SIMULATION OF WAVE ENERGY HARVESTING SYSTEM USING MATLAB SIMULINK

By

MUHAMMAD FAISAL BIN SARIM

FINAL PROJECT REPORT

Submitted to the Department of Electrical & Electronic Engineering
in Partial Fulfillment of the Requirements
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Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

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Approved:

Dr. Taib Bin Ibrahim
Project Supervisor

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK

May 2012

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 Faisal Bin Sarim

ABSTRACT

Wave is huge energy resource that recognized by the international community as a clean and renewable energy which can be an alternative for fossil fuel. In respond to that, this thesis discussed about the development of a complete simulation model of wave energy harvesting using direct driven linear generator. The objective of this project is to build a simulation model of linear generator and insert wave model to observe the output voltage of the system. A control scheme model is also developed in order to stabilize linear generator output and produce AC voltage that can be feed into the grid. Simulation model of the system is developed by converting equations and parameters involved with the system to Matlab Simulink block. Elements used to develop the control scheme are rectifier, inverter and also filter. Various test had been perform on the simulation model using different input wave to verify the performance of the whole model. The test results reveals that rectifier, inverter and LC filter is capable of altering wave energy harvester output to produce stable voltage that can be feed into the grid.

ACKNOWLEDGEMENTS

First, I would like to express my gratitude and praise towards God and I would like to thank my final year project supervisor, Dr Taib Bin Ibrahim for his guidance throughout my project. All his passion and knowledge will always be missed and remembered.

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LIST OF ABBREVIATIONS

AC	Alternating Current
DC	Direct Current
OWC	Oscillating Water Column
PMLG	Permanent Magnet Linear Generator
IGBT	Insulated Gate Bipolar Transistor
PWM	Pulse Width Modulation
EMF	Electromotive Force

CHAPTER 1

INTRODUCTION

1.1 Project Background

Wave power is abundant and pollution free in nature which make it very suitable as alternative for fossil fuel to generate electricity. The global wave power was estimated at 100 000 TW h/year and the world's electricity consumption is around 16 000 TW h/year [1]. Many countries such as Ireland, Canada and Scotland had started their research and development of wave energy plant. For example, the Basque government invested over 15 M euro for the development and installation of wave energy harvester, which will achieve 5 MW of power [2].

Figure 1 shows the estimated of worldwide wave power distribution mainly in the coastal area [3]. These data is collected based on satellite image and also calculation based on wave height and wave periods obtained from the buoy. This research reveals that Africa, Norway and Australia are among the most top county that have highest wave energy resources. This data can give the clear idea about the huge the amount of wave energy in the world.

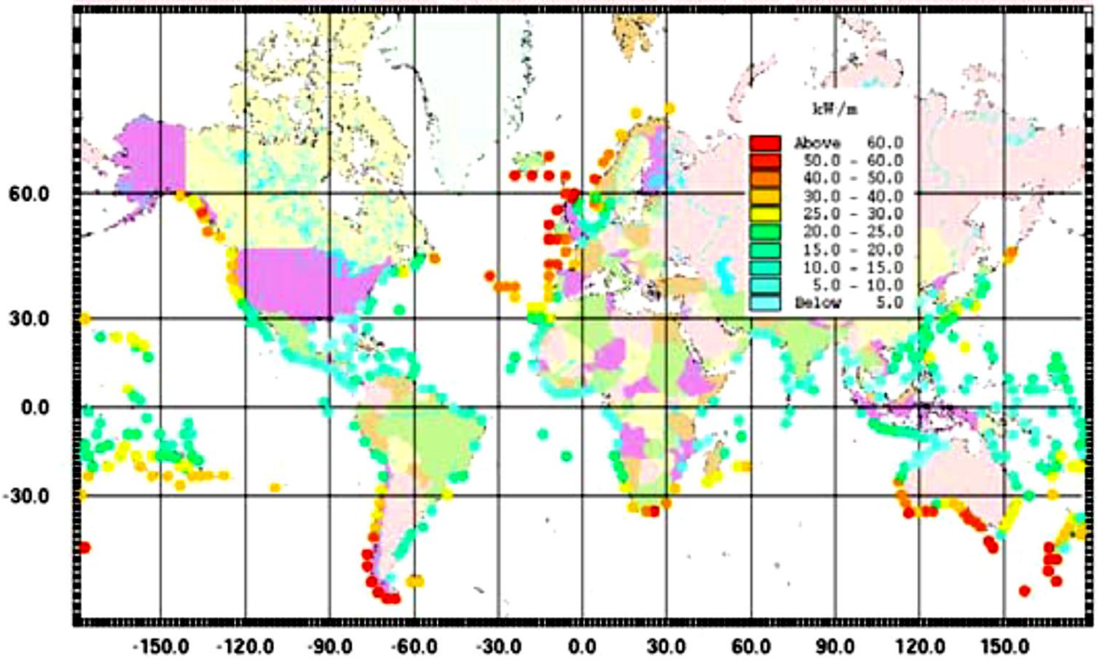


Figure 1 Global wave power estimates [3]

Wave measurement and energy estimation along Malaysian coast had also been done in the previous years. Data obtained from the research shows the amount of wave energy, wave height and also suitable location to harvest wave energy on Malaysia coastal area. Research that had been done by the researcher from Universiti Malaysia Terengganu is analysed to determine the suitability of the wave energy harvesting in Malaysia.

Figure 2 shows the wave computed and estimated wave height along the east peninsular Malaysia throughout the year. As will be seen, the wave height is changed a lot. This is due to the changing of monsoon that happens on November and also April. As the result, this will become a design challenge to build an efficient wave energy harvesting system in this area with huge different in wave height throughout the year.

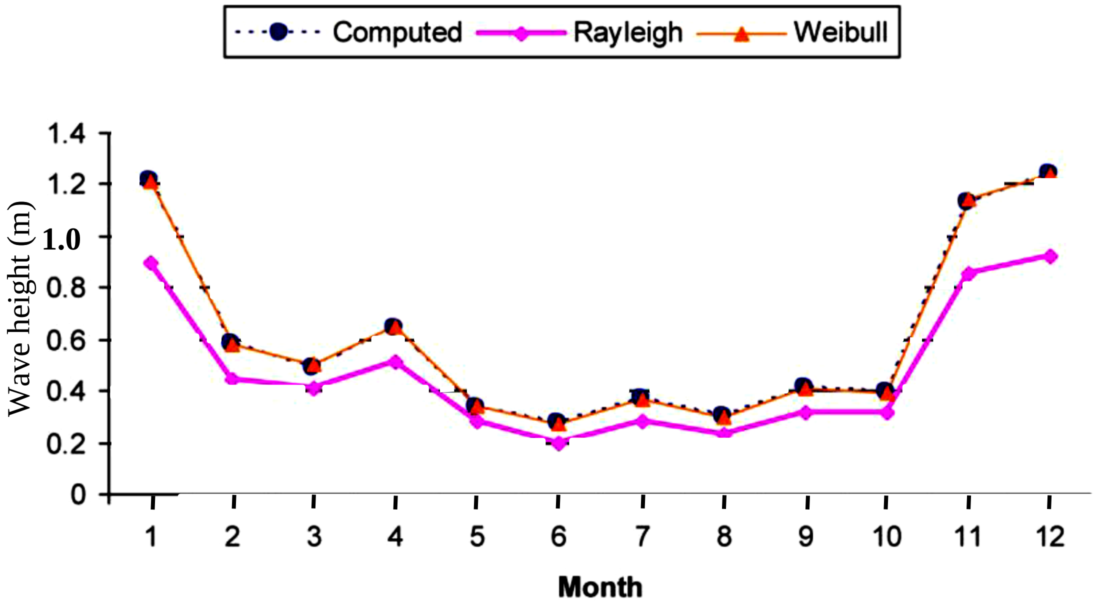


Figure 2 Actual and estimated monthly mean of significant wave height [4]

Wider research about wave energy in Malaysia had been done by team of researcher in Universiti Sains Malaysia covering Peninsular Malaysia and also Sabah and Sarawak coastal area. Finding shows that East peninsular Malaysia has higher amount of wave energy compared to West Malaysia, Sabah and Sarawak but unstable due to monsoon seasons. Sabah and Sarawak coastal area display much more constant and stable amount of energy throughout the study year. Table 1 show the amount of wave power available in the Malaysian coastal area while Figure 3 shows the location of the study for the research.

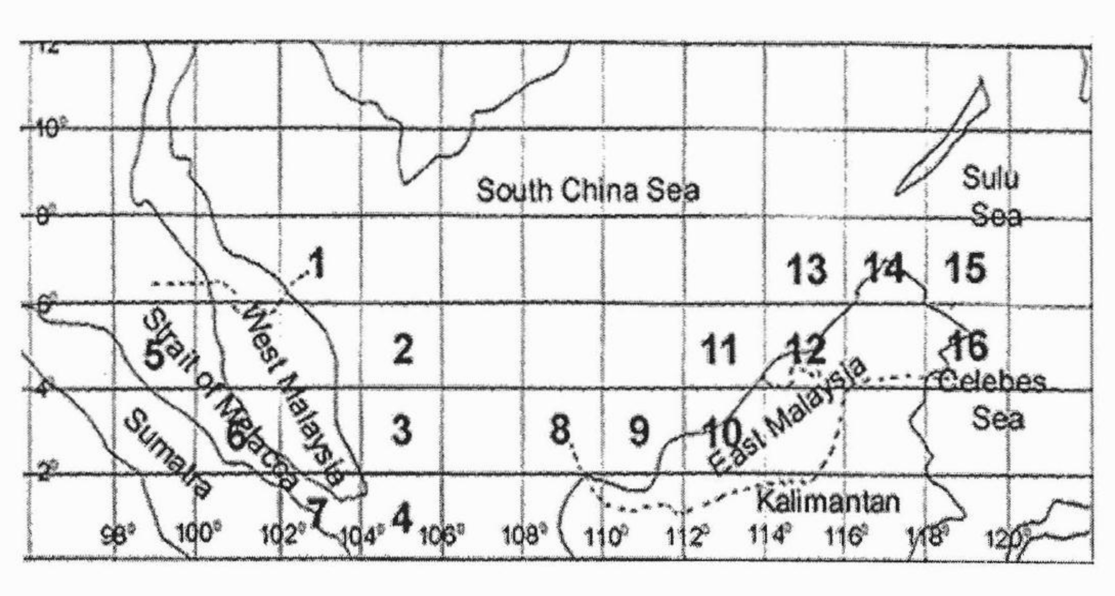
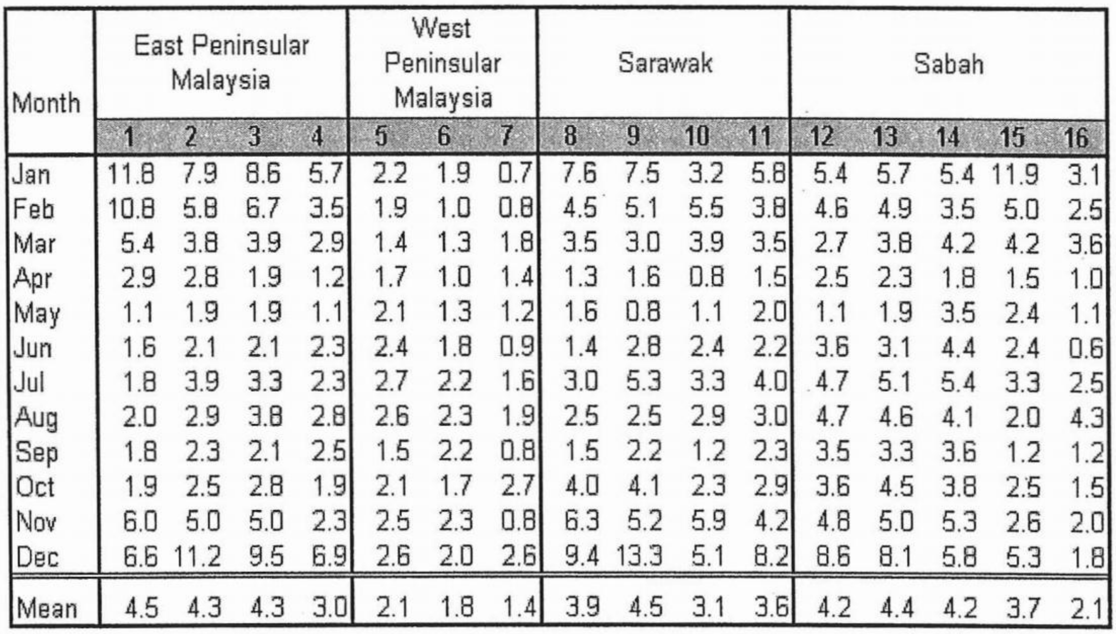


