Improving the Efficiency of an Offshore Wave Energy Converter for Power Generation

by

Goh Aik Shien

16051

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

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Universiti Teknologi PETRONAS,
32610 Seri Iskandar,
Perak Darul Ridzuan.

CERTIFICATION OF APPROVAL

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Approved by

Assoc. Prof. Ir.Dr. Perumal A/L Nallagownden

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
January 2016

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 expect as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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GOH AIK SHIEN

ABSTRACT

Ocean is one of the renewable sources of energy that can supply part of the world's energy necessities and consequently lessen the percentage of consumption of fossil fuels and additional non-renewable resources. Water waves have a quite high power density with a total global power of approximately 1-10 TW, equivalent to a large segment of the world's current total energy consumption. The wave to electrical conversion encompasses wave energy converter (WEC), electrical generator, and signal conditioning end. This work is based on the selection and analysis of most suitable electrical generator which makes the overall wave energy conversion system simplest and reliable. The majority of wave energy conversion systems are based on conventional rotational generators which not only require mechanical interface i.e. turbine, hydraulic pump but make complicated system, incur losses and increases maintenance. On the other hand, direct-drive linear generators offer massive advantages in the field of wave energy conversion; they do not require any mechanical part, they form simple configuration and in turn increases the reliability. The literature survey has been carried out on direct-drive linear generators for wave energy conversion, it is analyzed that air-cored linear permanent magnet generator (Li-PMG) is suitable choice as compared to others. The selected linear generator is based on distributed winding configuration which enhances the electromagnetic characteristics and improves the overall efficiency as compared to existing linear generator with concentrated winding configuration. In order to determine electromagnetic characteristics and predict efficiency of selected linear generator Finite Element Analysis (FEA) has been carried out by ANSYS Ansoft Maxwell software. The FEA results for selected and existing linear generator are presented which shows that selected linear generator has higher electromagnetic characteristics and improved efficiency.

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

There are many different ways energy can be extracted from the ocean's waves: tides, currents and thermal and salinity gradients. The ocean wave, which is undeniably the most abundant form of energy on earth, has been the subject of research for many years. The first known patent for a wave energy converter (WEC) was registered in 1799, followed by hundreds more patents being registered in the ensuing 170 years [1]. Since the 1940s, the most significant work was done by the late Yoshio Masuda from Japan, who is considered the father of modern scientific wave energy research [2]. He developed navigation buoys which were powered by surrounding waves. He employed a method which would eventually become known as the oscillating water column (OWC). The buoys were commercialized in Japan and the USA.

To improve the efficiency and reliability of WEC, it is desirable to reduce the number of moving parts. This idea also manifests itself in the wind energy industry where the gearbox between the turbine and the generator is removed. This is then called a "direct drive" system, where the turbine directly drives the generator without any intermediate power conversion stage. In direct drive wave energy converters (DD-WECs), the heave motion (translation) of the waves is usually employed to directly drive a linear generator (LG). These devices are usually point absorbers and classified as oscillating bodies with translation motion. In concept, a floating buoy acting against a fixed reference is the most simple forms of a point absorber.

Overall, the simplicity of operation and absence of an intermediate power take off (PTO) is what makes DD-WECs very attractive, especially when the required maintenance works are much avoided. A higher efficiency is also expected and has in fact been demonstrated in DD-WECs with permanent magnet linear generators (PMLGs) at all loads [9]. In addition, DD-WECs do not contain any hydraulic fluid [10] which stimulates concern for the environment if leakage should occur. It is therefore easy to see why DD-WECs have received much research attention in recent years and why the work in this thesis is also focused in this area. However, as mentioned, none of these devices are commercially viable yet and this indicates that there exist areas for improvement in DD-WECs.

1.2 Problem Statement

Conventional electrical generators for wave energy conversion are mostly “rotating generators”, which employ mechanical interface such as; turbine, gearbox and hydraulic pump, which not only makes system complicated but increases maintenance and affects the overall efficiency of generator. Furthermore, the WEC required by these type of generator are also very massive and bulky like; pelamis, tapered channel (TAPCHAN) and so on, which are very difficult to design on small scale level.

