# LINEAR GENERATOR PERFORMANCES DETERMINATION FOR WAVE HARVESTING SYSTEM

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# LINEAR GENERATOR PERFORMANCE DETERMINATION FOR WAVE HARVESTING SYSTEM

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**A thesis submitted**
**in fulfillment of the requirements for the degree of Bachelor Mechanical Engineering (with Honours)**

**FACULTY OF MECHANICAL ENGINEERING**



**UNIVERSITI TEKNIKAL MALAYSIA MELAKA**

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# DECLARATION

I declare that this thesis entitled "Linear generator performances determination for wave harvesting system" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



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| Date | :........................................................ |

# APPROVAL

I hereby declare that I have read this thesis and in my opinion this thesis is sufficient in terms of scope and quality for the award of the degree of Bachelor of Mechanical Engineering (with Honours).

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| Signature | :........................................................... |
| Supervisor Name | : Dr. Yusmady Bin Mohamed Arifin |
| Date | :........................................................... |

# DEDICATION

To my beloved family, friends and teachers

# ABSTRACT

Wave energy is a classic example of renewable energy. The energy amount is measured by speed and height of wave, wavelength and water density. The stronger the waves, the more capable it is to produce power. Motion energy that is produced by the wave energy is used to do tasks such as generate electricity, powering plants and pumping of water into reservoirs. Wave energy does not emit hazardous gasses to the environment. This is why it is known as completely clean source. On the other hand, fossil fuels, oil, coal and natural gas contribute to pollution as they release dangerous gasses such as carbon dioxide, nitrous oxide, methane and ozone to the atmosphere. Linear generators in wave energy conversion depends on high force, low speed, irregular motion and cost. Their performance varies when they have some changes in applying those requirements. The purpose of this study is to develop a linear generator test rig and investigate the performance of the system by testing different linear generator configuration. An experimental setup was developed consists of DC motor, solenoid magnet, wave plotter and crankshaft shapes. The experiment is conducted using different crankshaft shapes. Plywood was cut in different shapes and named as A (semicircle), B (star), C (spur gear) and D (droplet). Wave plotter was used to determine the wave patterns of different shapes. Multimeter and speed controller were used to collect the current readings. Performance of the system is determined by the current produced by solenoid magnet due to crankshaft shapes. Shape B shows the highest current among the other but the reading starts to drop as the motor speed increases. Speed of motor inversely proportional to the current because as armature current increases, the flux produced also increases due to the series combination. So that, if armature current is reduced, flux is reduced which will increase speed of the motor.

## *ABSTRAK*

Tenaga ombak adalah contoh klasik tenaga boleh diperbaharui. Jumlah tenaga diukur dengan kelajuan dan ketinggian ombak, panjang ombak dan ketumpatan air. Semakin kuat ombak, semakin berpotensi untuk menghasilkan tenaga. Tenaga gerakan yang dihasilkan oleh tenaga ombak digunakan untuk melakukan tugas-tugas seperti menjana tenaga elektrik, menjana loji janakuasa dan mengepam air menjadi takungan. Tenaga ombak tidak mengeluarkan gas berbahaya kepada alam sekitar. Maka ia dikenali sebagai sumber yang bersih sepenuhnya. Sebaliknya, bahan api fosil, minyak, arang batu dan gas asli menyumbang kepada pencemaran kerana mereka melepaskan gas berbahaya seperti karbon dioksida, nitrous oksida, metana dan ozon ke alam sekitar. Penjana gerakan lurus dalam penukaran tenaga ombak bergantung pada daya yang tinggi, kelajuan yang rendah, gerakan tidak tetap dan kos. Prestasinya berbeza apabila mereka mempunyai beberapa perubahan dalam melaksanakan keperluan tersebut. Tujuan kajian ini adalah untuk membangunkan peralatan ujikaji penjana gerakan lurus dan mengaji prestasi sistem dengan menguji konfigurasi penjana gerakan lurus yang berlainan. Peralatan ujikaji yang dibangunkan terdiri daripada motor DC, solenoid magnet, pelakar ombak dan bentuk engkol. Eksperimen ini dijalankan dengan menggunakan bentuk engkol berbeza. Papan lapis dipotong dalam bentuk yang berbeza dan dinamakan sebagai A (separuh bulatan), B (bintang), C (gear taji) dan D (bentuk titisan air). Pelakar gelombang digunakan untuk menentukan corak gelombang yang terhasil daripada bentuk yang berbeza. Multimeter dan pengawal kelajuan digunakan untuk mengumpul bacaan arus elektrik. Prestasi sistem ditentukan oleh arus elektrik yang dihasilkan oleh magnet solenoid disebabkan oleh bentuk engkol. Bentuk B menunjukkan arus tertinggi di antara yang lain tetapi bacaan mula menurun apabila kelajuan motor meningkat. Kelajuan motor berkadar songsang dengan arus elektrik kerana arus deras meningkat, aliran yang dihasilkan juga meningkat disebabkan gabungan siri. Jadi, jika arus angker dikurangkan, fluks dikurangkan seterusnya meningkatkan kelajuan motor.

## ACKNOWLEDGEMENTS

All through my adventure in Universiti Teknikal Malaysia Melaka (UTeM), numerous individuals were included both straightforwardly and by implication helping me construct my scholastic profession. It would have been close difficult to finish this adventure without the help of these individuals. Hence, I am accepting this open door to address names that bolstered the finish of this proposal.

To start with, I might want to entire heartedly thank my supervisor, Dr. Yusmady Bin Mohamed Arifin from the Faculty of Mechanical Engineering UTeM for his unified direction, assistive supervision, and precious help towards the consummation of this exploration.

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| WEC | Wave Energy converters |
| LPMG | Linear Permanent Magnet Generator |
| TENG | Triboelectric Nanogenerator |
| AWS | Archimedes Wave Swing |
| DC | Direct Current |
| PVC | Polyvinyl Chloride |
| AC | Alternating Current |
| LED | Light-Emitting Method |
| PTO | Power Take Off Method |

# CHAPTER 1

# INTRODUCTION



## 1.1 Background

### 1.1.1 Wave energy

Wave energy is a classic example of renewable energy. When wind blows over the sea surface, it conveys the energy to the waves. The energy amount is measured by speed and height of wave, wavelength and water density. The stronger the waves, the more capable it is to produce power. Motion energy that is produced by the wave energy is used to do tasks such as generate electricity, powering plants and pumping of water into reservoirs.

Wave energy is highly predictable. They are available 24/7 and harbor more energy compared to wind energy and solar energy. Wind energy and solar energy cannot be predictable. Wind speed slows down unexpectedly might affects electricity while solar energy depends on sun, which cloud coverage and night hours can reduce sun exposure leading to less efficiency. Moreover, wave energy is an endless resource. Humans will continue consuming it to the very end.

Wave energy does not emit dangerous gasses to the atmosphere. This is why it is known as completely clean source. On the other hand, fossil fuels, oil, coal and natural gas contribute to pollution as they release dangerous gasses such as carbon dioxide, nitrous oxide, methane and ozone to the atmosphere.

### 1.1.2 Wave Energy Converters

Wave Energy Converters (WECs) change wave power into electricity. The WECs can be categorized into three types based on their size and direction of elongation. They are attenuators, point absorbers and terminators. Attenuators lie in parallel to the wave and they essentially they ride the waves. Figure 1.1 shows Pelamis wave farm, which is developed by Ocean Power Delivery is an example of attenuators WECs.



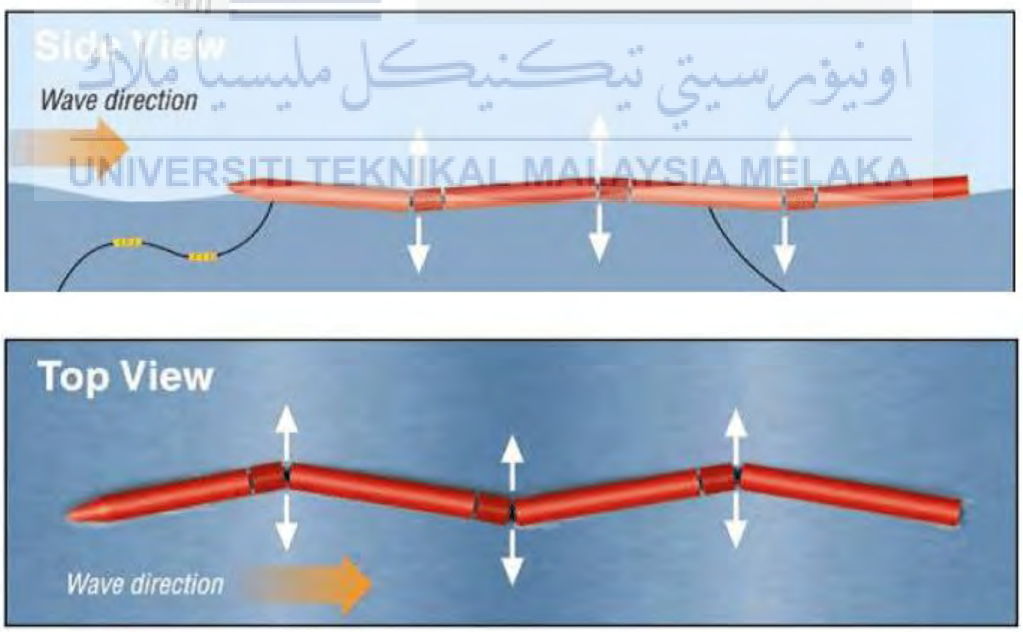


Figure 1.1 Pelamis wave farm (https://alchetron.com/Pelamis-Wave-Energy-Converter )

Point absorbers are buoy-type WECs that harvest wave energy from all directions due to their size which is smaller than wavelength. They are placed offshore at or near the ocean surface. They have floaters on movable arms as shown in Figure 1.2. The motion energy from the arms captured in common hydraulic line and transmitted into electric current.

