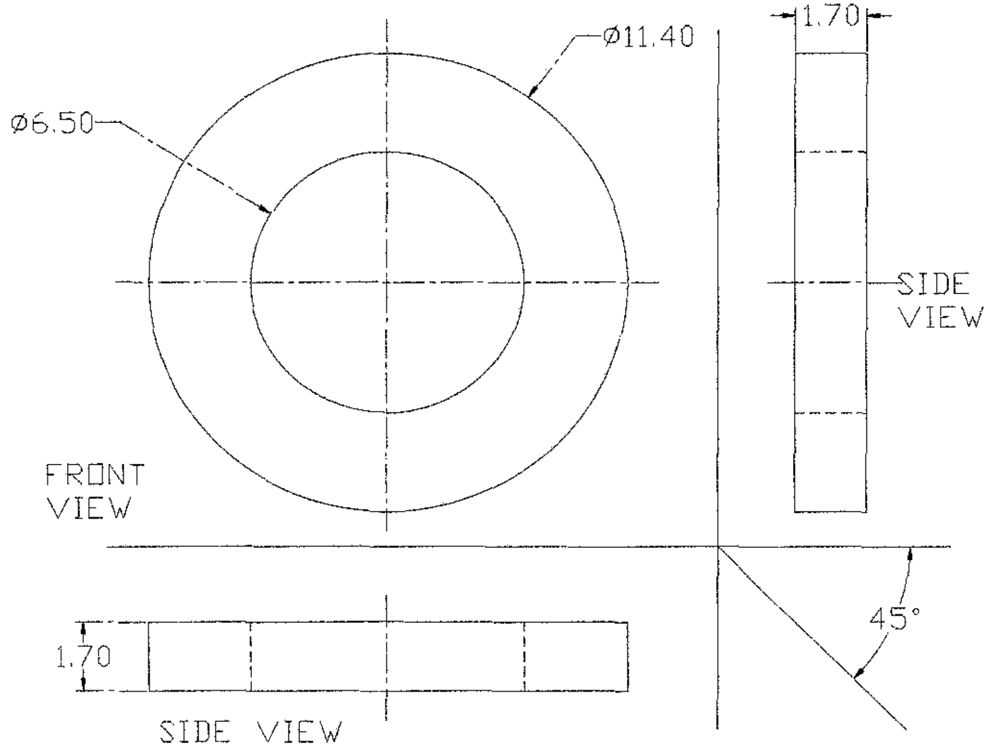
Dimension of Stator



Note: All dimensions are in centimeter unit **Scale: 1:1**

APPENDIX E

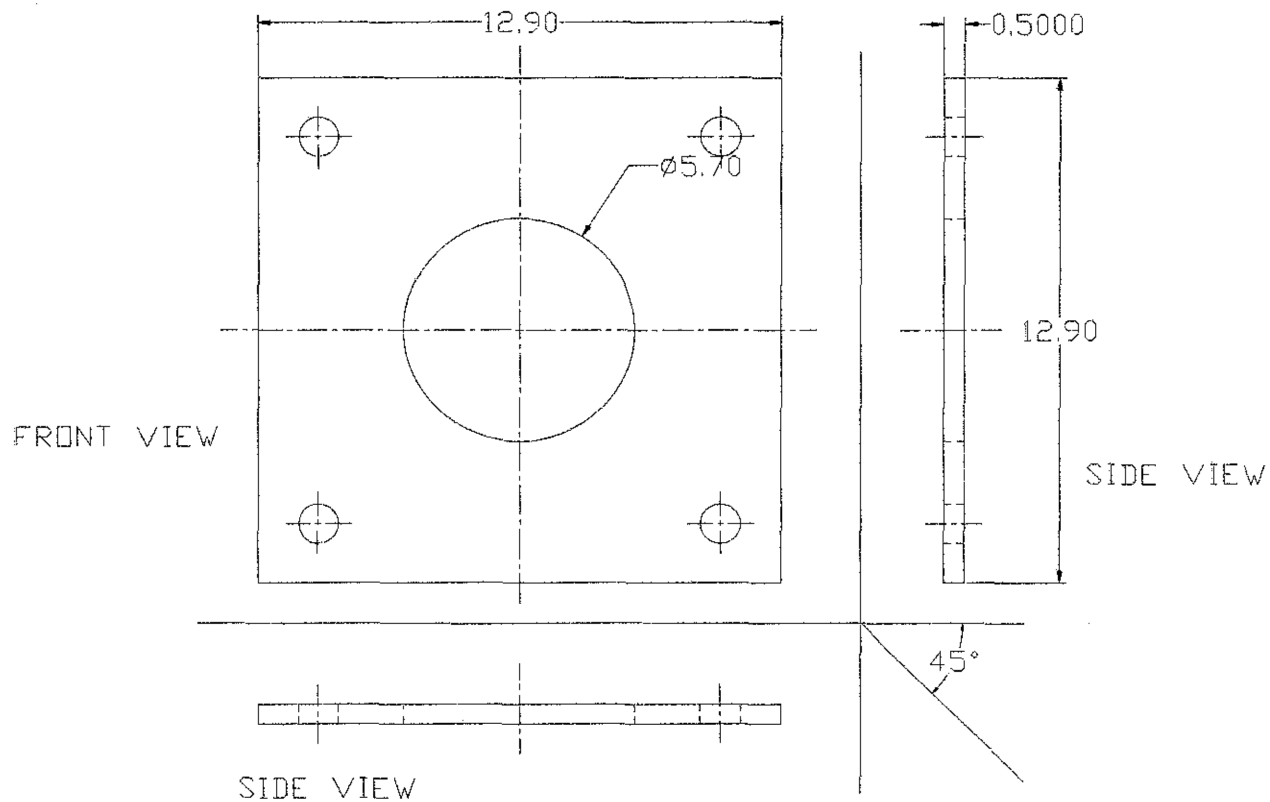