1.3 Objectives and Scope of Study

This thesis presents the design and analysis of a direct-drive linear generator which produces 50 watts electric power. The main objectives are:

- To survey literature and propose an electrical generator for wave energy converter, which is simple and efficient.
- To determine electromagnetic characteristics of proposed generator using Finite Element Analysis (FEA).
- To perform efficiency analysis of proposed generator by FEA software Maxwell V.16.0.

CHAPTER 2

LITERATURE REVIEW

With the continuing exertion to identify ways of energy generation, ocean wave energy has attained a foremost attention. The exploitation on renewable energy sources gained worlds' wide attention in the context of sustainable development. Despite significant research and development, we are hindered from fully exploit the free energy. Various types of WEC have been invented and improvised over the years, are now capable of capturing most of the vast energy contained in ocean wave.

2.1 Wave Energy Converter (WEC)

The rotation of the earth around the solar system and moon's gravity fields are responsible for generating waves to some extent [3]. However, the most appropriate wave for energy conversion is the product of wind blowing over the ocean surface, which in turn are created by the heat differential on earth [3], [4]. Waves are therefore another form of physical energy transformed from solar energy emitted by the sun. Wave energy is particularly attractive because it is much more spatially concentrated than both solar and wind energy [5], [6], [3] and, although variable, it is also more persistent [6] and predictable [5], [4] than both solar energy and wind energy.

Taking into account the fact that the world's oceans covered roughly 75 % of the earth's surface [7], wave energy is abundant and a very promising renewable energy source. It has been predicted that around 2000 TWh of energy could be extracted annually from the ocean as technology develops [12]. Like any other forms of renewable energy, wave energy potential is different at different areas over the world.

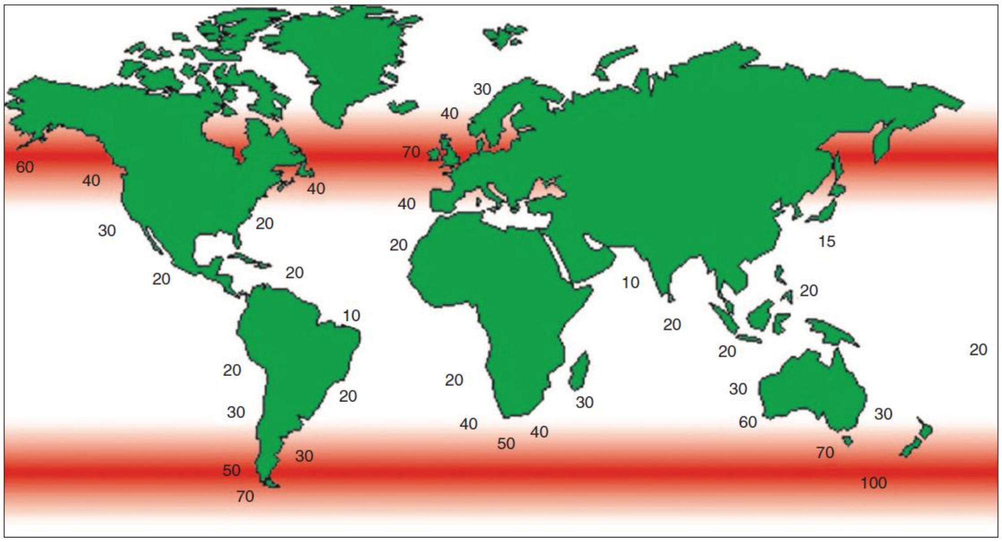

FIGURE 1. Global wave power distribution in kilowatt/meter of crest length

2.2 Classification of WECs

4 classifications have been categorized for effortless identification among hundreds of registered WECs. They have been catalogued based on the operation principle, operating location, PTO and directional characteristics. Each classification is further elaborated as below:

2.2.1 Classification Based on Operation Principle

A. Oscillating Water Column (OWC)

This WEC would require an artificial chamber with an underwater opening to the sea and another orifice serve as the air vent. The pressure inside the collector is alternately pressurized as the oscillating waves change the seawater level inside the chamber. As the water column rises, the air is compressed then decompresses as the water column falls. Energy is extracted from the rotating turbine fixed at an orifice above the water column which is energized by the bidirectional airflow created during the rise and fall of water surface in the confined collector [5].