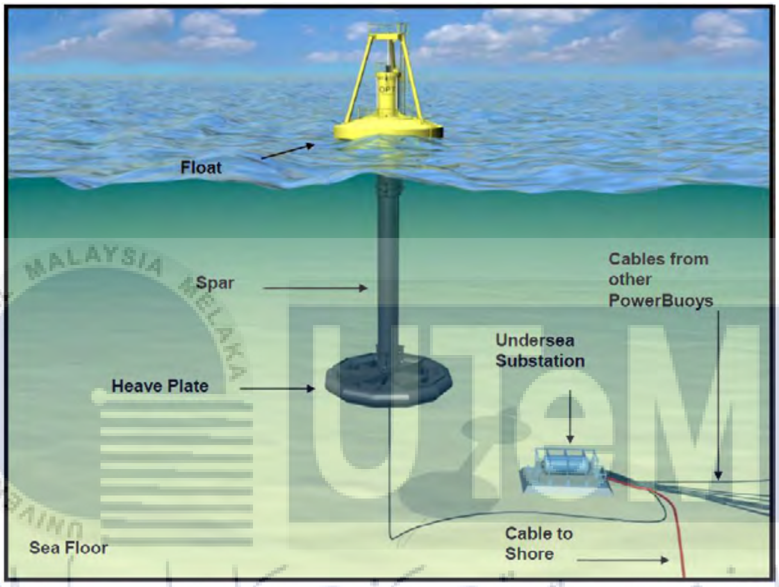


Figure 1.2 Point absorber (https://kaankoca.wordpress.com/tag/point-absorbers/)

Figure 1.3 shows terminator device that have their principal axis parallel to the wave front and physically intercept waves. The terminators are same as attenuators but they are perpendicular to the wave propagation direction. Salter's Duck, developed at the University of Edinburgh is terminator type of WEC.

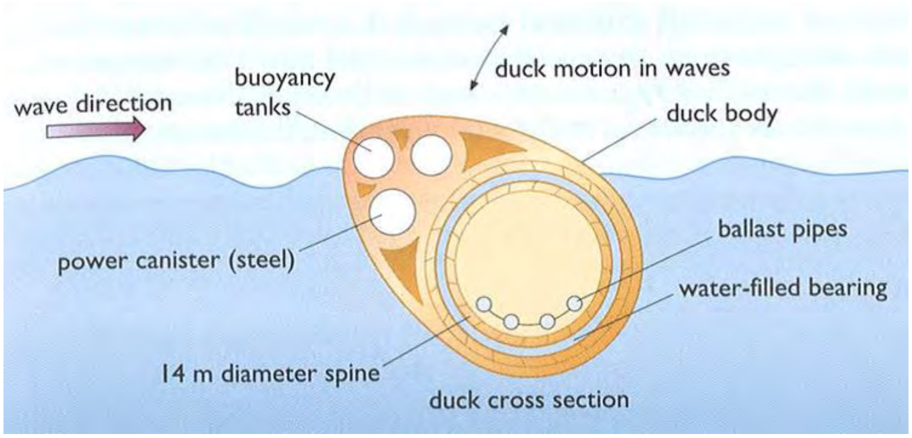


Figure 1.3 : Terminator type WEC (https://wave-energies.weebly.com/types-of-wec.html)

### 1.1.3 Linear Generator

Linear generator works on the principle of electromagnetic induction similar to any other generators. But it is differs from other generators because it works on linear motion while other generators work on rotatory motion. Linear motion is motion in straight line when magnet moves in to electromagnetic coil. This changes the magnetic flux passing through the coil and induces the flow of electric current which can be used to work. Linear generator is used to convert back forth motion directly to electrical energy. There are various conventional generator types that can be used in wave energy conversion, such as linear induction machines, linear synchronous machines with electrical excitation, linear switched reluctance machines and linear permanent-magnet synchronous machines.

## 1.2 Problem statement

Wave energy is the lowest cost renewable energy sources by its high power density. Compared to solar and wind energy, wave energy is more predictable by offering better possibility of being dispatched to an electrical grid system. The conversion of wave energy to electricity is the most harmless way to generate energy, hence it does not give any waste or destroy the environment. Wave energy foreseen to be the best solution for the electrical power supply in upcoming years as it provides clean energy production and incorporated along with green technology available as well as supportive sustainability conceptual of living. Linear generators in wave energy conversion depends on high force, low speed, irregular motion and cost. Their performance varies when they have some changes in applying those requirements. The main purpose of this project is to develop wave generator which is simple and less expensive. Besides that, the wave generator should be environmental friendly and not releasing dangerous gases.

## 1.3 Objectives

The objective of this project are as follows:

1. To develop a test rig for wave harvesting system
2. To compare performance of different linear generator configuration



## 1.4 Scope of the project

The scopes of this project are :

1. Using different crankshaft shapes to simulate different wave pattern.
2. Produce electricity through linear generator

# CHAPTER 2

# LITERATURE REVIEW



## 2.1 Introduction

The purpose of literature review is to provide knowledge on topic and place own research within the context of existing literature making a case for why further study is needed. This chapter review previous researches on wave energy conversion, linear generators, types of generators and Archimedes Wave Swing (AWS).

## 2.2 Wave energy conversion

Waves as a source of renewable energy offers several benefits than other methods of energy generation. First and foremost, sea waves has the highest energy density than other renewable energy sources. Waves are produced by winds then generated by solar energy. Solar energy intensity of typically 0.1– 0.3kW/$m^2$ horizontal surface is converted to an average power flow intensity of 2–3kW/$m^2$ of a vertical plane perpendicular to the direction of wave propagation just below the water surface. Besides that, limited negative environmental impact in use. Thorpe details the potential impact and presents an estimation of the life cycle emissions of a typical near shore device. In general, offshore devices have the lowest potential impact. Natural seasonal variability of wave energy, which follows the electricity demand in temperate climates. Waves can travel large distances with little energy loss. Lastly, wave power devices can power up to 90% of the time, compared to 20–30% for wind and solar power devices. (Drew et al., 2009)

Wave energy conversion systems are categorized in different ways (Polinder et al., 2007). One possible way of classification is according to the operating principle with their power take off systems. Four important types are the following :

(i) Oscillating water columns (OWC) have air turbines that drive rotating generators.

(ii) Overtopping devices such as the Wave Dragon that have hydro turbines that rotating generators.



(iii) Hinged contour devices such as Pelamis use hydraulic power take off systems.

(iv) Buoyant moored devices such as the Archimedes Wave Swing (AWS) with (2-7 configuration)

### 2.2.1 Power Take Off Method

The power take off (PTO) system converts the captured mechanical energy into electrical energy. In both wave and tidal systems a mechanical interface can be employed to convert the slow rotational speed or reciprocating motion into high speed rotational motion for connection to a conventional rotary electrical generator. Direct drive is also an option, but is not typical in currently developed marine devices. The energy conversion mechanisms within a wave energy converter can be divided into 3 areas: device, PTO and electrical generation system (including generator and power converter), all of which have losses associated with them (Polider et al., 2007

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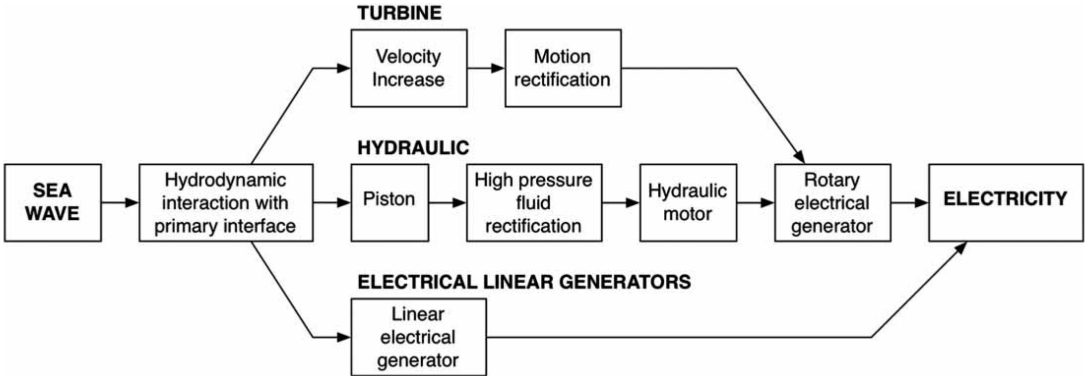



Figure 2.1 : Power take of method mechanisms (Polinder et al., 2007)



## 2.3 Linear generator

Linear generators are rarely used. Rotation motion mostly used to convert mechanical energy to electrical energy. Rotating generators used in conventional power stations, in hydro power stations, in wind turbines, and in vehicles. Linear motors or actuators are used in transportation system, robotic systems and positioning stages. Mostly, these systems have a low power level. However, there are a few applications with power levels comparable to the power levels of wave energy converters, such as maglev trains, aircraft launching systems for future aircraft carriers and roller coasters driven by a linear machine.

When these linear systems have to break, the machine is also operated in generator mode. However, in this case the objective is not to convert energy from a mechanical from to an electrical form in an efficient way, the objective is just to slow down the motion or to position the moving part. Linear generators in wave energy converters are characterized by a high force (depending on the size of the wave energy converter) and a low speed. The main other application of generators with a high force and a low speed is in direct-drive wind turbines. There are many correlations between the problems in direct-drive wave energy conversion and direct-drive wind energy conversion. However, the irregular motion in wave energy conversion makes direct-drive wave energy conversion more difficult than direct-drive wind energy conversion.