Figure 3 Distribution of wave energy in Malaysia [5]

Table 1 Monthly mean of wave power in kW/h [5]



Month	East Peninsular Malaysia				West Peninsular Malaysia			Sarawak				Sabah				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Jan	11.8	7.9	8.6	5.7	2.2	1.9	0.7	7.6	7.5	3.2	5.8	5.4	5.7	5.4	11.9	3.1
Feb	10.8	5.8	6.7	3.5	1.9	1.0	0.8	4.5	5.1	5.5	3.8	4.6	4.9	3.5	5.0	2.5
Mar	5.4	3.8	3.9	2.9	1.4	1.3	1.8	3.5	3.0	3.9	3.5	2.7	3.8	4.2	4.2	3.6
Apr	2.9	2.8	1.9	1.2	1.7	1.0	1.4	1.3	1.6	0.8	1.5	2.5	2.3	1.8	1.5	1.0
May	1.1	1.9	1.9	1.1	2.1	1.3	1.2	1.6	0.8	1.1	2.0	1.1	1.9	3.5	2.4	1.1
Jun	1.6	2.1	2.1	2.3	2.4	1.8	0.9	1.4	2.8	2.4	2.2	3.6	3.1	4.4	2.4	0.6
Jul	1.8	3.9	3.3	2.3	2.7	2.2	1.6	3.0	5.3	3.3	4.0	4.7	5.1	5.4	3.3	2.5
Aug	2.0	2.9	3.8	2.8	2.6	2.3	1.9	2.5	2.5	2.9	3.0	4.7	4.6	4.1	2.0	4.3
Sep	1.8	2.3	2.1	2.5	1.5	2.2	0.8	1.5	2.2	1.2	2.3	3.5	3.3	3.6	1.2	1.2
Oct	1.9	2.5	2.8	1.9	2.1	1.7	2.7	4.0	4.1	2.3	2.9	3.6	4.5	3.8	2.5	1.5
Nov	6.0	5.0	5.0	2.3	2.5	2.3	0.8	6.3	5.2	5.9	4.2	4.8	5.0	5.3	2.6	2.0
Dec	6.6	11.2	9.5	6.9	2.6	2.0	2.6	9.4	13.3	5.1	8.2	8.6	8.1	5.8	5.3	1.8
Mean	4.5	4.3	4.3	3.0	2.1	1.8	1.4	3.9	4.5	3.1	3.6	4.2	4.4	4.2	3.7	2.1

Proven to be great a source of energy, extensive research had been done in order to extract this great amount of wave energy. As the result, there are various types of wave energy harvester used around the globe ranging from Oscillating Water Column (OWC), hinged contour devices and overtopping devices. However directly driven linear generator is proven to be the most advantageous technique compare to rotating turbine and other techniques [6]. This is due to the simplicity of the system that result in lower maintenance cost and also prolong lifespan.

A full simulation model of linear wave energy harvester can help understand output of the system and also any flaw. Thus it is crucial to implement a simulation model that is close enough to the actual device. So, study about ocean wave and its relation with power produce by the energy harvester system need to be done. All elements of the wave energy harvester such as linear generator, wave characteristic and also controller need to be study in depth to construct the simulation.

1.2 Problem Statement

Previous section had shown the potential of wave energy around the globe including in Malaysia coast. However the utilization of wave energy to generate electricity is 10.6%, far too small compare to fossil fuel and other renewable energy [6]. Thus, research on wave energy conversion system is required to increase the wave energy utilization to generate electricity.

Direct driven linear generator is one of the techniques to convert wave energy into electricity. Since wave energy is new, limited data is available regarding the direct driven linear generator. Developing the actual devices to observe the performance of the system will consume huge costs and time. Simulation model of the system will help understanding the system and detect any problems.

Major problem in wave energy devices is caused by the non-uniform frequency and amplitude of ocean wave. This will result in unstable output of the direct driven linear generator in term of frequency and amplitude. Thus, output of the system will not be able to feed directly into the grid.

1.3 Objectives

i. **To build a simulation model of wave energy conversion process using Simulink.**

   This model is consisted of Non-uniform ocean wave model and directly driven linear generator model. Non-uniform ocean wave model is defined to generate input wave that has changing amplitude, frequency and ripple similar to real ocean wave. Combination of these two blocks, with ocean wave model as the input for the system will produce uncontrolled output voltage of the system.

ii. **To propose a suitable controller to control output power before it can be feed to the grid.**

As mentioned in the earlier part, output power of linear generator is fluctuated due to the nature of wave which has irregular amplitude and frequency. Thus the control strategy will have to handle the output power of the generator to produce output voltage with constant frequency and voltage.

iii. **To test the proposed suitable controller with different type of input wave.**

This is crucial to determine the robustness of the controller and also the whole system. Input wave applied to the system is varies in term of amplitude and frequency while the relationship between input wave and output voltage is observed. Besides, output voltage produced from input wave with ripple and without ripple is also observed and compared.

1.4 Scope of Study

Chapter 1 of this paper is discussing about the problem statement and the significant of the project. Thorough review about the wave energy distribution is displayed to show the suitability of the project in certain area. Objectives of the project are also highlighted to give clear view about the outcome of the project.

Chapter 2, details review on wave energy, linear generator and also control scheme available for the plant is performed. This is important to give clear understanding about the project and also elements involved to complete this project.

Chapter 3 is highlighting about the methodology used to implement this project. Details about project activities and also flow of the project are displayed.

Chapter 4, results of the project is obtained and observed to determine whether the objectives of the project are fulfilled.

Finally, Chapter 5 cover the conclusion of the project and also further works possible for this project.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

This chapter illustrates about ocean wave energy in term of power distribution and also height characteristic of wave in Malaysia. Power and energy calculation for ocean wave is also discussed in detailed. Thorough review about linear generator is performed to give clear understanding on how linear generator works and also parameters involved in the operation. Also discuss is the control scheme available that can be implant to the system to obtain desired output.

2.2 Energy Conversion

There are a lot of references such as textbooks [6] [7], journals [2] and article [8] [9] discussing about wave energy conversion using linear generator. Among the book is Ocean Wave Energy by Joao Cruz, which discussing about the wave energy and also several techniques to harvest this type of energy. Among the technique discussed is directly driven linear generator with several topology available which selected as the method used in this project.

Harvesting wave energy using linear system is proven to be more advantageous compared to rotating generator and also other techniques. This is because linear generator system increase the system efficiency because mechanical energy of wave movement is used directly instead of changes it to rotating movement. Firstly, buoy used to transform wave movement into vertical movement with certain speed. Mechanical energy produced then used to move the generator and produce electricity. Figure 4 shows the conversion process of wave energy to mechanical energy by buoy before transformed to electrical energy by linear generator.

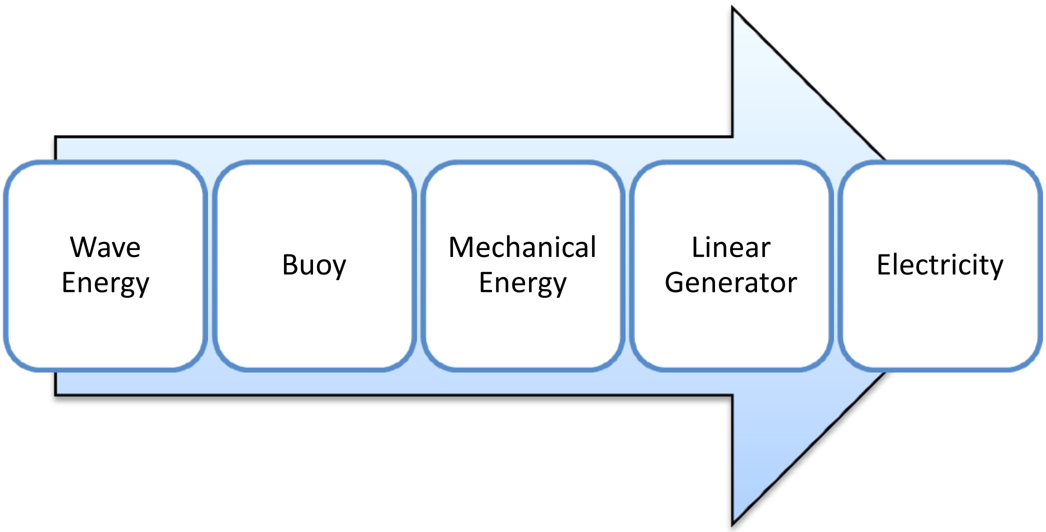


Figure 4 Wave energy conversion to produce electricity

2.3 Wave Energy

Study about wave power conversion requires complete knowledge about the ocean wave itself. Ocean wave consist of longitudinal and transverse wave which mean the water particle not mowing forward but only move in circle. Power or energy is the only element that transfers forward. It is imperative to look at the kinetic and potential energy of the wave before considering device to harvest the wave power.

Several important parameters used to determine the wave energy which include wavelength, λ and radius of water particle motion, α. However this circular motion of water particle only applicable in deep sees with depth twice of wavelength, λ. Ocean wave in the shallow water will experience decrease in α and water particle now move in ellipse motion. The amplitude of water particle decrease exponentially with depth but this effect is negligible if depth is more than 0.5λ.