B. Overtopping Device

A reservoir is installed above sea level on this device to capture as much energy potential as possible behind this conversion system, which is seawater. To generate electricity, the confined fluid will be released back to the ocean through turbine generators. A common technique practiced to amplify the amount of energy captured by the device is the use of collectors to converge incident waves and amplify the wave amplitude [13].

C. Wave-Activated Bodies (WABs)

This type of device can be operated above water surface or submerged. It composed of several units that are flexible in motion and oscillate about a fixed point. The waves provide the excitation in the system the moment it is placed in the water. The relative motions of the bodies mentioned can be expressed as roll, heave, and pitch [14].

2.2.2 Classification Based on Location

A. Shoreline converters

As the name suggested, this WECs are located at near shore land, incorporated in wave barrier like structures so that it can be placed at the bottom of the sea of shallow region, which gives the advantages of easier maintenance and installation. Moreover, their easy features avoided mooring and underwater cable to transfer the generated power to the grid. Nonetheless, the approaching wave losses its’ energy as it ripple towards the shore. On the other hand, there is a concern on the effect on implementation of the system to the surrounding environmental from land to sea because the sea shore would be reshaped while lack of proper land already cause difficulties for the development of this technology [5].

B. Near-shore converters

The near-shore converters are installed to the bottom of sea and located far away from the shore. It could be in the range of hundreds of meters up to a few kilometres away. The sole reason in doing so is to allow the system to harvest most of the energy that the waves posses. However, the designed structure must be able to withstand potential high stress when the waves overtopped it [5].

C. Offshore converters

Offshore converters could be operated in floating manner or immersed in deep sea region. It has the advantage to capture the high potential energy of the vast seas before the wave diverged. Nevertheless, survivability remains as the main concern for these devices especially on the matter of long term operational functionality. The structure of this converter has to be highly reliable to avoid unnecessary maintenance costs and designed to withstand exceptionally high stress from the direct impact with strong waves [4].

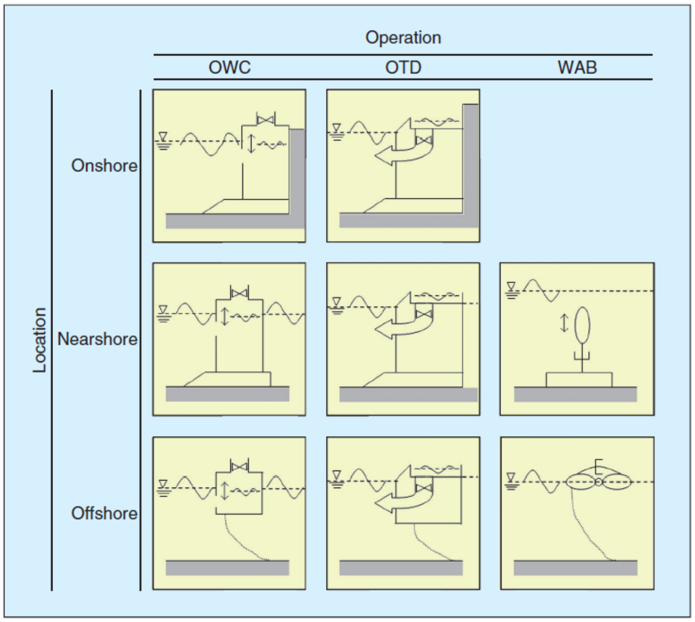

FIGURE 2. WEC classification based on operation principle and location.

2.2.3 Classification based on Power Take Off (PTO) System

Linear generators, turbines and hydraulic systems are the 3 most commonly applied types of PTO systems in WEC. The variation proposed different ways of electricity generation which match the suitability to its' intended features.