Generators are based on the principle of inducing electrical tension on the wire that moves in a magnetic field with the action of a mechanical force. Generators consist of two main parts stator and rotor. The moving part is called as rotor while fixed part is called as stator. There is an air gap between stator and rotor, because the rotor can be moved. (Sahin and Ozdinc, 2015)



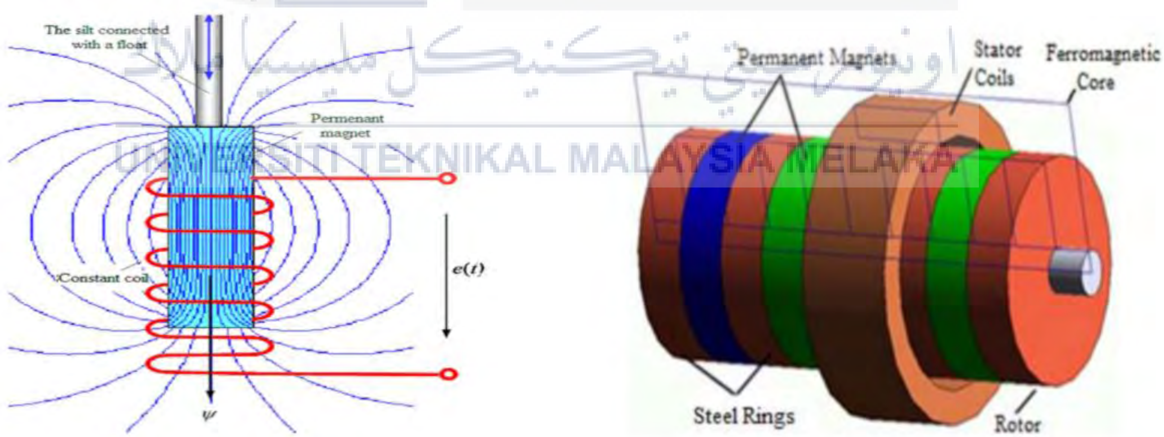



Figure 2.2 : Linear generator schemes that having a permanent magnet rotor (Sahin and Ozdinc, 2015)

The moving part of the linear generator in which the rotor consists of four fixed ring magnet is in the designed system. The magnets which are used for rotors, are Neodymium-Iron magnets, is the value of each 3000 Tesla. Non-magnetic permeability steel rings are placed between the permanent magnet and their poles are placed as N-S and S-N as shown in Figure 2.3.

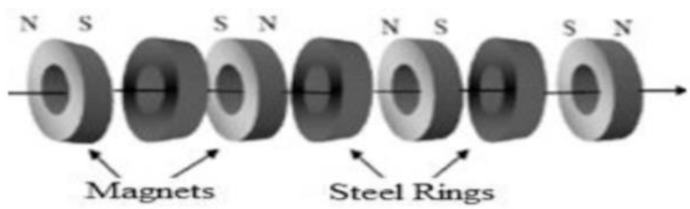



Figure 2.3 : The placing of the magnets according to the poles

(Sahin and Ozdinc, 2015)



Sahin and Ozdinc (2015) reviewed that to design efficient linear generator, the length of the rotor should be equal to the length of the winding field in the stator. Therefore, this area is the maximum variation of magnetic flux. A mechanism is required which reduces friction losses between rotor and stator with a minimum air gap. The mechanism has to be fixed to the rotor to move only vertical direction with wave motion. The bigger conductor cross section reduces the power losses. It is noted that the obtained voltage value can be increased with the addition of power electronic circuits and more smooth direct current voltage can be obtained.

### 2.3.1 Characteristic of linear generator

The requirements for linear generators applied in wave energy conversion systems are high peak force, low speed, irregular motion and low cost. Other characteristics of linear generator systems in wave energy conversion systems are the following: (Polider et al., 2007)

(i) There is a high attractive force between translator and stator.

(ii) The air gap between stator and rotor is mostly relatively large. It is complicated to build a mechanical construction for a generator with a small air gap because of manufacturing tolerances, the limited stiffness of the complete construction, the large attractive forces between stator and translator and thermal expansion

(iii) Because of the irregular motion of continuously varying speed, the grid connection of the wave energy converter always has to be done using a power electronic converter that connects the voltage of the wave energy converter with a varying frequency and amplitude to the grid with a fixed frequency and amplitude.

However, linear generators for wave energy conversion have some disadvantages. Their efficiency is physically limited. They are large and high cost. The bearing load are large and the bearings are not maintenance-free. More research is necessary to solve these problems. The next sections will discuss these problems and discuss further research to solve these problems.



### 2.3.2 Signal Processing

One issue of linear electrical generators is converting the signal to one appropriate for grid connection. If the motion of the WEC is sinusoidal, the induced electromagnetic force (EMF) varies in amplitude and frequency during a wave cycle. As the translator reciprocates, the speed is continuously changing, resulting in a varying frequency of the induced voltage. Figure 2.4 shows a typical EMF plot from a variable reluctance permanent magnet machine excited by a sinusoidal displacement. For grid connection, this waveform, which is variable in both frequency and amplitude, must be rectified before conversion into a sinusoidal fixed voltage and frequency wave form using power electronics. The rectification can be passive or active. A passive rectifier can be a simple diode bridge, and this is characterized by having a power factor of one. The active power can be increased if the power factor is not equal to one, which can be accommodated by an active rectifier (Drew et al., 2009).

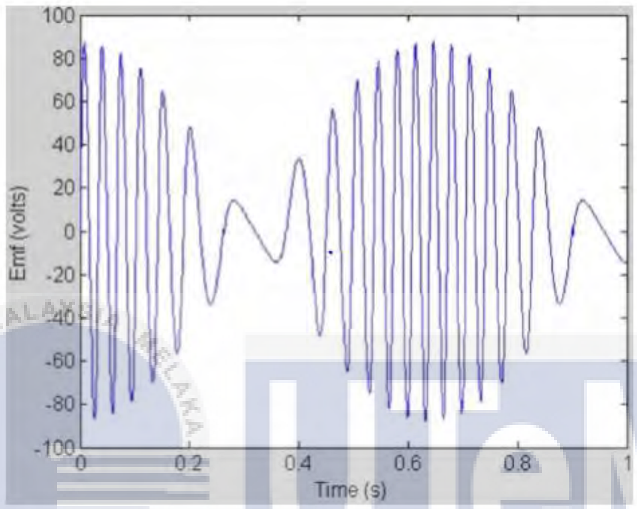



Figure 2.4 : Typical EMF plot (Drew et al., 2009)



## 2.4 Linear Permanent Magnet Generator

There are different types of generators used in wave energy conversion system. According Polinder et al., (2007), permanent-magnet synchronous machines are the most suitable generator type for wave energy conversion. The generator system for the Archimedes Wave Swig (AWS) could be seen as a state-of-the-art generator for a wave energy converter. It is a permanent magnet generator with surface mounted magnets. It has a three-phase full pitch winding with one slot per pole per phase. It is double-sided to balance the attractive forces and balance the bearing loads.

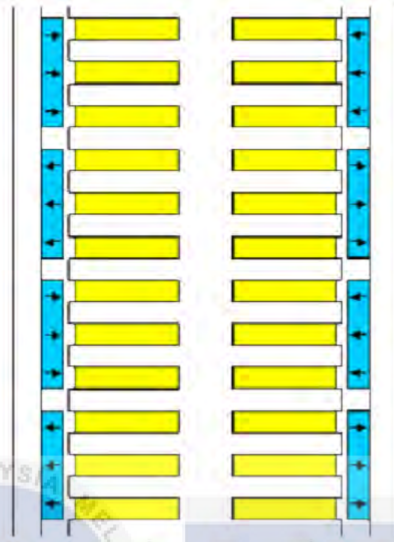
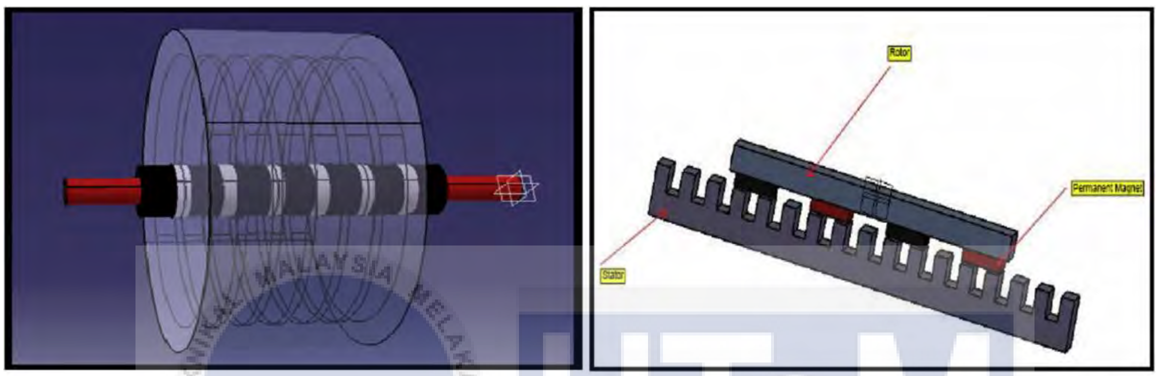


Figure 2.5 : Sketch of a cross section of the linear permanent magnet generator of the AWS (Polinder et al., 2007)



Polinder et al., (2007) states that permanent-magnet linear synchronous generator (PMLSM) with magnets on the translator (the moving part) has a rather high force density, has a reasonable efficiency at low speeds, magnets are not that expensive anymore and there is no electrical contact to the translator.

Based on Rao et al., (2016), linear generators are being widely used in embedded power generation. Among various reviews of linear generators, tubular and rectangular type permanent magnet machines offer high efficiency and a high power force density. As the number of moving parts and maintenance costs are reduced, a permanent magnet linear generator (PMLG) becomes more efficient, more compact and light weight as compared to a conventional generator. A PMLG for wave energy conversion is generally designed with a translator which moves back and forth in a tubular stator or over a linear stator. As the translator is provided with permanent magnets and the stator with winding coils, the axial-directional magnetic flux which links through stator windings generate an induced EMF. The magnitude of the desired emf is based on linear speed of translator, number of stator winding turns and the total flux linking the stator winding.