Dimension of Coil



Note: All dimensions are in centimeter unit **Scale: 1:1**

APPENDIX F

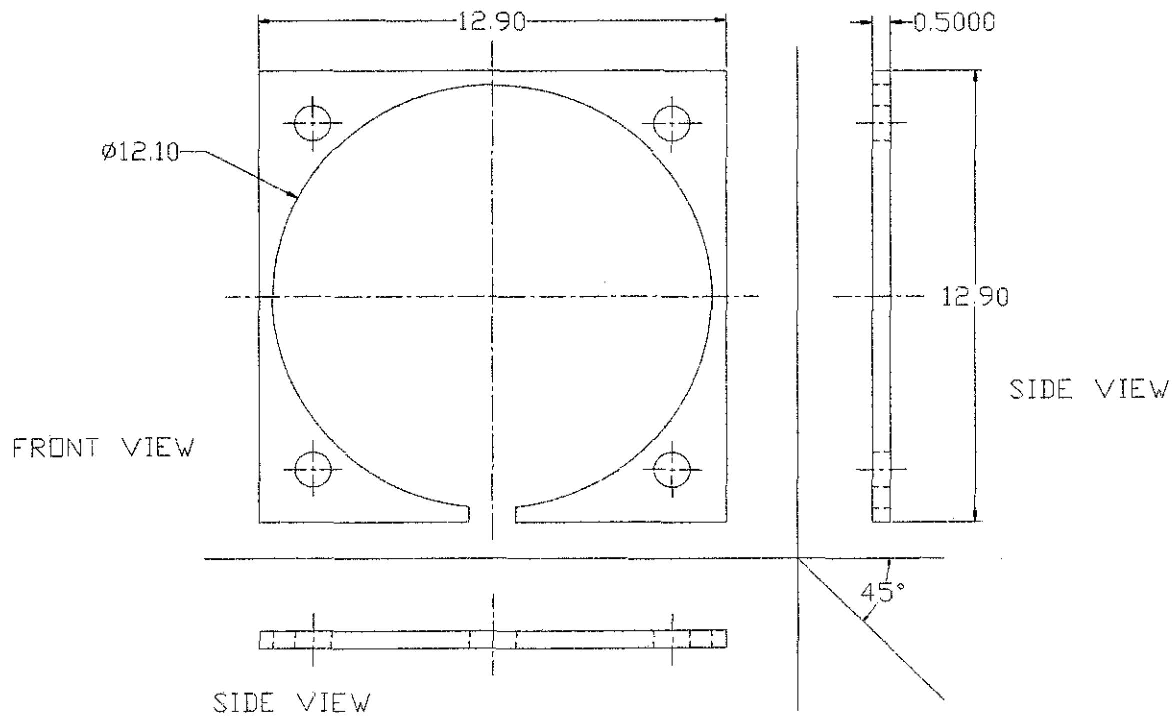
Dimension of Paper Plate [A]