2.2.4 Classification Based on Directional Characteristics

A. Point Absorber

This device absorbs energy transferred from the buoy ripple near to water surface. The device could be make operating while floating on water surface or mounted to the sea floor. This method is exceptional as it employed the oscillating waves to provide the translational motion that is later converted by systems to drive the generators [12].

B. Terminator

Terminator WEC devices are installed perpendicularly to the motion of waves. The structures intercept and direct the water into a storage reservoir to create a moving fluid to be passed through turbines. The device extends perpendicularly against the wave direction, which holds back the incoming waves. Considering resonance factor when building the structure could boost the energy capture [5].

C. Attenuator

Attenuator device is well resembles by Pelamis WEC. The device is a long float aligned to be parallel to wave propagation. It has connected hinged joints installed. Movements along the long length body are limited to create energy. Compared to terminator, this device experience lower forces as it possess lower area perpendicular to the waves [10].

2.3 Direct-drive Linear Generator (DD-LG)

The most common type of electrical generator is the rotary generator. Rotor inside of the generator rotates with the prime mover. Electromotive force (EMF) is induced in the stator's coils through the rotating excitation magnetic field on the rotor. The magnetic field on the rotor could be excited electromagnetically or permanent magnets (PMs). If a rotary generator is unrolled, a flat topology can be obtained which is known as linear generator (LG), where the rotor is renamed as translator for its linear reciprocation shown in Figure 3.

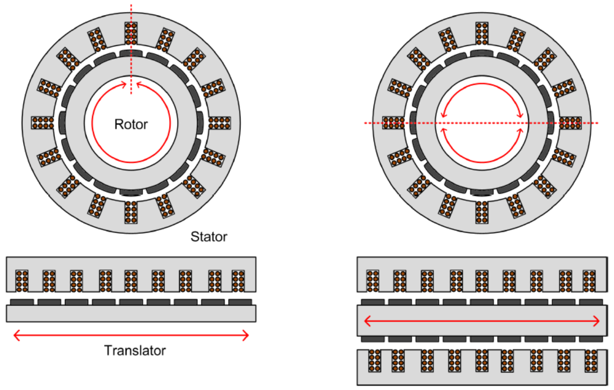

FIGURE 3. Structure difference between rotary generator (upper diagrams) and linear generator (lower diagrams)

There are a few types of linear generators namely variable reluctance permanent magnet (VRPM), transverse flux permanent magnet (TFPM), vernier hybrid permanent magnet (VHPM) and longitudinal flux permanent magnet (LFPM). Each of them possessed individual controller design, maintenance requirements, reliability and efficiency. They are generally classified based on their power triggering method. To fully utilize the same surface area of power generating components, either the stator or translator in the LG would be required to be longer than the other [8].

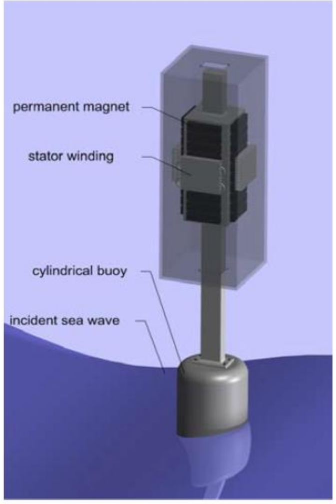

FIGURE 4. Configuration of electromechanical arrangement for power generation from sea waves [22]

As we are observing the generated power initiated through the stator coil to determine the efficiency of the device, there are a few parameters which should be study before hand. First, is the induced coil voltage (V) as a reaction to the linear motion of PMs on the translator. According to Faraday's law, the induced EMF is directly proportional to the number of turns on coil (N) and the rate of change of magnetic flux passing through the stator core. Assuming that PMs distributed evenly on the translator is of same type of material, the average flux density (B) would be fixed at all time and the rate of change of coil area subjected to magnetic field can be measured through translational velocity (V) multiply travelled distance (l) [8].

$$V = NBlV \qquad (1)$$

The generator is designed with the intention to produce steady constant current, thus property such as current density (J) and conductor area (A) are all fixed when installed. Therefore, power generated through the coil (P) is scaled linearly with respect to speed of translator [8].