(a) Tubular type PMLG (b) Rectangular type PMLG

Figure 2.6 : Types of PMLG (Rao et al., 2016)



Figure 2.6 (a) is a tubular type with a long translator as compared to the stator and the second one is a vertical rectangular type with long stator as compared to the translator. A translator employing Neodymium-Iron-Boron (NdFeB) rare earth permanent magnets is considered for both types of machines. The rare earth permanent magnets are considerably more expensive than ferrite magnets but can produce highmagneto-motive force for a relatively small magnet height.

Figure 2.6 (b) is a rectangular shaped translator which is made from M3 silicon steel with four magnets mounted on one side of the translator. The stator cores of both types of linear generator are considered with silicon steel laminations. In the tubular type PMLG the stator with a 3-phase concentric winding and round copper conductors in six slots is considered. In the vertical rectangular type PMLG four poles and twenty four slots are selected for the stator and a 3-phase lap winding with flat copper wire to obtain a better coil fill factor is considered (Rao et al., 2016).

### 2.4.1 Electromagnetic Theory

The basic electromagnetic theory briefly reviewed by Asy'ari et al, (2017) that it is foundation for understanding the operation of permanent magnet linear generator. For a circuit carrying a current was adopted to express the magnetic intensity dH produced by a line element dL of the current circuit. In design generator a magnetic field was quantified using appropriate formula also the permeability as a function. The magnetization, M is the magnetic moment per unit volume at a given point in a medium. The magnetic moment is associated with the orbital and spinning motion of electrons. It has the same unit as the magnetic field intensity. The stator and translator linear system are shown in Figure 2.7.

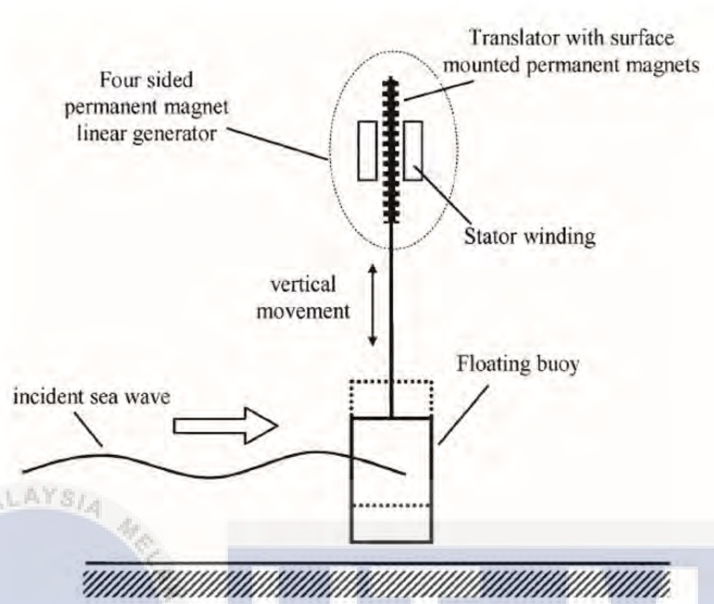



Figure 2.7 : Heaving Linear Generator Power Take-Off Device for Wave Energy Conversion (Asy'ari et al., 2017)



The second Maxwell's equations was adopted here, that is also known as Gauss law. It states that the net flux, B in any volume is zero. Unlike electrical field lines a magnetic field line must complete a closed continuous curve. This must always be taken into account in the design of the magnetic circuit of a linear generator.

## 2.5 Spring assisted Triboelectric Nanogenerator

Recently, triboelectric nanogenerator (TENG) has emerged as a powerful technology for harvesting mechanical energy. This is because of high output power, high efficiency, low fabrication cost, and no pollution. The TENG can convert mechanical energy from a variety of sources to electricity through the coupling effect of contact electrification and electrostatic induction. (Tao et al., 2016).

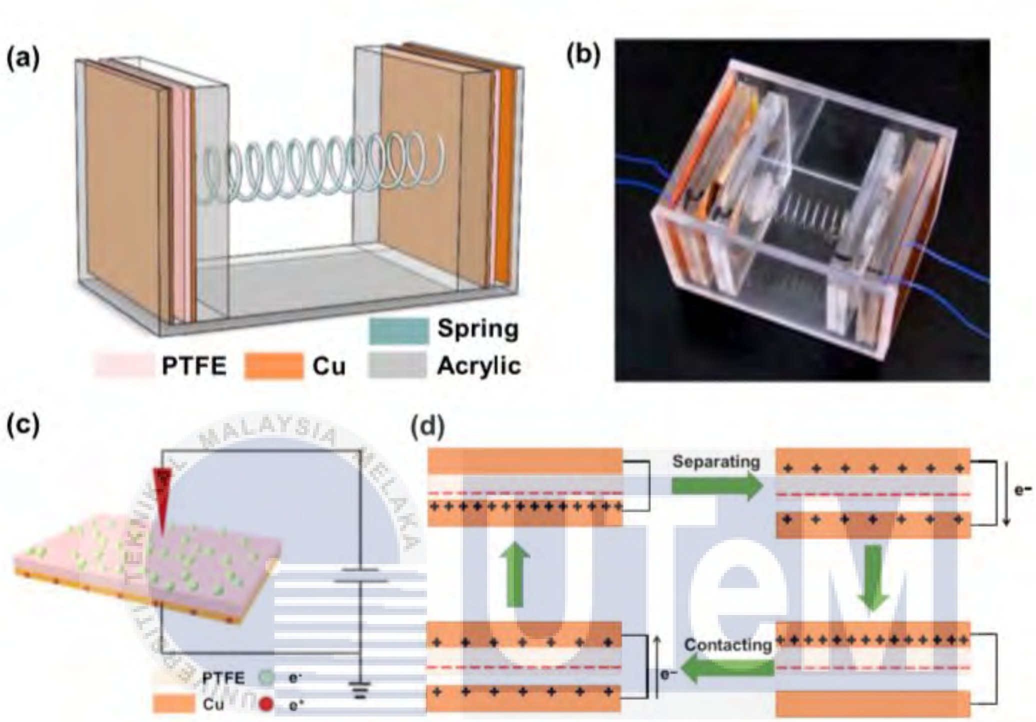



Figure 2.8 (a) Schematic illustration of the spring-assisted TENG structure. (b) Photograph of the fabricated spring-assisted TENG device. (c) Schematic the electron injection process for generating negative charges on the surface of PTFE. (d) Working principle of the spring-assisted TENG device. (Tao et al., 2016)



## 2.6 Archimedes Wave Swing (AWS)

According to Polinder (2004), the AWS is a cylindrical air-filled chamber. The waves move the lid of this chamber, called the floater, in vertical direction with respect to the bottom part, which is fixed to the sea-bottom. When a wave is above the AWS, the AWS volume is reduced by the high water pressure. When a wave trough is above the AWS, the volume increases because of the air pressure inside the AWS. From this linear motion, energy can be extracted and converted into electrical energy. The AWS is a unique wave energy conversion system because it is completely submerged. This is important, because this makes the system less vulnerable in storms. Besides, it is not visible, so that the public acceptance is not such a problem as for, for example, wind farms. To prove the principle of operation behind this idea, a few small models have been developed (scale 1:20 and 1:50 to the final system). These models showed that the system worked and validated the models predicting the hydrodynamic forces on and the hydrodynamic damping of the floater. As a next step, a pilot plant of the AWS has been built at the Portugese coast. The main objective of this pilot plant is to prove that the complete system works and can survive.

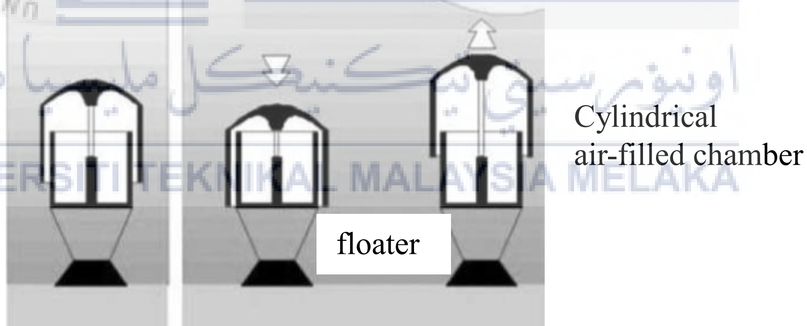



Figure 2.9 : Sketch of AWS illustrating the operation principle (Polinder, 2004)

However the linear PM generator currently applied in the AWS has disadvantages. Research by Polinder (2004), states that the generator is very large and expensive. To obtain a commercially viable system, the generator should be made as cheap as possible. Besides that, the attractive force between the stator and the translator (the moving part) causes big problems for the bearings, which should be made maintenance-free. Even when the generator is made double sided to balance the attractive forces (as is currently done), deviations from the ideal air gap result in severe bearing loads. Furthermore, losses in the generator have to be kept at an acceptable level to decrease cooling problems and increase the annual energy yield.

## 2.7 Experimenting linear generator design

Based on research done by Sahin and Ozdinc (2014), stator was designed with number of turns according to voltage values and number of poles. 8 pieces of octagonal were cut for 4-pole winding. Iron cores are fixed on the 3 cm diameter-plastic pipe. The 0.45 mm diameter-copper wire that is enamelled was used for winding and 600 winds are wounded for each pole. Then, E-shaped iron sheets were cut in the desired size for the design of the stator and attached to each other. Later, insulated E-shaped cores were placed on top of the octagonal pulleys in 45◦ between each other as shown in Figure 2.10.



Figure 2.10 : Four pole linear stator (Sahin and Ozdinc, 2014)

Measurements are taken at oscilloscope without the iron core and wave period is set to about 1 second. For each period of wave, the peak to peak voltage value is measured maximum 800 mV. Then the necessary iron cores were added to prevent losses of magnetic flux on stator and measurements were repeated. After iron cores were added on a generator system, measurements which were repeated showed a significant increase on the voltage value. From this study, design of a linear motion generator for wave power was realized. In this context, the four pole linear generator which is made of special magnets was designed. The iron cores required for flux are observed to increase the efficiency.