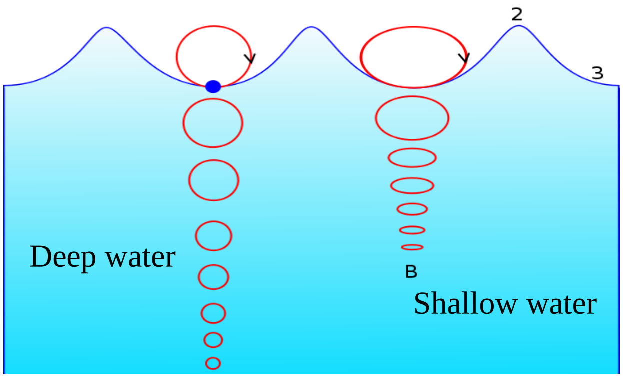


Figure 5 Water particle motion in deep and shallow water [10]

The next focus is to determine the energy and power present in ocean wave. This is important to give rough idea about the power generating capability of ocean harvester. In details, wave energy consists of kinetic energy and potential energy. Kinetic energy, E_K for moving object is given by the equation

$$E_K = \frac{1}{2}mv^2 \tag{2.1}$$

Where:

m	mass of the object
v	velocity of the object

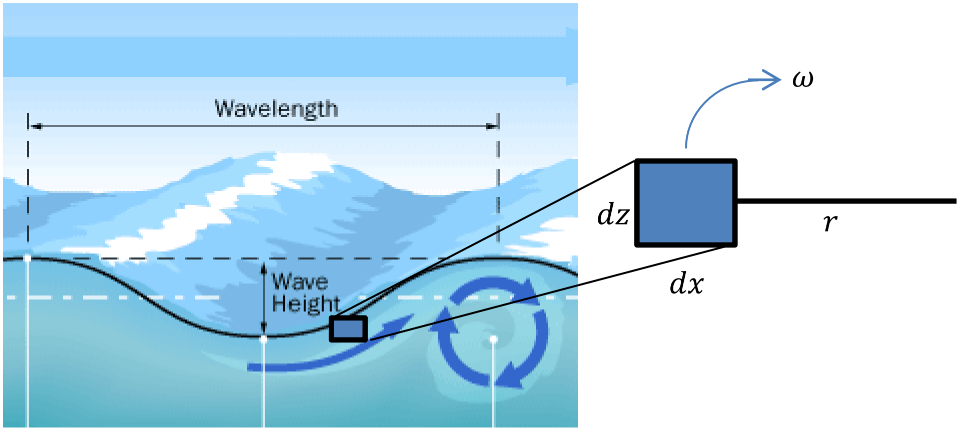


Figure 6 Water strip across wave [11]

If we consider a strip of water with a unit width of wave front, height dz and length dx in x and z axis, the volume of the strip of water with density ρ is

$$dV = length \times height \times width = dx \times dz \times 1 \tag{2.2}$$

Thus, mass is

$$dm = \rho \times \mathrm{dv} = \rho \times dx \times dz \tag{2.3}$$

While velocity, v is

$$v = r\omega \tag{2.4}$$

Where:

r	radius of circular orbit below surface,	$r = ae^{kz}$
ω	angular velocity,	$\omega = \sqrt{{2\pi g}/{\lambda}}$

Hence

$$\partial E_K dx = \frac{1}{2}mv^2 = \frac{1}{2}\rho dxdz\, r^2\omega^2 \tag{2.5}$$

Now instead considering a strip of water, a column of water is moving in the same phase.

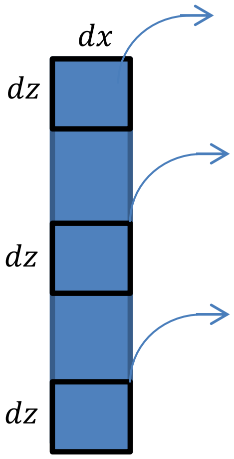


Figure 7 Column of water strip in wave

Total kinetic energy of the column is

$$E_K = \int_{z=-\infty}^{z=0} \frac{1}{2}\,\rho\, a^2 e^{2kz} \omega^2\, dz = \frac{1}{4}\rho\frac{\omega^2 a^2}{k}\, dx \tag{2.6}$$

Where

k wavenumber, $k = {}^{2\pi}/_{\lambda}$

ω angular velocity

Thus,

$$E_K = \frac{1}{4}\rho a^2 \frac{2\pi g}{\lambda}\frac{\lambda}{2\pi} dx = \frac{1}{4}\rho a^2 g \tag{2.7}$$

2.4 Different Type of Wave Energy Conversion System

In this section, some of the techniques and concepts of wave energy converters is reviewed and compared. Among the popular devices are Oscillating Water Column, Pelamis device, Wave Dragon and also Direct Driven Linear Generator.

Oscillating Water Column convert ocean wave movement into pneumatic energy of air to rotate Well's Turbine and rotate the generator. Well's turbine has the special characteristic that allow it to rotate in the same direction with bi-directional air flow passing through the turbine [12]. However, the performance of Well's Turbine is affected by stalling behaviour, which caused the turbine to stall when the air flow through the turbine exceed some value [6]. The conversion from vertical movement to rotational movement by the devices also reduced the system efficiency and durability.

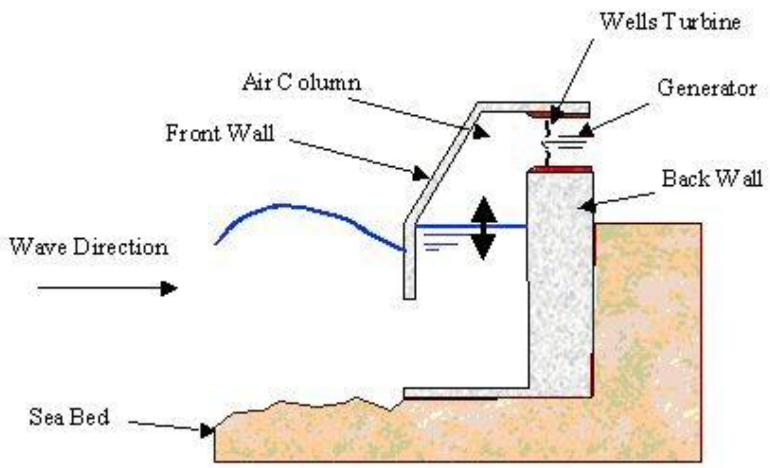


Figure 8 Oscillating Water Column [12]

The Pelamis wave energy converter developed in Scotland is a semi-submerged device consists of few cylindrical sections that linked by hinged joints. When wave pass through the length of the machine, the cylindrical sections of the device articulates around the joints. This induced motion of the joints is resisted by hydraulic rams which then pumped high-pressure oil through hydraulic motors. Finally, the hydraulic motors drive the electrical generator in the device to produce electricity [6].

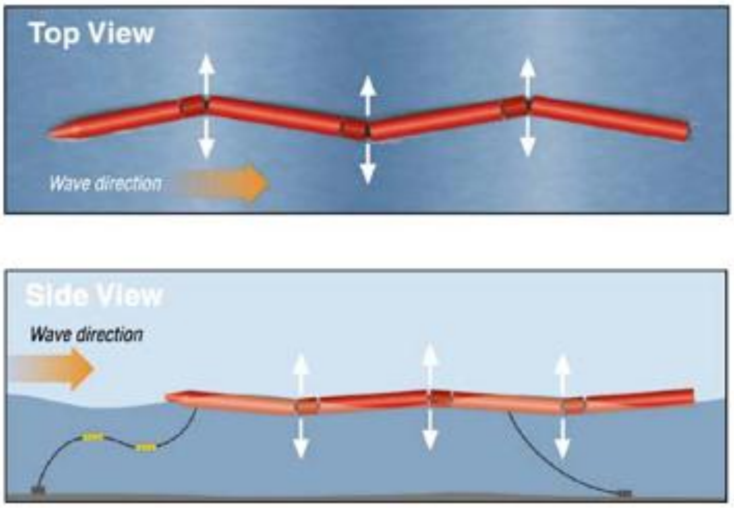


Figure 9 Pelamis Wave energy converter [6]

Wave Dragon uses the concept of overtopping principle to harvest wave energy. This device consists of a curved ramp on the front face that collects water from wave into the reservoir at the back of the device. From the reservoir, the water is channelled back to the sea through low head hydro turbine that generates electricity as the water flows. Wave Dragon design only allowed it to be deployed in water with depth above 20 meters [6].

Figure 10 The Wave Dragon prototype in Northern Denmark [6]

2.5 Direct Driven Linear Generator

There are few generators that could possibly be used to transform mechanical energy of wave into electricity. In OWC system, torque produced by Wells turbine is used to rotate generator to generate electricity. The most preferred Wells turbine driven generator is the squirrel cage induction generator. This type of generator is cheap, small rugged, maintenance free, does not require separate excitation and synchronization to the grid [12].

However, the only generator applicable in linear system using buoy is linear alternator. Linear generator operates without using any gear or crankshaft. This creates a major advantage of linear generator compared to rotating generator. Operate with less mechanical component, linear generator can overcome wear and tear problem due to excess movement such as stiffness, mass friction and backlash [13].

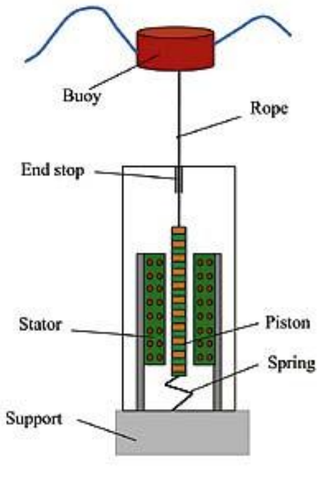


Figure 11 Linear generator with buoy [14]

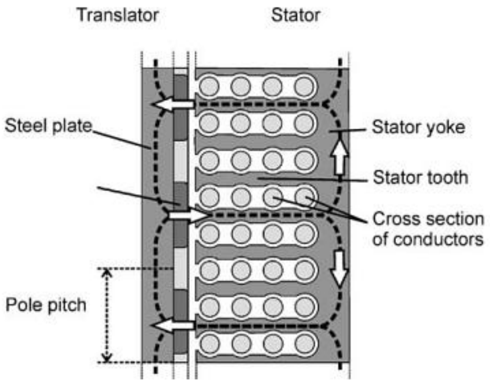


Figure 12 Cross-sectional view of linear generator [6]

Linear generator model is derived from equation involving magnetic and electrical elements. The first parameter that taken into consideration is vertical displacement of the buoy, y(t). By assuming the wave condition is perfect sinusoidal, vertical displacement can be determine by equation below, where d is the maximum vertical displacement of the buoy and ω_m is ocean wave frequency in rad/s.

$$y(t) = \frac{d}{2}\sin(\omega_m t) \tag{2.8}$$

The flux applied to the coils with respect to time can be determined by the following equation where lambda is the magnetic wavelength. The variable $\widehat{\Phi}$ is the value of peak flux produce by generator's magnet.

$$\emptyset(t) = \widehat{\Phi}\sin\left[\frac{2\pi}{\lambda}\cdot y(t)\right] \tag{2.9}$$

According to Faraday's law of induction, voltage induce in tightly wound coil wire can be calculated by differentiating the magnetic flux and multiply by the number if turns of wire [15].

$$v(t) = N\frac{d\emptyset}{dt} \tag{2.10}$$

2.6 Control Strategy

The main objective of control strategy in the system is to stable output voltage so it can be feed to the grid and used by electrical equipment. Vast number of research had been done to propose a suitable control strategy regarding to OWC wave energy harvester. However, the output power and torque of the system is required so that analysis can be done on the effect of stalling behaviour to the system.

In linear energy harvesting system, controller is also required since the output voltage of the linear generator is not a perfect sinusoidal. As the nature of ocean wave that have irregular amplitude and also changing frequency, the linear generator output will be the same. This is because wave movement is transfer directly into the generator by the buoy.

One of the control strategies that can be implemented on the system is to change the generator output voltage to DC voltage. In DC, output voltage is easier to be manipulated. Originally, AC voltage is fluctuating due to the ocean wave condition. DC to DC boost converter can be used to regulate the output voltage to the desired value [16].