$$P = V[NBlJA\cos(\Theta)] \qquad (2)$$

Based on the experiment conducted by researchers from Oregon State University, Corvallis, Oregon [8] intended to propose the most suitable LG for transforming wave motion into electricity, the vernier hybrid machine (VHM) is selected to be most promising, followed by linear synchronous motor (LSM). The inducing magnetic field could be stimulated with the implementation of PMs or direct current field windings excited via external power source. VHM utilize PMs while another configuration is better known as Linear Synchronous Homo-polar Machine (LSHM). However, both VHM and LSM faced cogging issue due to attractive forces between stator and translator. Air gap machine does not face this problem. Furthermore, high force density machines such as VHPM and Transverse Flux PM (TFPM) machine is difficult to construct and has low power factor [17].

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2.4 Finite Element Analysis (FEA)

Numerical methods such as Finite Element Method (FEM), Boundary Element Method (BEM), Finite Volume Method (FVM), and Finite Difference Method (FDM) have been developed into computer software to solve for engineering problems in a fast and effective manner [16].

In order to optimize the electric machines performance, its electromagnetic field has to be modeled. FEM is the most common technique employed to perform this task [20,21,22] because if its' ability to solve wide range of engineering problems [19]. The designs are further tested under different scenarios or configurations which allow more precise calculation on the responding machine parameters.

CHAPTER 3

METHODOLOGY

3.1 Linear Permanent Magnet Generator (Li-PMG)

In literature several linear generators exists such as Vernier hybrid, longitudinal flux iron-cored and so on. The major drawback in these types of machines is large magnetic attraction force and cogging force which is not available in air-cored machines. Therefore, the linear permanent magnet generator with air-cored configuration is selected. The selected linear generator 2D model and 3D interior view is shown in Figure 5.

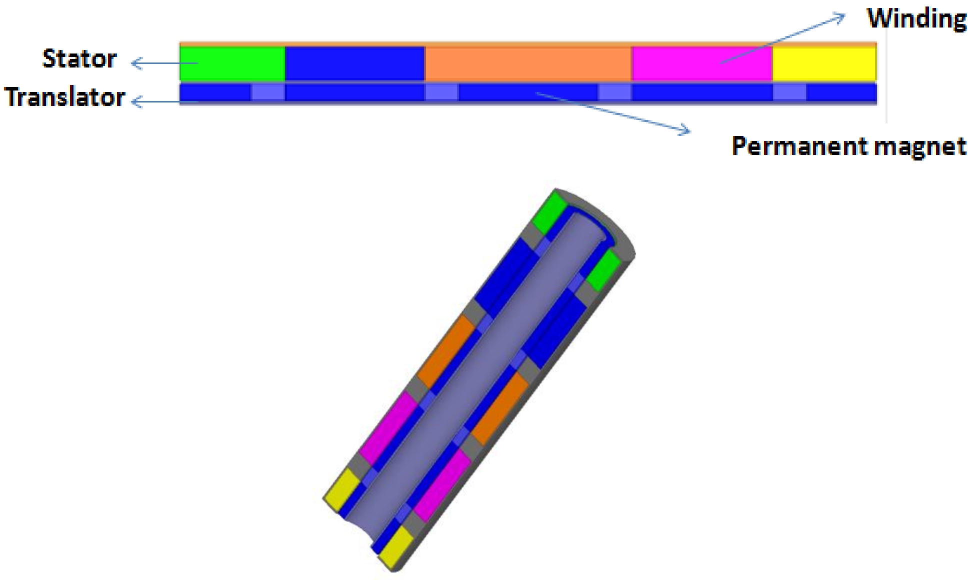

FIGURE 5. Design of linear generator

The translator carries radially magnetized permanent magnets with spacers placed between them in order to provide smooth flux path. The stator employees distributed winding configuration which decreases copper losses.