Based on study by Asy'ari (2017), stator was designed from acrylic material and stator frame built within slots. Rotor design uses 10 pieces of permanent magnet type ferrite. DC Fan used as a load capacity. In testing permanent magnet linear generator was initiated by utilizing an induction motor as the prime mover. The performance of generator was distinguished by amount of coil in each slots, with the number of turns in each slot. Initial winding process was in clockwise direction, from the first slot to the forthcoming slot was connected in anticlockwise direction. As a conclusion, higher the number of total windings in each slots, higher the output voltage of PMLG.



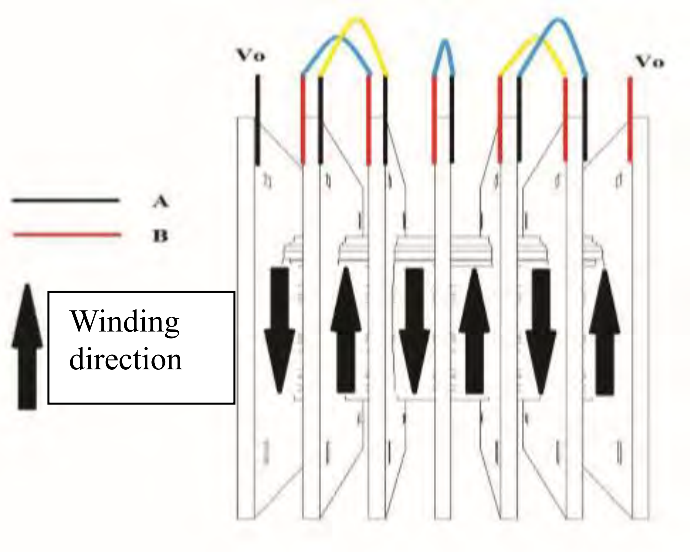



Figure 2.11 : Design direction and relationship coil in each slot (Asy'ari, 2017)

## 2.8 Dynamic Responce of a Buoy-Linear Generator System

According to Bing Chen et al, 2017, the dynamic response of a buoy-linear generator system to wave action is studied by a two-dimensional numerical model featuring finite element and volume of fluid (VOF) methods for incompressible viscous flow. For both resonant and non-resonant cases, the motion of the buoy and the translator of the on-board linear generator, the primary conversion efficiency of wave power and the wave transmission and reflection coefficients are analyze. When the system reaches maximum efficiency, which implies that it works in a resonant state, the normalized relative oscillating amplitude of the translator $\frac{A}{\frac{H}{2}}$ is well above 1, and the normalized maximum relative velocity of the translator $\frac{|V\max|}{V_0\max}$ is well above 2. When the system works in a situation far away from resonance, corresponding to low efficiency, the normalized oscillating amplitude and maximum velocity of the translator dramatically decrease to well below unity and close to unity respectively.



The maximum primary conversion efficiency is close to 25%, slightly lower than that achieved by using the buoy itself to extract wave power. To reach maximum efficiency, a lighter translator has to move faster and have a larger displacement than a heaver one. When the incident wave frequency departs from the natural frequency of the linear generator, the energy conversion efficiency deteriorates rapidly.

The wave transmission and reflection coefficients for a buoy-linear generator system are at the same level as those for a solo buoy system. When wave energy conversion reaches maximum efficiency, the corresponding wave transmission coefficients, Kt are in the range of 0.7–0.75, and the corresponding wave reflection coefficients, Kr are in the range of 0.2–0.3. When the converter works in a non-resonant state extracting less wave energy, it acts more like a freely floating buoy. Kt is always larger and Kr is always lower than that of the resonant cases. Although utilizing larger buoys is an obvious option for improving performance, considering the cost and convenience of building, transportation and deployment, using multi rows of smaller buoys seems a better choice.

# CHAPTER 3

# METHODOLOGY



## 3.1 Introduction

This chapter describes methodology used in this project to determine performance of linear generator in various parameters. The flow chart of the project is shown in Figure 3.1. This project starts by studying working principle of linear generator towards wave conversion. After identified about linear generator, a test rig will be fabricated using linear generator. Wave patterns were simulated by using different pattern of crank shaft shapes. Linear movement of the magnet manipulated to produce electricity.

### 3.2 Overall flowchart

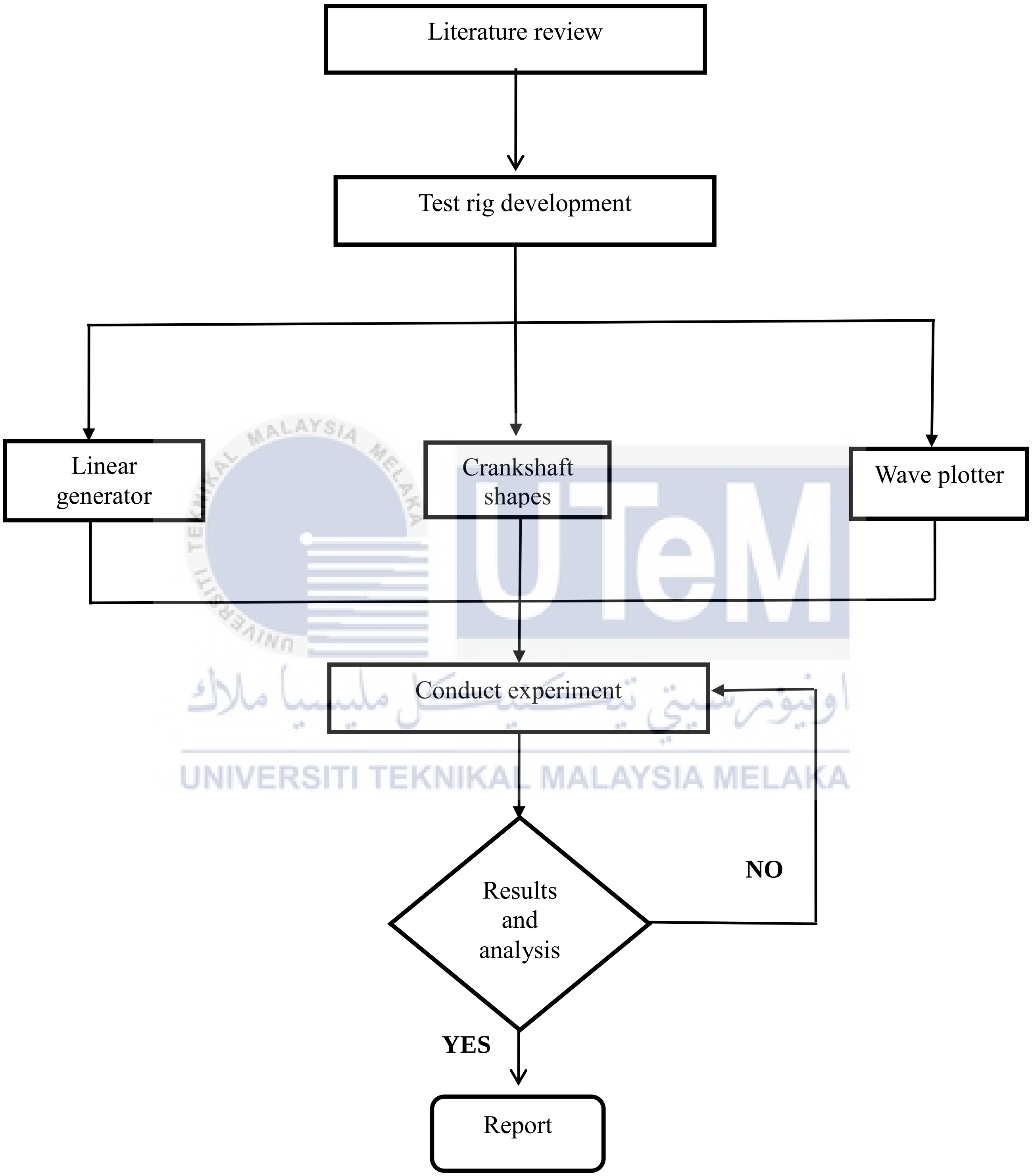





Figure 3.1 : Flow chart of methodology

## 3.3 Chronology of the project

The completion of this project depends on every stepping stone that has been crossed throughout the study. Important aspects such as objectives, scope and problem statement was established in order to ensure a systematic flow for this project. Objectives set for this project was to be able to develop a test rig using linear generator to determine performances in different parameters. However, before the beginning of the project, it is important to review journal and research papers. Next, it is important to build experimental setup to conduct experiments. The setup is fabricated as per requirements. Then the setup is tested with different parameters and data is collected. Necessary parameters such as current and voltage readings is observed and readings were taken.

## 3.4 Fabrication of test rig

A support frame is built in fabrication process. The support frame holds the parts and components required. Initially, the steel was cut as per the required dimension using a measuring tape, scribbler, marker and a cut-off machine. Grinding process were done at various stages of the fabrication using hand grinder. First, it was used to prepare the metal before being weld as it came with grey coatings and had rusty parts. Also, after welding in order flatten the surface that has been weld. Besides, the hand grinder was both used to grind and to trim off small chips from the edges of the metal bar. Type of welding used to join the metal pieces is the metal inert gas (MIG) welding system. The fabrication process involved three main processes; cutting, grinding and welding.

### 3.5 Experimental Setup

The test rig consist of three main components. They are wave plotter, crankshafts and solenoid magnet. Different shapes of crakshafts manipulates wave patterns.Wave plotter draws the pattern produced by cranshafts. Solenoid magnet produce induced current.