Note: All dimensions are in centimeter unit **Scale: 1:1**

APPENDIX F

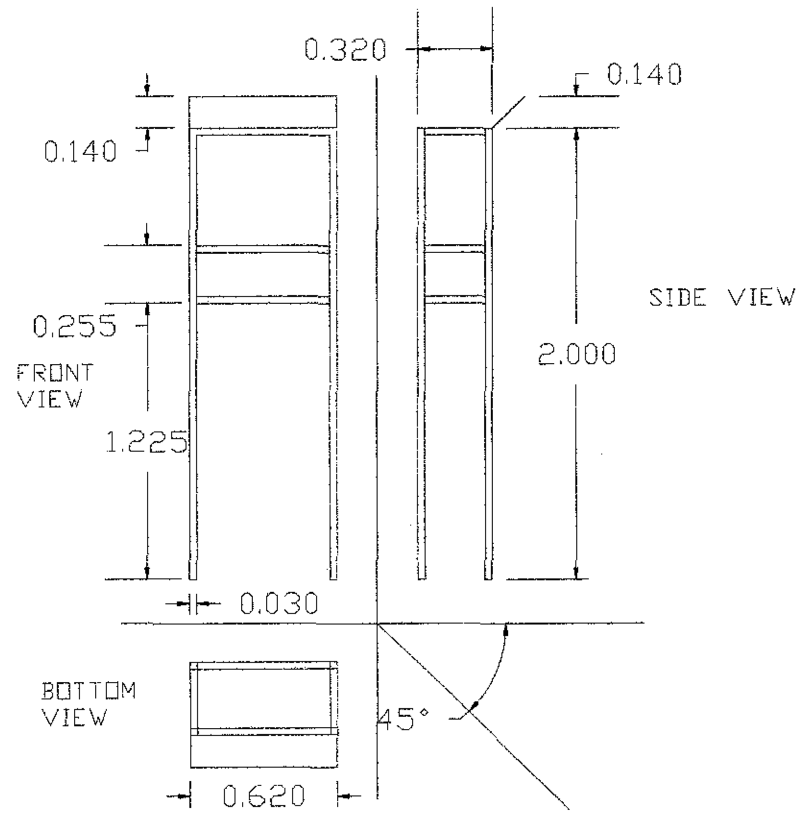
Dimension of Paper Plate [B]



Note: All dimensions are in centimeter unit **Scale: 1:1**

APPENDIX G

Dimension of Steel Framework



Note: All dimensions are in meter unit **Scale: 1:1**

APPENDIX H: **Suggested Milestone for the First Semester of 2-Semester Final Year Project**

No.	Detail/ Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic															
2	Preliminary Research Work															
3	Submission of Preliminary Report															
4	Seminar 1 (optional)															
5	Project Work															
6	Submission of Progress Report															
7	Seminar 2 (compulsory)															
8	Project work continues															
9	Submission of Interim Report Final Draft															
10	Oral Presentation															

Suggested milestone

Process

APPENDIX I: **Suggested Milestone for the Second Semester of 2-Semester Final Year Project**

No.	**Detail/ Week**	**1**	**2**	**3**	**4**	**5**	**6**	**7**		**8**	**9**	**10**	**11**	**12**	**13**	**14**
1	Project Work Continue															
2	Submission of Progress Report 1															
3	Project Work Continue															
4	Submission of Progress Report 2															
5	Seminar (compulsory)															
5	Project work continue															
6	Poster Exhibition															
7	Submission of Dissertation (soft cover)															
8	Oral Presentation															
9	Submission of Project Dissertation															

Suggested milestone

Process