In order to obtain DC voltage from the output of linear generator, passive rectifier using diode is used. As the linear generator used is in 3 phase, the rectifier must also be built in 3 phase system (refer figure below). However, rectifier alone will produce half-sinusoidal DC output voltage. This will be a huge problem when it needs to be converted back to AC. Thus, suitable DC-link capacitor is placed in the circuit to smoothen the DC output of the rectifier.

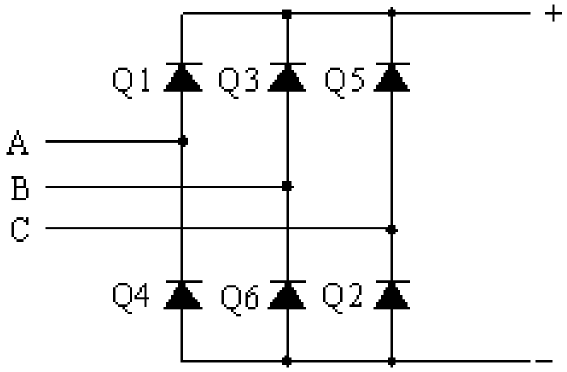


Figure 13   3-phase rectifier

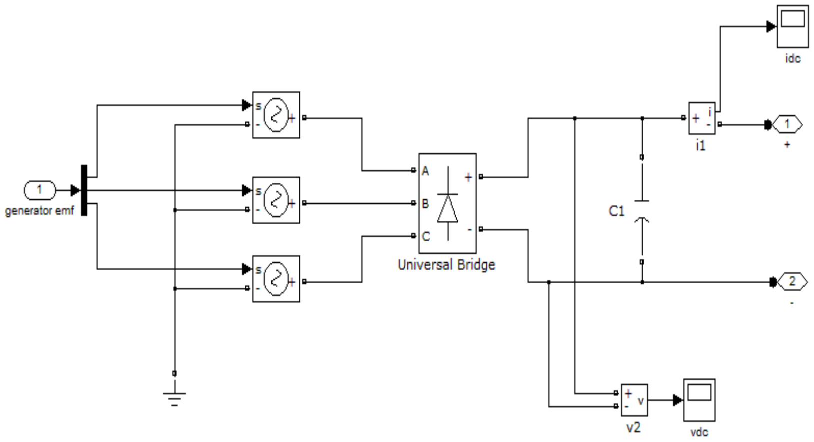


Figure 14   Simulink model of passive rectifier

Next element used in control strategy is DC-AC inverter. This device is playing important role to produce 50Hz voltage that can be feed directly into the grid. Component required to construct an inverter is Insulated Gate Bipolar Transistor (IGBT) and also Pulse Width Modulation (PWM) signal module. Fortunately, IGBT inverter block is available in Matlab Simulink and can be used directly with other SimPowerSystem components. LC filter is also attached to the inverter which functions as low pass filter. This will remove any ripple in the AC output voltage of the system and produce smooth sine voltage.

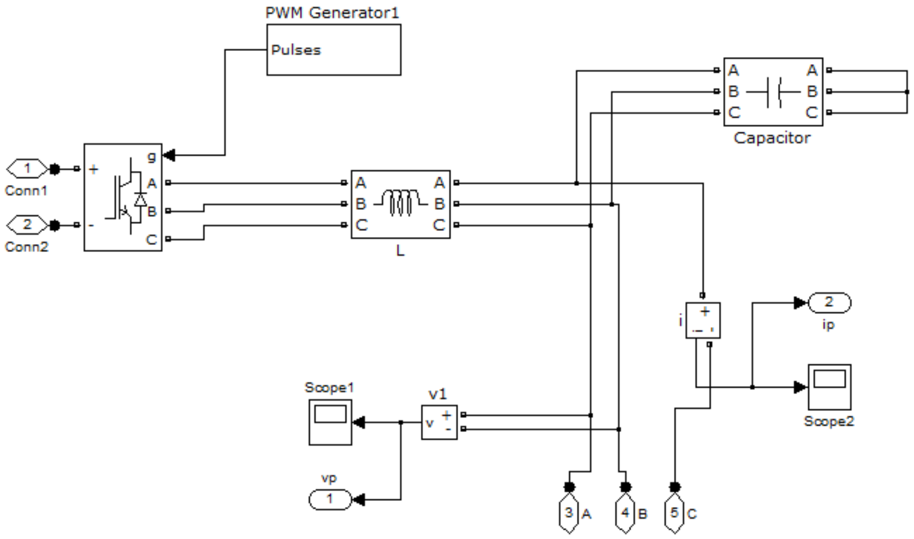


Figure 15 Simulink model of DC-AC inverter and LC filter

PWM block is crucial element for the inverter which produced the gating signal that turns the IGBT on and off. PWM is the most common signal used in inverter to drive the IGBT to produce AC voltage. In order to produce PWM signal, carrier signal and also modulating signal which has lower frequency than carrier signal. Fortunately, PWM generator block is available in Simulink and the modulating signal can be taken from inverter output or internal source in the PWM generator block. Frequency and amplitude of the inverter output voltage is determined by modulating signal and also modulation index value [8].

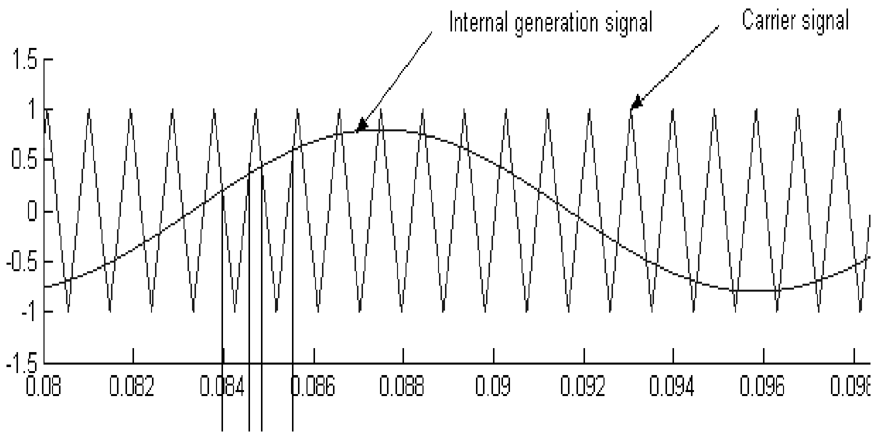


Figure 16 PWM triangular carrier and modulating signal [17]

2.7 Conclusion

This chapter shows a clear view about wave energy characteristic and wave power distribution worldwide and also in Malaysia. Besides, operation of linear generator, equations and parameters required to develop a simulation model of the directly driven linear generator is also made available. Final element of the system which is control scheme had also been explained. The next chapter will continue on the methodology and activities involved in order to complete this project.

CHAPTER 3
METHODOLOGY

3.1 Introduction

This chapter discusses on the project flow and activities involved from the beginning until the completion of the project. Tools and equipment used in this project is also presented in this chapter. The complete simulation model also introduces and explains.

3.2 Project Activities

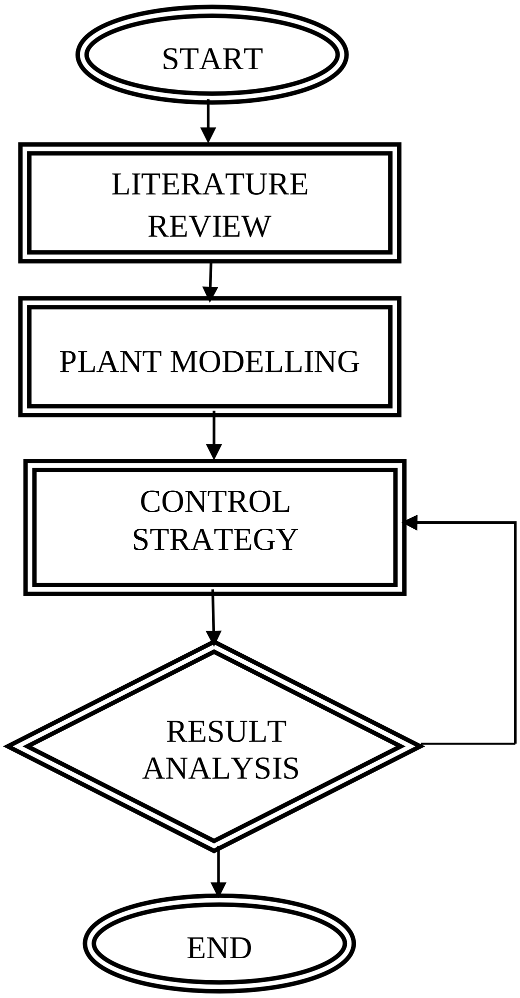


Figure 17 Project flow

Figure 17 shows the flow of the project starting from early stage until completion. This project began with literature review on wave energy conversion system using directly driven linear generator. At this stage, thorough study had been done on research paper, journal and also textbook that explain working concept wave energy, linear generator and also control scheme available for the system. The first element analysed is the wave energy itself. Detail analysis about linear generator operation and parameters involved is done. When the idea about the system output was clear, study about the available control strategy then implemented.

After completing the literature review period, modelling process initiated with basic plant model which consist of ocean wave model and generator model. Simulink model of ocean wave is constructed based on real ocean wave which has irregular amplitude, irregular frequency and noise. Other wave model such as ideal model, Non-uniform wave model without ripple and different amplitude and frequency wave model is also build. This variety of wave model is used to determine the robustness of the controller and also the whole system.

The next component in basic plant model is the linear generator model. These blocks is built base on the equation in section 2.2. Each equation is transform into functioning block that finally produce generator back EMF. Ocean wave model is placed together as the input for the generator model. On completion, linear generator model is tested with ideal wave and also Non-uniform wave input to verify its accuracy. When these two models completed, ocean wave block is placed as the input for the linear generator model. This basic plant model then used to produce uncontrolled output of the plant.

Next model built in this project is the control scheme model. Nature of the ocean wave is fluctuating with different amplitude and frequency. This factor affected the output of linear generator which cannot be feed directly into the grid. The objective of this model is to produce an acceptable output voltage that can be feed intro the grid based on the output EMF of linear generator. Linear generator output with Non-uniform wave model is analysed in detail to determine the control strategy required. Finally, this control scheme model is attached with the plant model as complete plant system.

Once the full model is ready and working as expected, the process of data collection and result analysis took place. The first test on the model is done with pure sine wave as the input. However, this does not represent the real situation where ocean wave is not ideal sine wave. Thus in order to make sure the model will work under real condition, Non-uniform wave model is applied as input for the system. All these test performed is mainly to verify the suitability of the control scheme. Comparison between controlled result and uncontrolled result is used to determine the performance of the control scheme.

If the result obtain in the test performed on the plant model is fail to meet the specific requirements, the control strategy will need to be revised to obtain desired output. During project implementation, control scheme is changed few times due to output voltage fail to meet specific constant frequency and amplitude. Finally, when the output voltage reaches desired specification, result and discussion will be compiled in the final report.

3.3 Tools

As no hardware implementation involved, the only tool used in this project is Simulink Matlab 2010 software. Simulink is great software to create simulation model of any system due to simplicity of creating functioning block from equation and parameter. Besides, there are enormous numbers of library available including Power electronics library. . Figure 14 shows the user interface of Simulink software and also default library available in 2010 version.