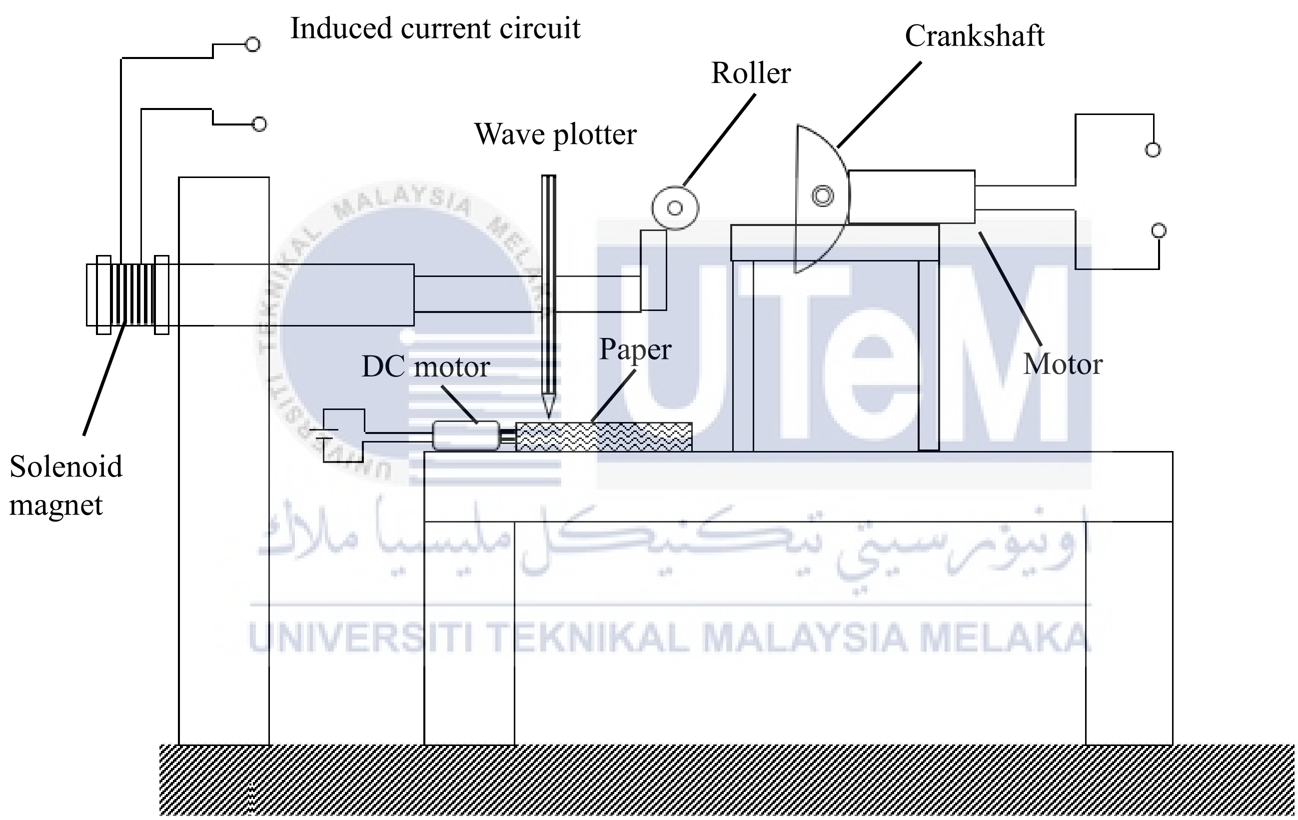



Figure 3.2 : Schematic diagram of complete setup

### 3.5.1 Solenoid magnet

A solenoid is a coil of wire wound around a polyvinyl chloride rod (PVC) usually in a helical fashion, with either a single layer or one layer upon another. It is basically multiple loops of wire, where the end of each loop is connected to the beginning of the next loop. The more turns related to a higher voltage, so the ability to produce more turns would be desired. Using a wire with the smallest diameter possible so that the wire could be wrapped as many times as possible around a pipe. For this project, the winding of coil is about 3000 number of turns

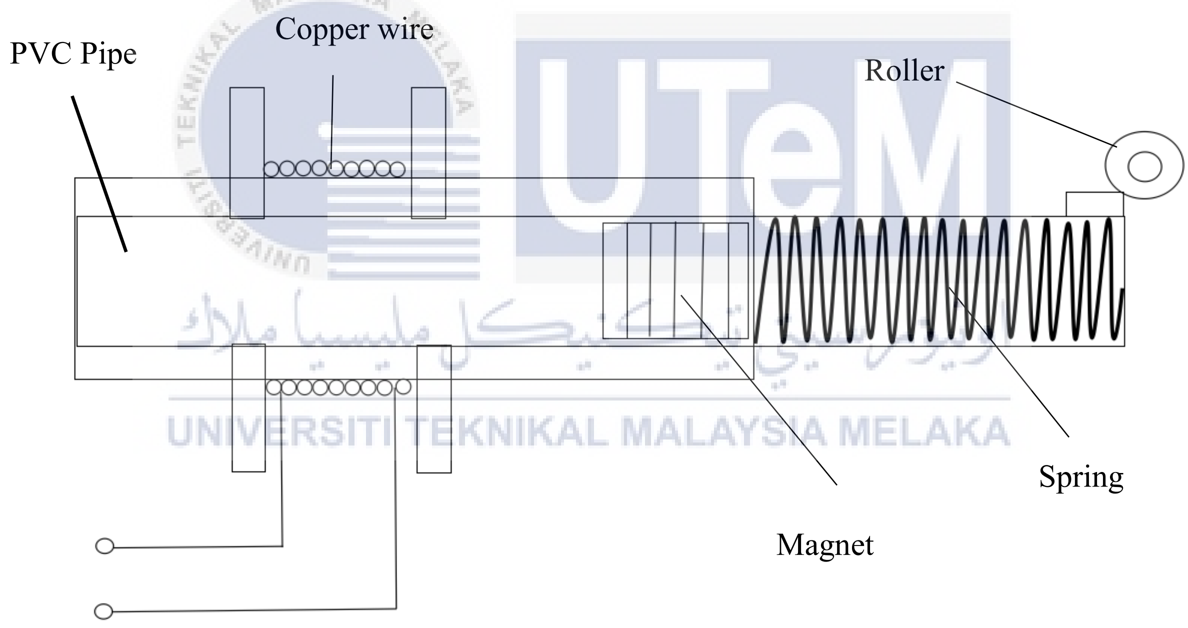



Figure 3.3 : Cross section of solenid magnet

### 3.5.2 Electric circuit

The AC motor connected to bridge rectifier. Diode 1 and diode 3 are forward bias. Diode 2 and diode 4 reverse bias. Once the switch on, LED lighten up.

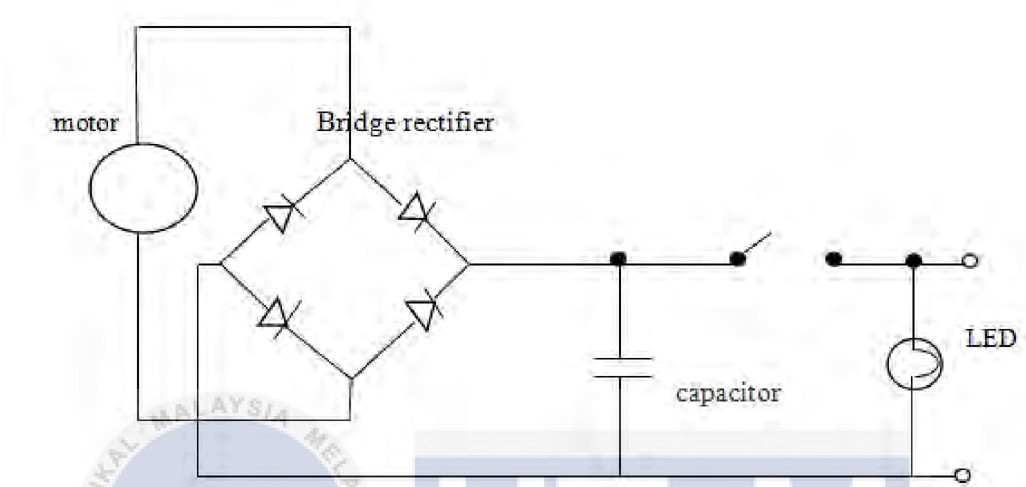



Figure 3.4 : Induced current circuit

### 3.5.3 Crankshaft

Plywood acts as crankshafts in this experiment. The plywood was cut in different shapes as shown in figure 3.5. All shapes radius are set at 5.5cm.

| | |
|---|---|
| Shape A (Semicircle)  | Shape B (Star)  |
| Shape C (Spur gear)  | Shape C(Droplet)  |



Figure 3.5 : Different shapes of crankshafts (plywood)

### 3.5.4 Wave Plotter

A DC motor attached at the corner of the frame. A straw is connected to the shaft of the motor. Then the straw was rolled by paper. When the DC mtor connected to battery the shaft starts to roll and pulls paper back. The pencil at spring starts draw the wave pattern.

## 3.6 Experimental Procedure

The power window motor act as power source in this experiment. The motor is connected to 12V car battery. Plywood plays a role as crankshafts. The plywood was cut in different shapes as shown in figure 3.5. Then the shape A attached to the end of motor's shaft. It was tighten using bolt and nut. A solenoid magnet was setup aligned to the shapes. Copper wire is coiled thickly on the PVC pipe. Then a spring with roller on the end is attached to the PVC to move the solenoid. When motor is turned on, the shaft rotates clockwise. As the shape rotates along with the shaft, it hit the tip of the roller. This makes the spring to extend and retract. The extraction and retraction produce magnetic flux in solenoid which is attached together with spring. It prove the presence of current and LED is light up. The readings of current and voltage is taken through multimeter. At the same time, there is a pencil attached at the spring to draw the wave pattern on the paper which is connected to DC motor. As the DC motor turned on, it pulled the paper back and the pencil drew the movement of the shape. This steps is repeated by replacing shape B, shape C and shape D. After that, the current reading was taken by controlling motor's speed using PMW controller. Motor's speed was fixed to 1, 2 and 3. Different shapes shows different current at different speed.

# CHAPTER 4

# RESULTS AND DISCUSSION



## 4.1 Introduction

This chapter cover the results and discussion of the experiment on the performances of linear generator with different shapes of crankshafts. This results in terms of wave patterns and current and voltage readings shows the performances of linear generator. All the results and discussions related to this experiment are explained in this section.

## 4.2 Linear generator performances

Performance of this linear generator system evaluated based on data recorded. About two observations were carried out on this experiment.

i. Linear input result when wave pattern plot by wave plotter

ii. Electric current produced by solenoid magnet

### 4.2.1 Wave pattern result at constant speed

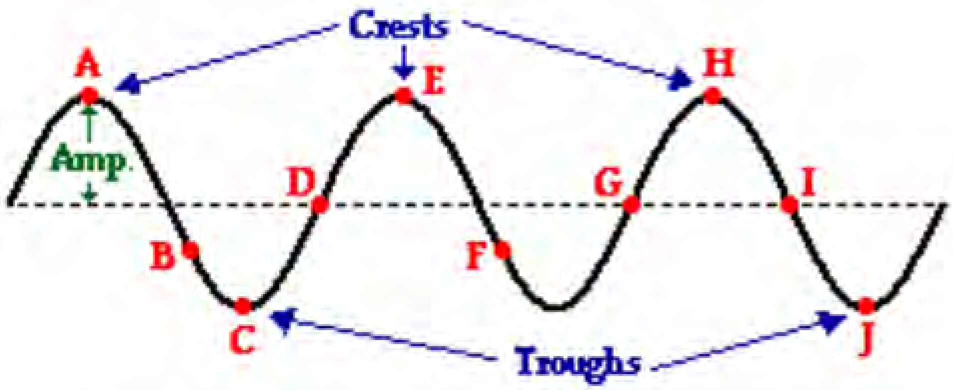



Figure 4.1 Wave definition

The wave shown above can be described by a variety of properties. One such property is amplitude. The amplitude of a wave refers to the maximum amount of displacement of a particle on the medium from its rest position. In a sense, the amplitude is the distance from rest to crest. Similarly, the amplitude can be measured from the rest position to the trough position. In the diagram above, the amplitude could be measured as the distance of a line segment that is perpendicular to the rest position and extends vertically upward from the rest position to point A.



The wavelength is another property of a wave that is portrayed in the diagram above. The wavelength of a wave is simply the length of one complete wave cycle. If you were to trace your finger across the wave in the diagram above, you would notice that your finger repeats its path. A wave is a repeating pattern. It repeats itself in a periodic and regular fashion over both time and space. And the length of one such spatial repetition (known as a wave cycle) is the wavelength. The wavelength can be measured as the distance from crest to crest or from trough to trough. In fact, the wavelength of a wave can be measured as the distance from a point on a wave to the corresponding point on the next cycle of the wave. In the diagram above, the wavelength is the horizontal distance from A to E, or the horizontal distance from B to F, or the horizontal distance from D to G, or the horizontal distance from E to H. Any one of these distance measurements would suffice in determining the wavelength of this wave.

Based on table 4.1, it can conclude that different shapes produce different wave patterns. Shape A which is look alike semicircle shape produced sine waves. Its wavelength is 2.75cm and amplitude is 3.75cm. Shape B,the star shape produced sine waves which are more close apart. Its wavelength is 1cm and amplitude is 3cm. Shape C, spur gear shape produced square type wave pattern. Its wavelength is 2.5cm and amplitude is 2.5cm. Lastly, shape D which is droplet shape also produced sine waves. Its wavelength is 3cm and amplitude is 1.5cm. Shape B produced shorter wavelength compared to other shapes. While shape D produced longer wavelength.



The peaks of waves is caused by pointing edge of shapes. Shape A has two edges. So that it produced shorter wavelength. Shape B has more pointing edges compared to other shapes. Its edges tap the roller more frequently and it caused to produced most shortest wavelength than others. Shape D has only one pointing edge so that its wavelength is more longer.

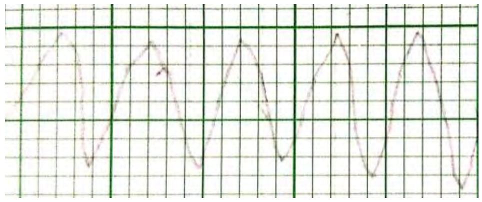
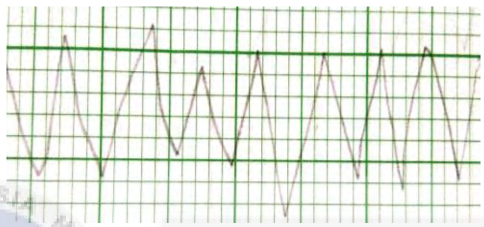
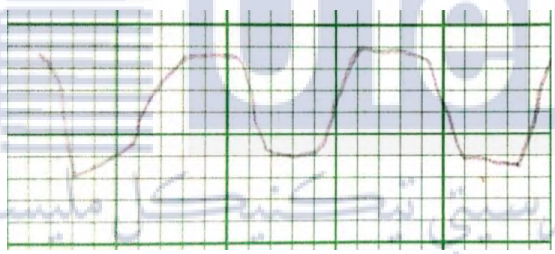
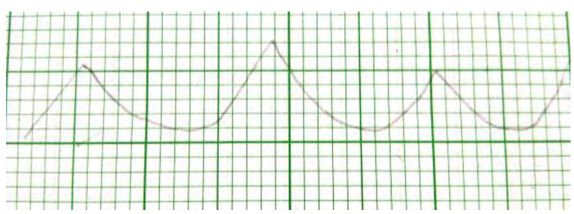
| | Wave Pattern |
|---|---|
| A |  |
| B |  |
| C |  |
| D |  |



Table 4.1 : Wave pattern produced by different shapes

### 4.2.2 Current produced by the linear generator

Figures below show the current readings for all the shapes at different speeds. Three different speeds were used to find current readings for every five minutes. Figure 4.2 shows current readings at speed 1. Based on that graph, shape B produced highest reading compare to other shapes. Current increased for every five minutes and reached 3.99A at 15 minutes. Shape A,C and D show almost nearest current readings when approaching 15 minutes. However, shape D produced least amount of current. It produced 1.98A at 15 minutes.

Figure 4.3 shows current readings at speed 2. The graph shows that shape B produce highest reading compare to other shapes. Current increased for every five minutes for all the shapes. For shape B, the current reached 4.25A at 15 minutes, which is higher than other shapes. Shape A,C and D show almost nearest current readings when approaching 15 minutes. However, shape D produced least amount of current. It produced 2.01A at 15 minutes.



Figure 4.3 shows current readings at speed 3. From that graph, it can conclude that, amount of current produced by shape B is the highest among the others. Current increased for every five minutes and reached 4.6A at 15 minutes. Shape A,C and D show almost nearest current readings when approaching 15 minutes. However, shape D produced least amount of current. It produced 2.05A at 15 minutes.

Current produced by the shapes influenced by their pointing edges. Shape B which is look alike star has many edges. The edges tapped the roller more frequently and it produces magnetic flux on solenoid magnet faster. On the other hand, shape D produces lowest current reading. Shape D has only one peak point where it tapped the roller quiet slower. The solenoid magnet produce magnetic flux slowly.