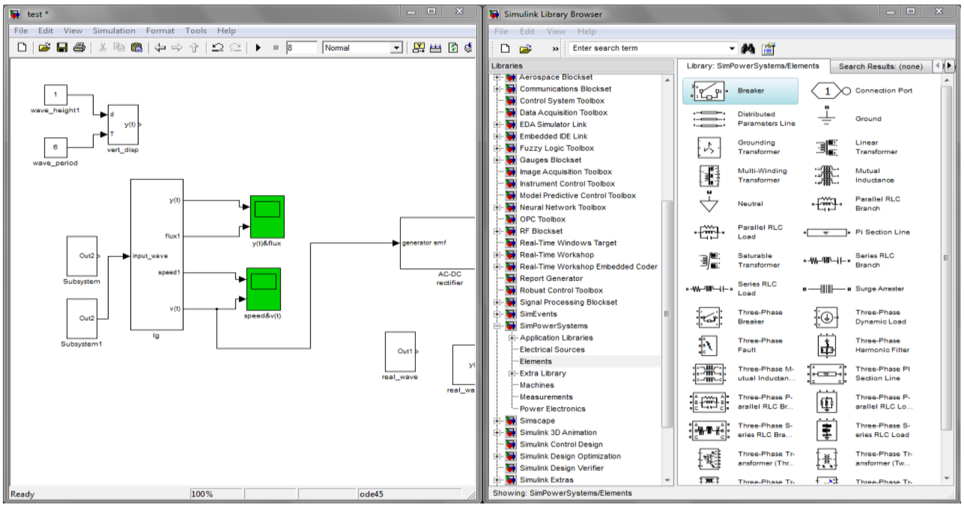


Figure 18 Simulink 2010 interface and SimPowerSystem library

3.4 Model of Wave Energy Conversion System

The wave energy conversion model consists of five main parts as shown in Figure 18. Wave model block functioned as input for the linear generator by generating wave height according to time. Linear generator model then calculated the output voltages correspond to the wave height. Other parameters such as vertical speed of translator, flux, and current of linear generator are also calculated for reference.

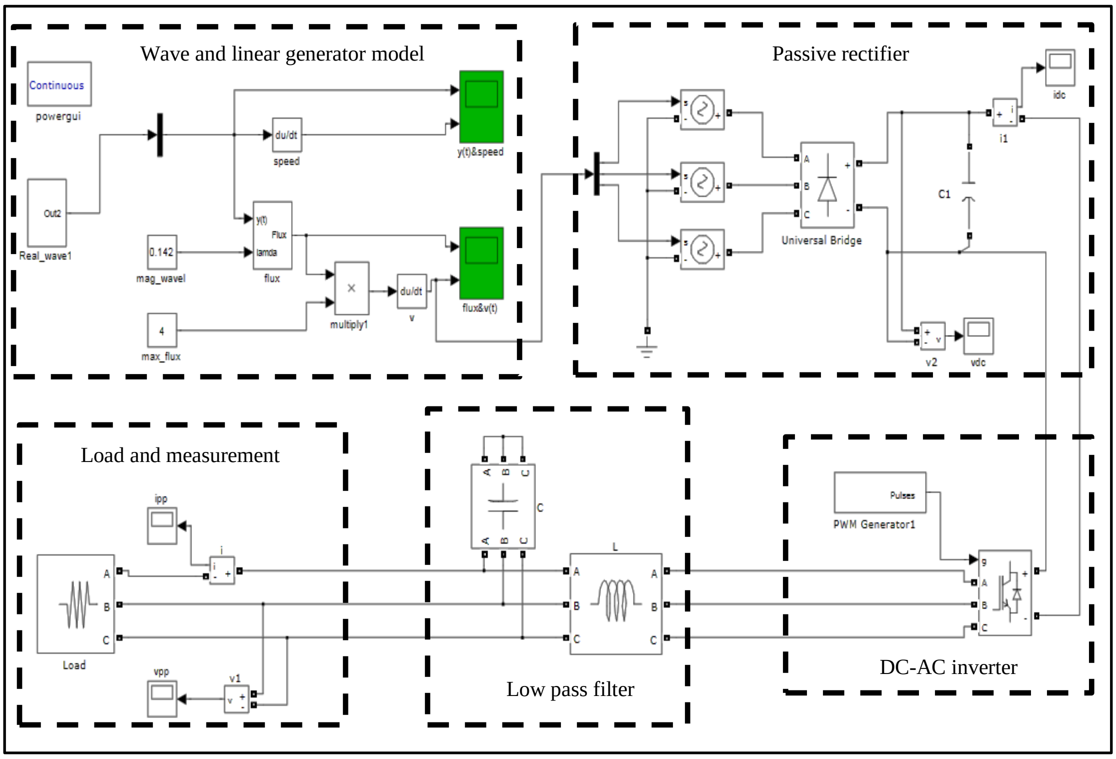


Figure 19 Complete model of wave energy conversion system using Simulink

Next element of the model is passive rectifier which is part of the control strategy. Uncontrolled alternate voltage from the linear generator is feed as the input for this rectifier. Diodes inside the rectifier block then convert the unstable alternate voltage from the generator into flat DC voltage. DC-link capacitor play important role for the rectifier to produce flat DC output.

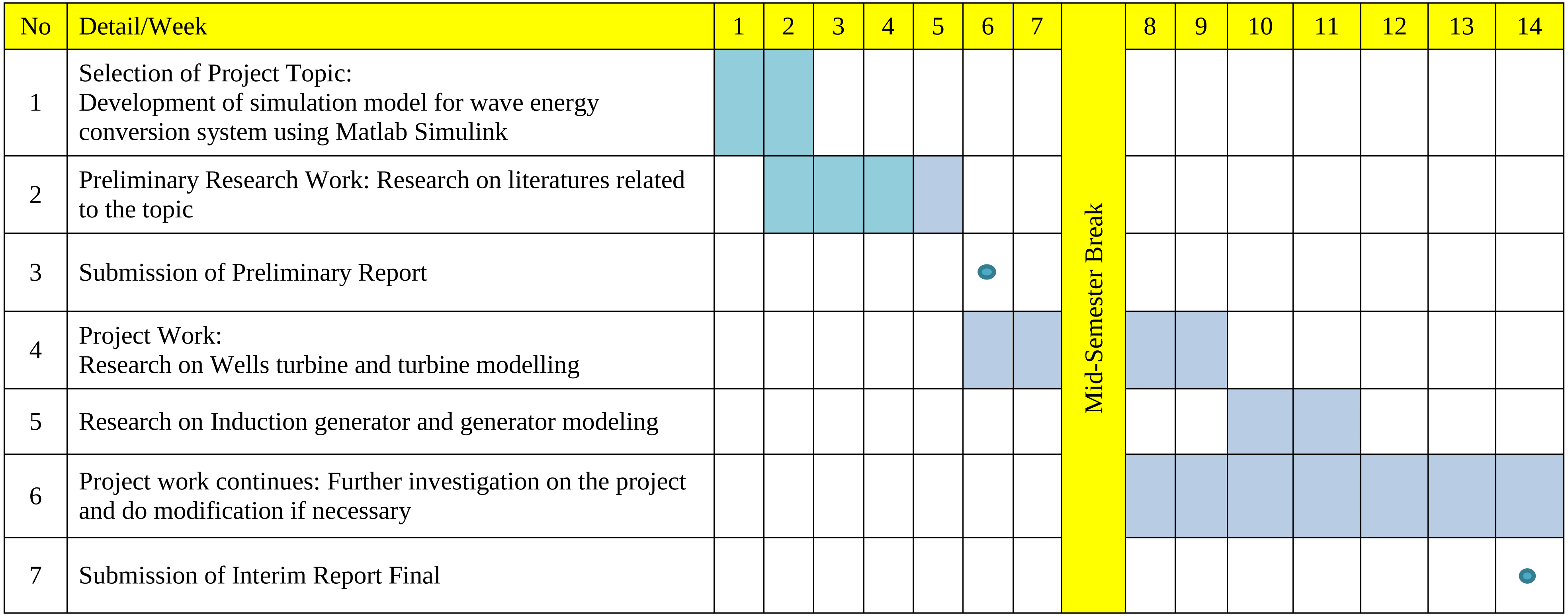
DC voltage then converts into stable AC voltage by DC-AC inverter block. Inverter block consists of IGBT driven by PWM signal. The frequency of the output voltage is determined by the PWM signal used. Even though the output voltage of the rectifier is stable in term of frequency and amplitude, ripples is yet to be removed.

Thus to produce smooth output, LC filter that functioned as low pass filter is applied. The entire high frequency ripple is then filtered out from the system producing smooth and stable AC voltage ready to be feed into the grid.

3.5 Conclusion

Details about the project implementation are already clarified in this chapter. Tools used and also the project flows should give the idea about the work involve in this project. Complete model of the system which consists of wave mode, linear generator model, control scheme and also load is also displayed for further reference. Gantt chart displaying the project schedule and key milestone is available on the next page. Thus, next chapter will discussed about the controlled and uncontrolled results obtained from this model. .

Table 2 FYP 1 Gantt chart and Key Milestone



No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Selection of Project Topic: Development of simulation model for wave energy conversion system using Matlab Simulink	🟦	🟦						Mid-Semester Break							
2	Preliminary Research Work: Research on literatures related to the topic		🟦	🟦	🟦	▨										
3	Submission of Preliminary Report						●									
4	Project Work: Research on Wells turbine and turbine modelling						▨	▨		▨	▨					
5	Research on Induction generator and generator modeling											▨	▨			
6	Project work continues: Further investigation on the project and do modification if necessary									▨	▨	▨	▨	▨	▨	▨
7	Submission of Interim Report Final															●

Table 3 FYP 2 Gantt chart and Key Milestone

No	Detail/Week	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Project work: Linear generator and ocean wave modeling	▨	▨	▨	▨	▨	▨		Mid-Semester Break							
2	Perform various testing on generator model							▨		▨						
3	Submission of Progress Report									●						
4	Controller modeling										▨	▨	▨			
5	Combining all Simulink model and perform final test for the model												▨	▨	▨	
6	Pre-EDX												●			
7	Submission of final report and VIVA															●

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

This chapter discusses all the result obtained from the simulation model developed in the Chapter 3. Output from linear generator model is obtained and compared using different wave model. Discussion about response of linear generator model with different input also included to verify the accuracy of the model. Controlled output of the full system is also reviewed to show the effectiveness of the control strategy.

4.2 Linear Generator Model

As mention is Chapter 3 (Methodology), linear generator model is tested with various different input waves ranging from ideal sine wave until Non-uniform wave model with changing frequency and amplitude. This test is only performed on the first block of the model, with other model is disconnected from the system to verify its input and output relationship. Results obtained from this test revealed that fluctuating wave condition produced linear generator output voltage that varies in frequency and also amplitude. Besides, ideal sine wave input is also produce non-uniform output voltage due to variation of vertical speed of the linear generator movement.

Figure 20 and Figure 21 show the input wave which is ideal sine wave and also flux of the linear generator. While Figure 22 and Figure 23 show the vertical speed of the buoy and uncontrolled output voltage of the generator. This test is only performed with one cycle of input wave because translator of the generator cut more than one magnetic flux in one cycle. As observed, even with ideal sine wave as the input, linear generator back EMF is not stable in term of frequency and amplitude due to the variation of vertical speed of the linear generator. This proved that control strategy is crucial in the system to compensate this fluctuating output.