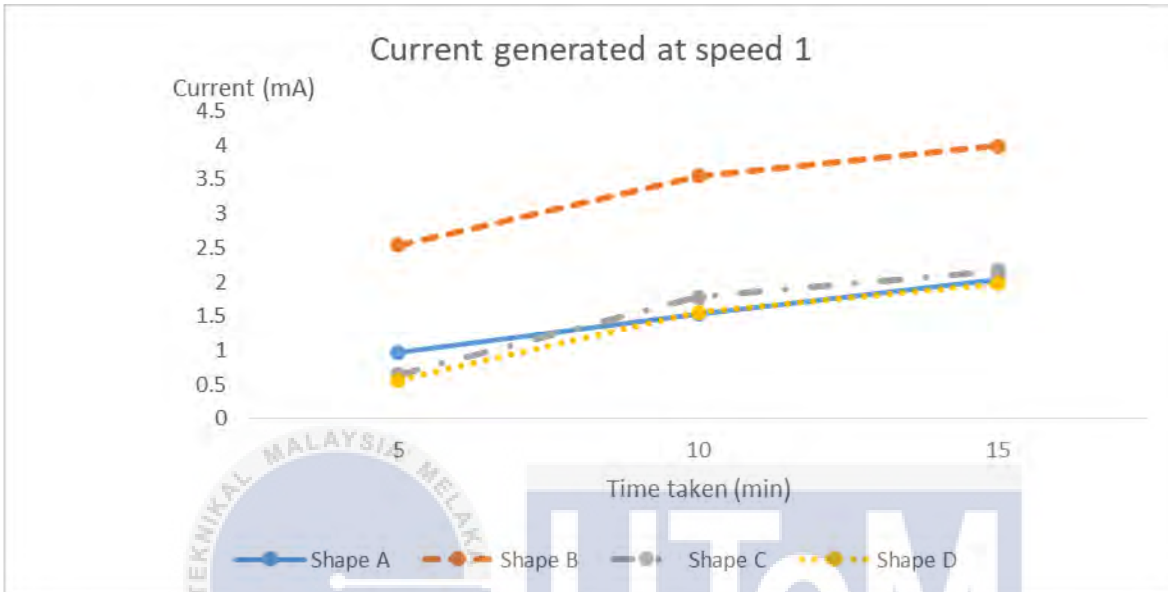



Figure 4.2 : Current readings for all shapes at speed 1



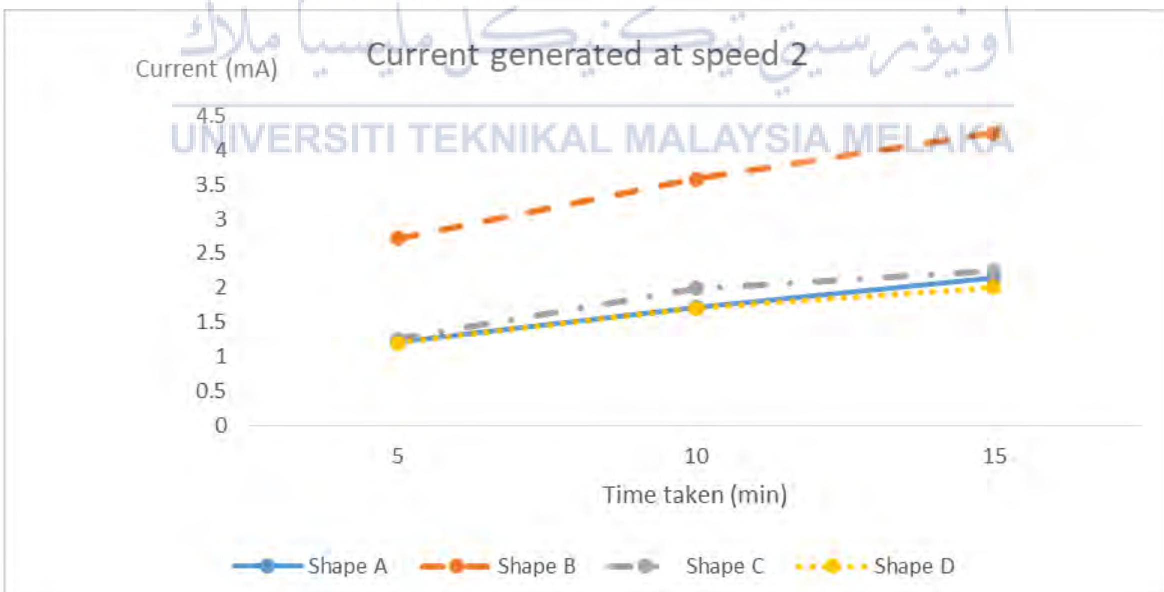



Figure 4.3 : Current produced by all the shapes at speed 2

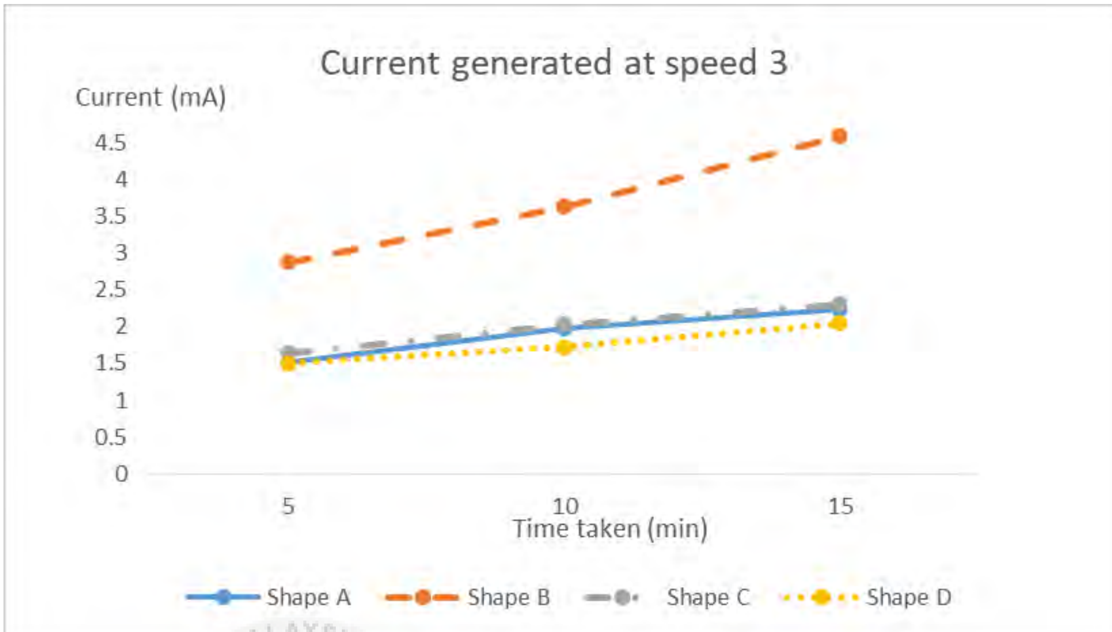



Figure 4.4 : Current produced by all the shapes at speed 3

# CHAPTER 5

# CONCLUSION & RECOMMEDATION

## 5.1 Conclusion

The main objective of the report is to develop a test rig for wave harvesting system. It has been achieved as the model has been fabricated and experimented. The second objective is to compare performance of different linear generator configuration was completed by testing four different shapes of crankshafts. Comparison of results is based on the wave patterns, voltage and current produced by the different shapes of crankshafts. Shape B shows the graph which has highest number of pointing edge (peak). It is due to it's peak points tapping the roller more frequently compared to other shapes. By tapping the roller more frequently, the spring extends and retracts causing the solenoid to produce current and voltage. It can concluded that speed of motor influence the amount of current produced. Shape B produced highest voltage and current compared to other shapes for every 5 minutes. However the reading starts to drop as the motor speed increases. While shape D produce less amount of current among the others. Speed of motor inversely proportional to the current because as armature current increases, the flux produced also increases due to the series combination. So that, if armature current is reduced, flux is reduced which will increase speed.

## 5.2 Recommendation

There are some improvement that can be done with this linear generator test rig. First the orientation, the winding pattern, and the placement of the coils in relation to one another. If two coils are close together, nearly all of the magnetic flux generated by the first layer coil will interact with the turns of the second layer coil, thus creating a large mutual inductance. On the other hand, coils that are spaced far apart from each other will have a much smaller mutual inductance. The presence of a magnetic material can also increase mutual inductance or test rig.

## REFERENCES

B. Chen, T. Bruceb, Clive A. Greatedc and Haigui Kanga. *Ocean Engineering 129 (2017) 374–381*

B. Drew, A. R. Plummer, and M. N. Sahinkaya. Department of Mechanical Engineering, University of Bath, Bath,UK. *Proc. IMechE Vol. 223 Part A: J. Power and Energy 2009*

H. Polinder, Michiel E. C. Damen, and Fred Gardner. I*EEE Transactions on energy converters, Vol.19, No.3, September 2004*

H. Polinder, M.A. Mueller, M. Scuotto and M. Goden de Sousa Prado. Electrical Power Processing Group. *Conference Paper-September 2007*

H. Asy'ari, Sarjito and Septian Heri Prasetio. Electrical Engineering Dept, Engineering Faculty, Universitas Muhammadiyah Surakarta. *AIP Conference Proceedings April 2017*

J. Tana, Jialong Duanb, Yuanyuan Zhaob, Benlin Heb, and Qunwei Tanga. *Nano Energy 2018*

J.Tao , Y. Yanyan, X. Liang, Z. Limin, X. Tianxiao, L. Zhong Wanga. Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences; National Center for Nanoscience and Technology (NCNST), Beijing 100083, China. *School of Materials Science* *and Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0245, USA 2016*

K. S. Rama Rao, T. Sunderan, M. Ref'at Adiris. School of Renewable Energy and Environment, Jawaharlal Nehru Technological University Kakinanda, India. 2016

M. E. Sahin and I. Ozdinc. Recep Tayyip Erdogan University/Department of Physics, Rize, Turkey. *Special issue of the International Conference on Computational and Experimental Science and Engineering (ICCESEN 2014)*

M. A. Mueller, H. Polinder ansd Nick Baker. Institute for Energy Systems, School of Engineering & Electronics, University of Edinburgh, Edinburgh, UK. *EH9 3JL. 2007*

# APPENDICES

## APPENDIX A : Current generated at speed 1

| Time taken | Induced current/mA | | | |
|---|---|---|---|---|
| | A | B | C | D |
| 5 | 0.98 | 2.54 | 0.65 | 0.56 |
| 10 | 1.54 | 3.55 | 1.78 | 1.56 |
| 15 | 2.03 | 3.99 | 2.16 | 1.98 |

## APPENDIX B : Current generated at speed 2

| Time taken | Induced current/mA | | | |
|---|---|---|---|---|
| | A | B | C | D |
| 5 | 1.21 | 2.72 | 1.26 | 1.2 |
| 10 | 1.72 | 3.58 | 1.99 | 1.7 |
| 15 | 2.15 | 4.25 | 2.24 | 2.01 |

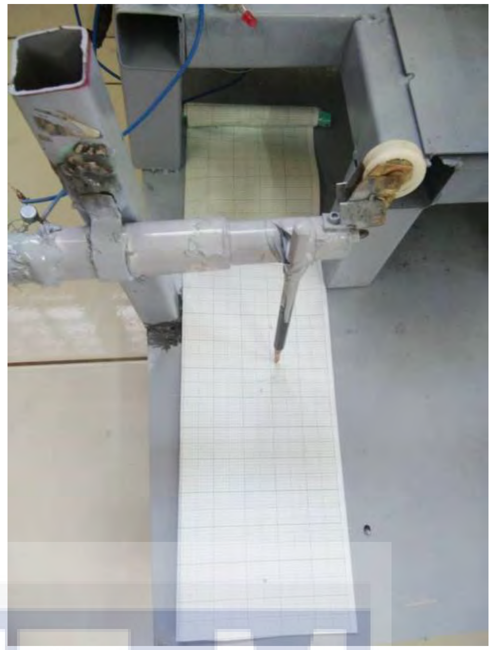


## APPENDIX C : Current generated at speed 3

| Time taken | Induced current/mA | | | |
|---|---|---|---|---|
| | A | B | C | D |
| 5 | 1.51 | 2.88 | 1.64 | 1.5 |
| 10 | 1.98 | 3.64 | 2.03 | 1.72 |
| 15 | 2.24 | 4.6 | 2.31 | 2.05 |

**APPENDIX D : Complete experiment setup**

## APPENDIX E : Wave Plotter



## APPENDIX F : ELECTRIC CIRCUIT