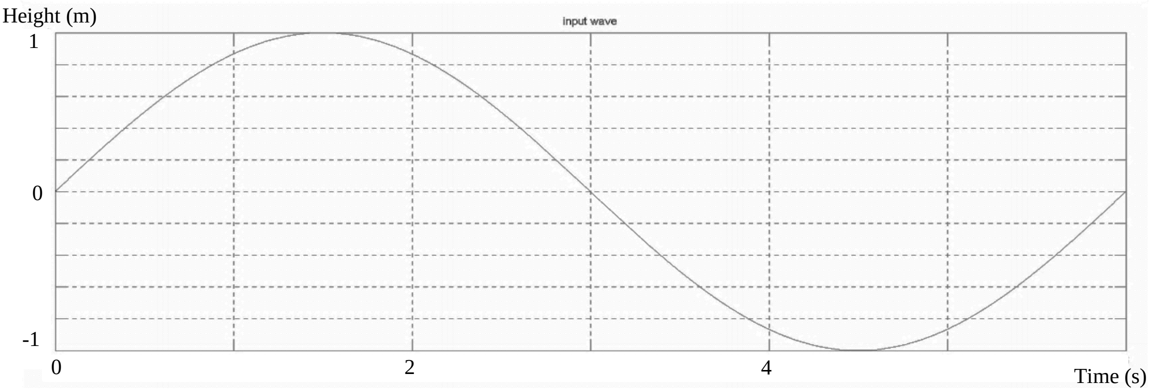


Figure 20 Ideal wave input

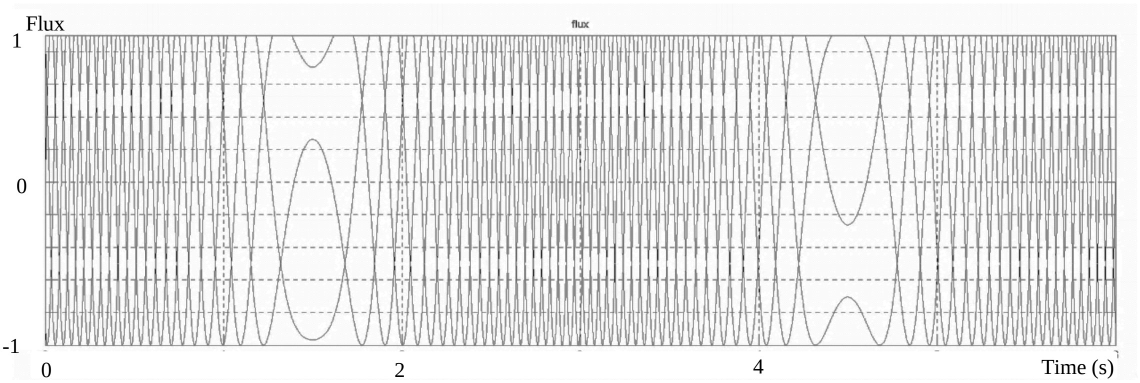


Figure 21 Linear generator flux

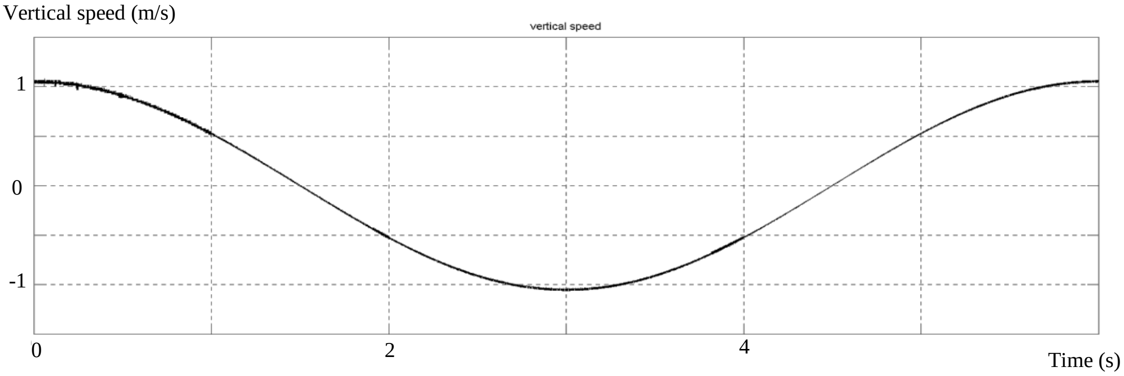


Figure 22 Vertical speed of linear generator

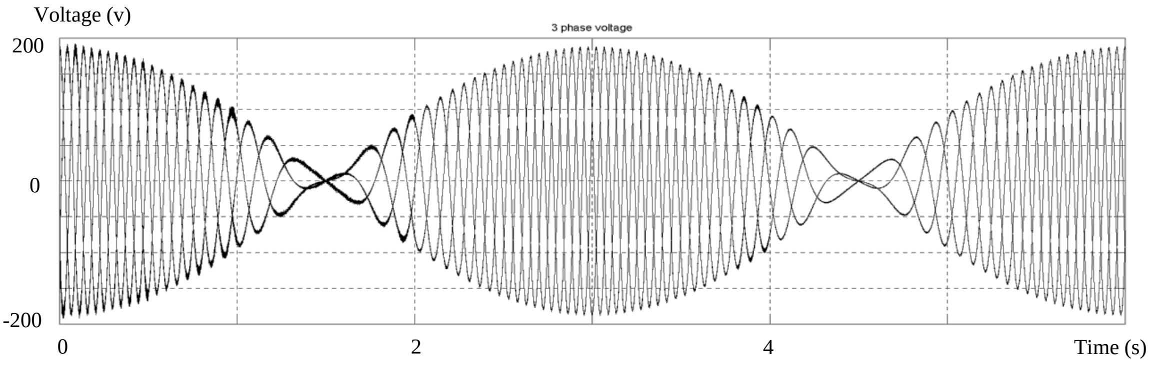


Figure 23 3-phase voltage of linear generator

In addition to the ideal wave test run on the linear generator, several other wave input is applied to the system. The objective is to observe the input output relationship between the wave model and also linear generator output. In order to compare the output voltage, three ideal waves with different amplitude is applied and the result is compared. The same technique is used to observe the output of linear generator when input wave with different frequencies is applied.

For the simplification of the test run on the linear generator model, the magnetic wavelength, λ is set to 2 meters. This will results in linear generator output voltage to be exactly the same with input wave in term of shape. If output of the linear generator is not similar with input wave, linear generator model is not working properly. Besides, the result of the test is also determined by comparing the simulation result with the actual linear generator output. Figure 25, 27 and 28 show the output of the linear generator during the test and the result of those tests are compiled in the Table 4.

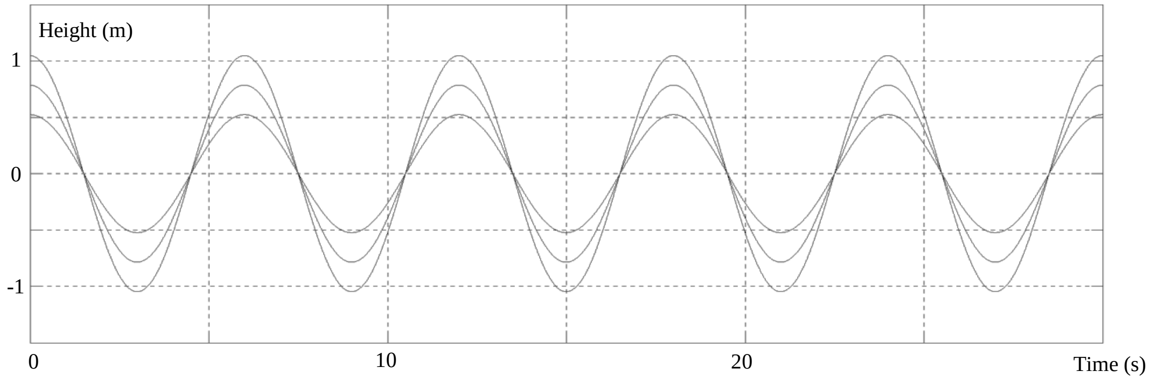


Figure 24 Different amplitude of input wave

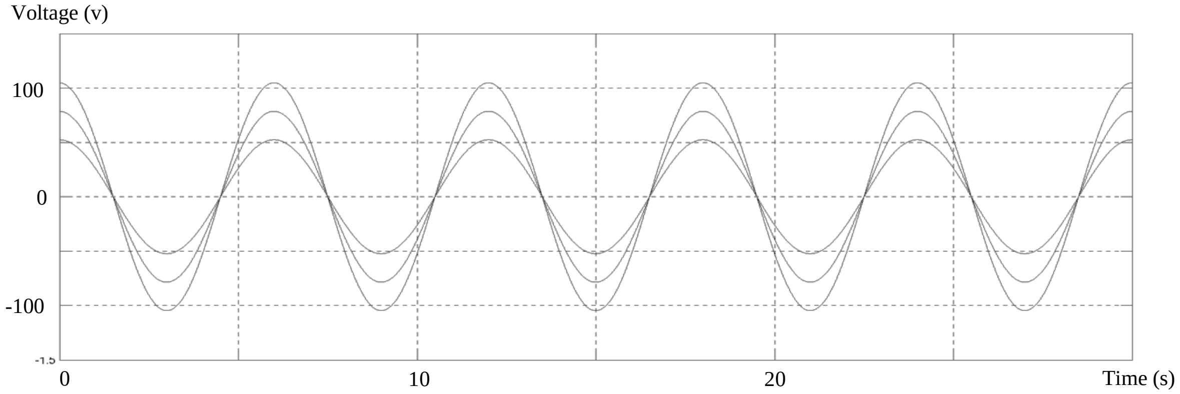


Figure 25 Different amplitude of linear generator outputs

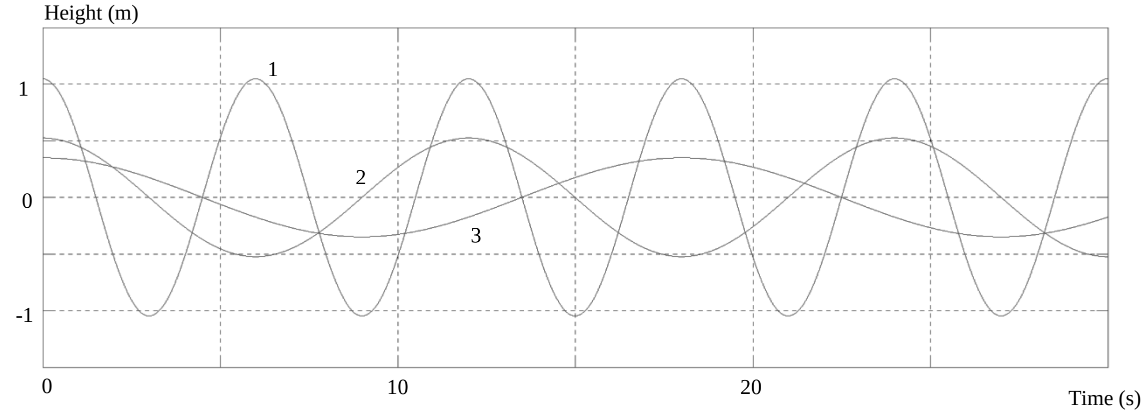


Figure 26 Input waves with different frequencies

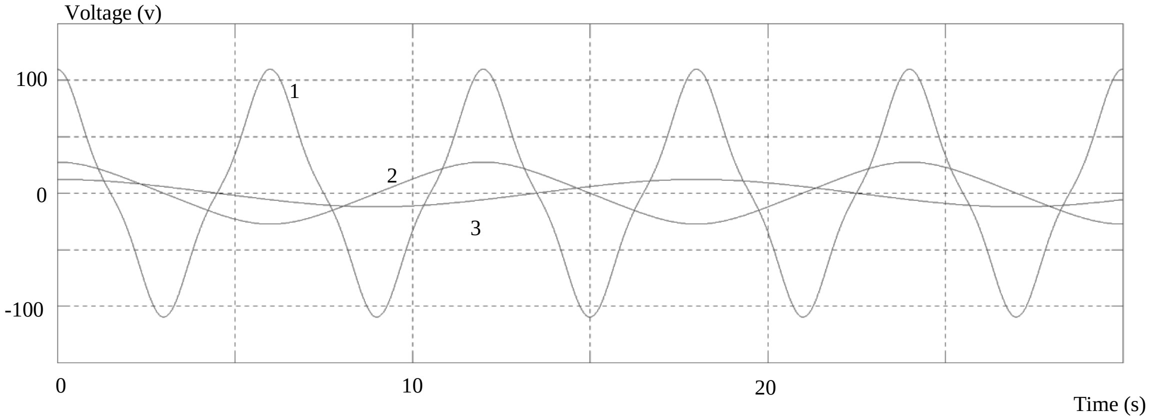


Figure 27 Different frequencies of linear generator outputs

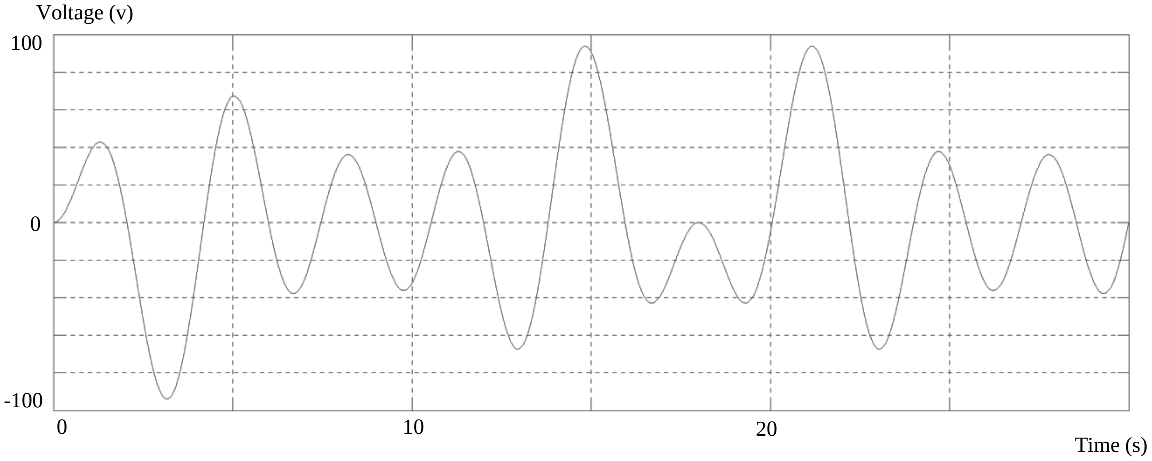


Figure 28 Linear generator output voltage with non-uniform wave input

Table 4   Test performed on linear generator model

Test		Observation	Pass/fail
1.	Different wave amplitude	Generator output voltage and flux amplitude is changed according to input wave.	Pass
2.	Different wave frequency	Voltage frequency of the generator changed according to ocean wave frequency.	Pass
3.	Wave with changing amplitude and frequency	Output voltage and flux value changed and produce similar wave shape with input wave.	Pass

4.3   Control Scheme with Ideal Wave Model

As the project continues, the control scheme model is attached to the system. Similar with linear generator model, control scheme is tested with ideal AC voltage at the first place. Then the complete system consists of plant and the control scheme is verified using ideal ocean wave model. Ideal wave model make it easier to troubleshoot any problem in the modelling as the output of the system is expected. Figure 29 shows the controlled output of the system when linear generator output is feed into the control scheme block.

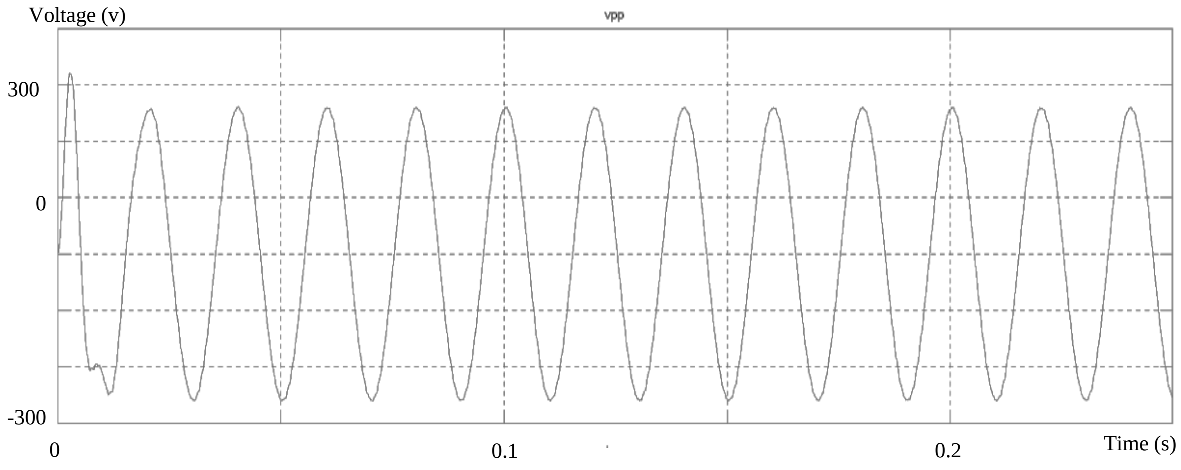


Figure 29   Controlled output voltage versus time

4.4 Non-uniform Wave Model

The final simulation performed with the directly driven linear generator model and the control scheme is the Non-uniform wave simulation. Non-uniform wave model with changing frequency and amplitude is feed as input while the output voltage is observed to make sure desired frequency and amplitude is obtained. However, the maximum amplitude of the model is set to 1 meter from the centre while. Besides, Ripple is also introduced in the actual wave model to simulate critical condition and vibration during operation.

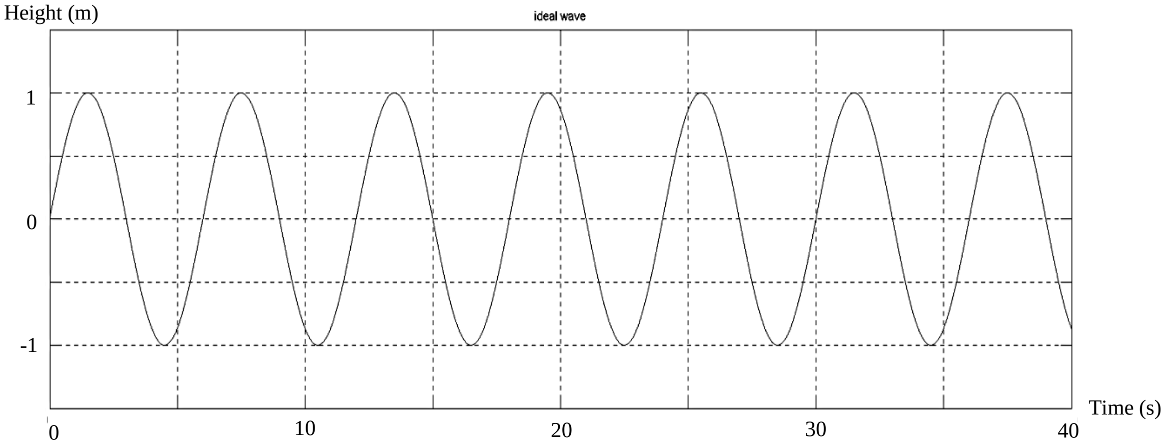


Figure 30 Ideal wave model

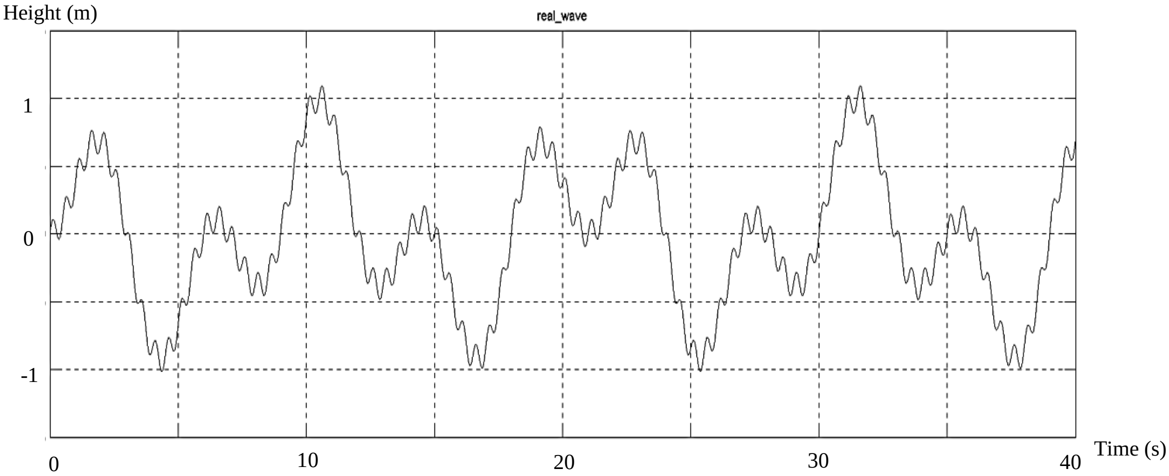


Figure 31 Non-uniform wave model

As the Non-uniform wave model is feed as input, linear generator output is observed and compared with the uncontrolled result and also result with ideal wave model. This stage is crucial because hardware implementation and real case scenario will be almost similar the situation produced by Non-uniform wave model. Ripple in the input wave caused excessive movement in the linear generator. Uncontrolled output of linear generator in Figure 33 and Figure 34 give clear picture about the effect of fluctuating sea condition towards linear generator output.

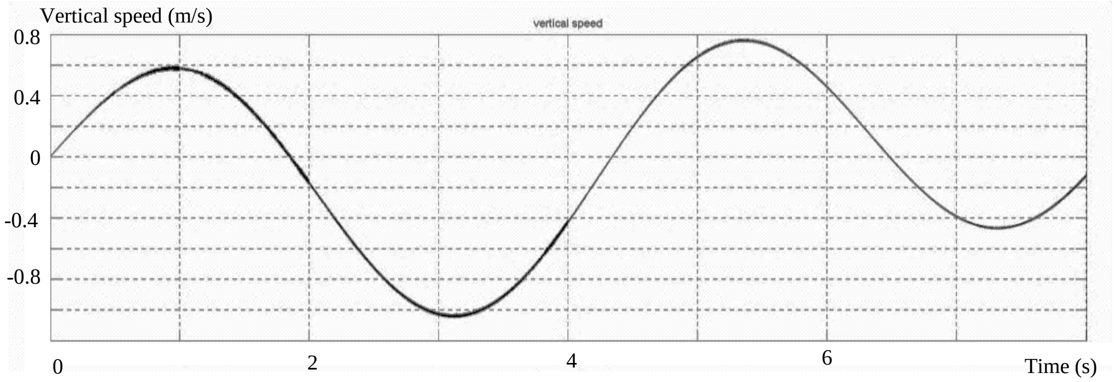


Figure 32 Vertical speed with non-uniform wave as input

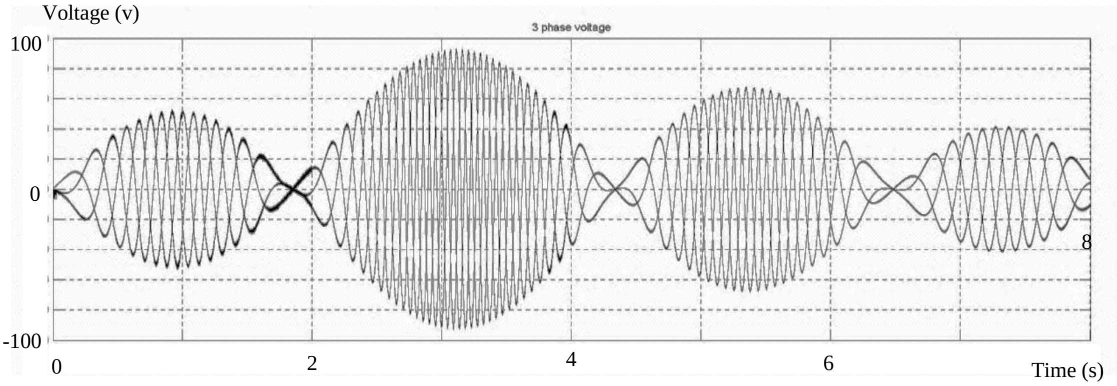


Figure 33 Uncontrolled linear generator output with non-uniform wave as input

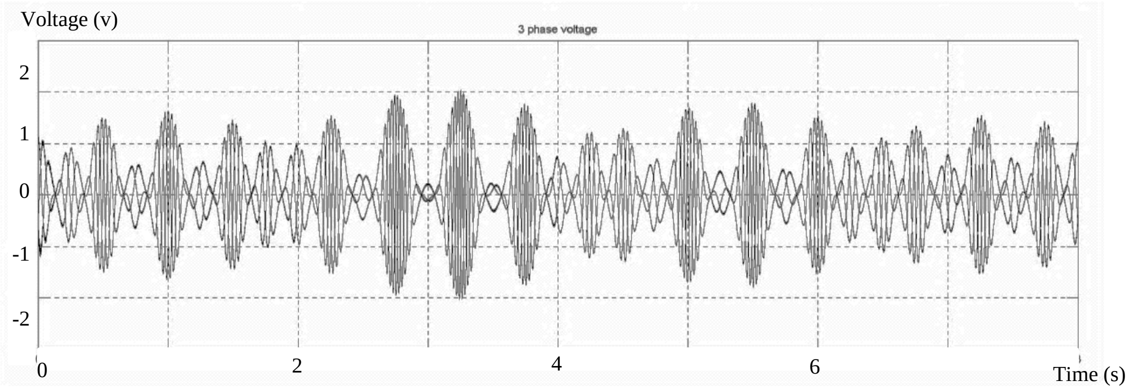


Figure 34 Generator output with rippled non-uniform wave as input

4.5 Control Scheme with Non-uniform Wave Model

As revealed in section 4.3, the output of linear generator is available and verified with ideal wave model and also Non-uniform wave model. This enable the test on the control scheme performed with Non-uniform wave model as the input. In Figure 34, LC filter or low pass filter is removed from the model to show the output voltage of the system before filtering process occurs. It is crucial to determine the correct parameter to build the low pass filter to make sure the control scheme can produce smooth AC voltage before feeding it into the grid.

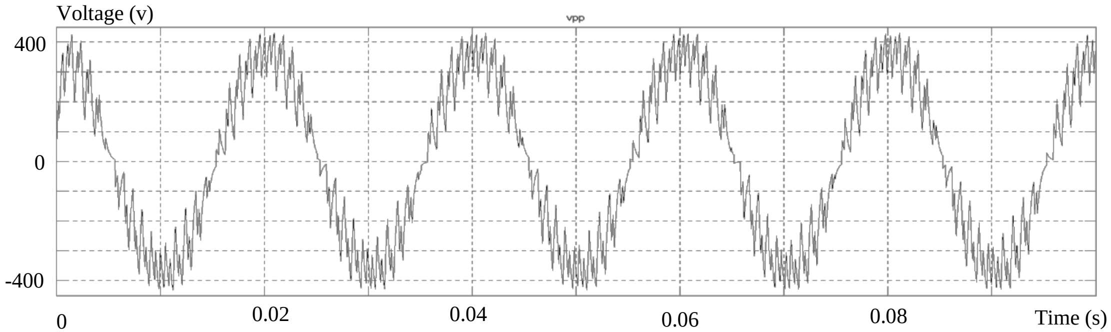


Figure 35 Output voltage of control scheme (without LC filter)

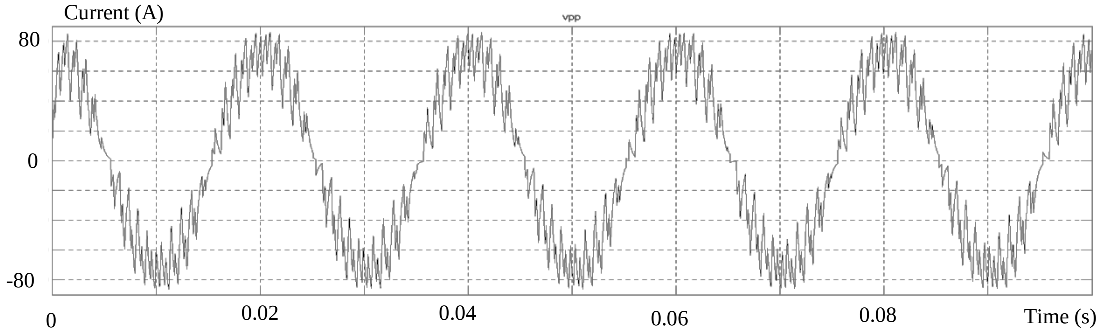


Figure 36 Output current of control scheme (without LC filter)

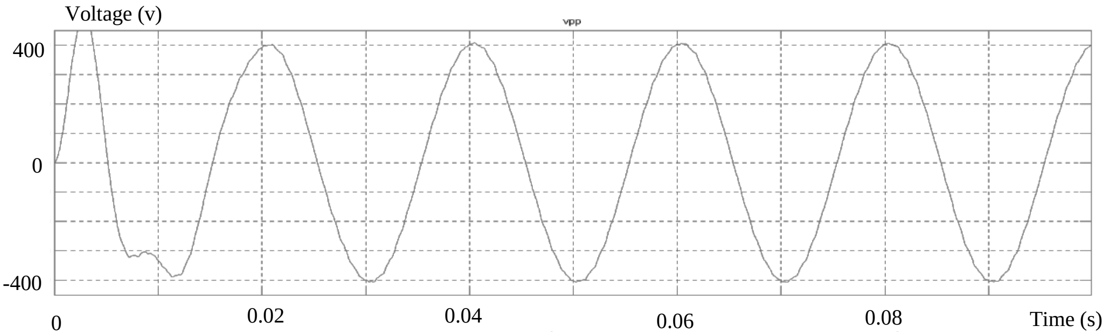


Figure 37 Output voltage of control scheme (with LC filter)

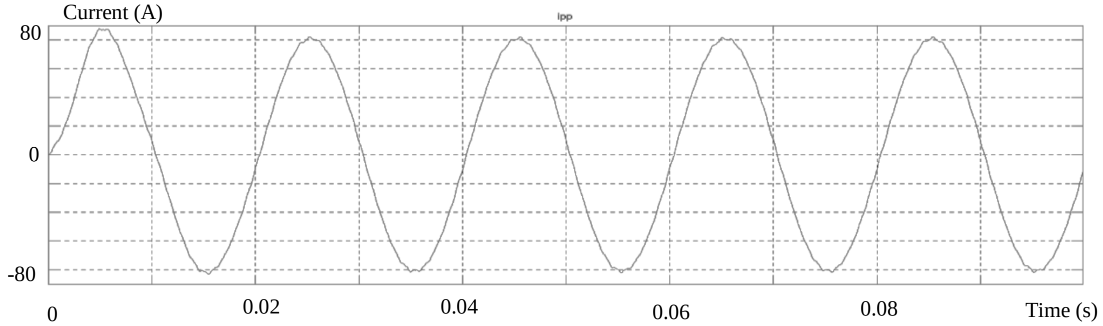


Figure 38 Output current of control scheme (with LC filter)

Figure 37 and Figure 38 shows the final output of the simulation model with Non-uniform wave model as the input for the system. This proved that control scheme build can be used to alter the output of the directly driven linear generator and produce desired 50Hz voltage with constant amplitude. In this simulation run, the DC-link capacitor inside rectifier module is set to have initial voltage. This is to simulate that the system is already in steady state and to save simulation time. DC voltage and current in rectifier module is measured but not explain in detailed here as it is the same as any 3-phase rectification process.

4.6 Conclusion

Detailed results of the plant simulation model and control scheme had already discussed in this chapter. Comparison between controlled and uncontrolled result show the effectiveness of the control scheme proposed. Besides, clear figure about the types of input applied to test the system is also displayed. In the final chapter, conclusion based on the result obtained and discussed in this chapter will be followed. Furthermore, suggestion for further improvement to improve the result obtain will also be available.

CHAPTER 5

CONCLUSION AND FUTURE WORKS

A directly driven wave energy conversion system using linear generator and also suitable control scheme has been simulated. Simulation model of the complete plant consist of ocean wave model, linear generator, control strategy, load and also measurement devices. Output frequency of the system is set to 50Hz to match with the national grid frequency as the objectives is to produce output that can be feed directly into the grid.

Various tests had been performed on every model build to ensure the performance and the accuracy of the model. Linear generator model undergo several test with different input wave to observe its input output relationship and make sure the voltage induced is correlated with the input wave feed to the system. This step is crucial to make sure linear generator model is working perfectly before building the control scheme model. When verified, output of linear generator is used as reference to build the control scheme for the plant.

The concept used in the control scheme is basically to convert AC voltage induce by the linear generator to DC voltage using rectifier. Passive rectifier built using diode and also DC-link capacitor to ensure smooth DC output is produced. Following the rectification process is the DC-AC inverter to produce desired AC voltage as the final output of the system. IGBT is used as the switch in the inverter while PWM signal generator available in Simulink used as the gating signal generator for the IGBT.

Finally, complete model of the directly driven linear generator and control scheme built is run and the result is observed and analysed. Controlled voltage of the system is compared with the uncontrolled voltage to determine the effectiveness of the control scheme used. Input wave is also varies to make sure the control scheme build is robust enough to handle any possible wave condition. However, this model reveals that critical change in wave height in long time will affect the output voltage of the system causing the output voltage to drop to certain value.

Further research on this project can be done especially in term of wave characteristics especially in Malaysian coastal area. This will give idea about the amount of energy available and the scale required to build this type of wave energy in Malaysia. Furthermore, extensive research on control strategy model should be done to improve the system performance. Besides, further research on control strategy is needed to produce pure sine wave output and able to compensate with critical change of wave height.

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