3.2 Finite Element Analysis (FEA)

To determine electromagnetic properties and analyze efficiency finite element analysis (FEA) has been carried out. The time-stepping finite element method is used**.** The transient mode and axisymmetrical coordinate system is used. The main design parameters are given in Table 1.

Parameter	***Value***
Output Power, P_{out}	50 Watts
Velocity, V	1.5 m/sec
Pole width	50 mm
Number of turns per coil, N	1200
Length of spacer, L_s	10 mm
Width of spacer, W_s	4.8 mm
Length of magnet, Lm	40 mm
Width of magnet, Wm	4.8 mm
Width of yoke, Wy	1 mm
Length of yoke, Ly	200 mm
Width of supporting yoke, Wsy	11 mm
Stop time	25 ms
Time step	0.02 sec
Step size	0.001 sec

TABLE 1. Design parameters

3.3 Efficiency Analysis

Later in the design optimization process, the goal is to reconstruct the electrical machine to ensure better performance in terms of efficiency. The efficiency of a linear generator can be calculated [15] as follows;

$$Efficiency = \frac{Pout}{Pin} = \frac{Pout}{Pout + Plosses}$$

$$P_{losses} = P_{cu}\ (copper\ loss)\ + P_{iron}\ (core\ loss)$$

To gauge the performance efficiency of the linear PM generator, losses in the machine has to be taken into account during computation. The two losses are copper loss and core loss [15]. The copper loss has to do with the power loss as heat energy in the resistance of winding and the squared root mean square (rms) current. The relationship is given as follow [15]:

$$P_{cu} = I^2 R$$

Where I is rms current (A) while R is winding resistance (Ω). It is obvious that the winding will get heated as the amount of injected current increases. The conductor's resistivity is derived from:

$$R = \rho \frac{L}{A}$$

Where R, ρ, L, A are: resistance of coil, resistivity of copper, length of wire and area of coil. The length of coil is associated with the radius of stator. As the size of stator increases, the induce EMF rises. At the same time, there will be more copper loss [21].

The core lossesof linear PM generator are made up ofhysteresis loss (P_h), eddy current loss (P_c), and excessive loss (P_e). It can be expressed as [20]:

$$P_{fe} = P_h + P_c + P_e$$

Where;

P_{fe} is core loss in watts; P_{hi} is hysteresis loss; P_{ci} is classical eddy current loss and P_{ei} is excessive loss.

To reduce hysteresis loss, high grade magnetic material with low hysteresis area is chosen for the core. To minimize eddy current losses, laminated construction is employed. The core of the stator and translator is made up M-36 electrical steel material, which gives the lowest core loss [6]. The B-H curve of M-36 steel is shown in Fig. 6. Both losses copper loss and core loss are determined by injected winding current. In core loss, the BH curve and BP loss curve are required to be imported into software database in order to calculate it.

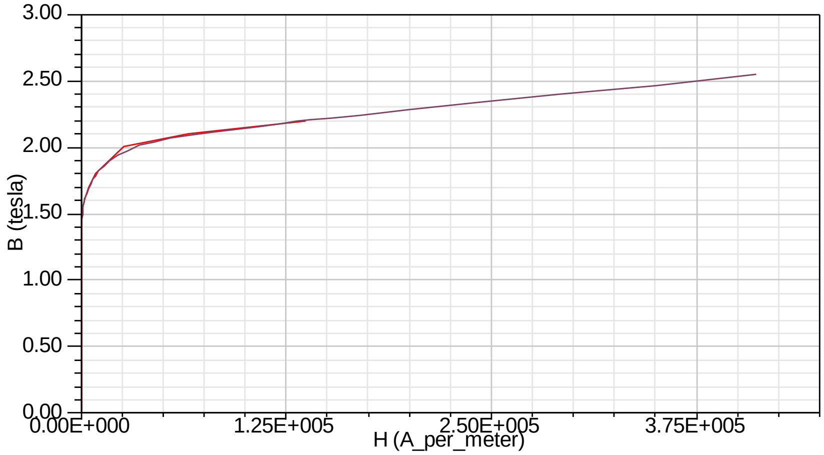

FIGURE 6. B-H curve of M-36 Steel

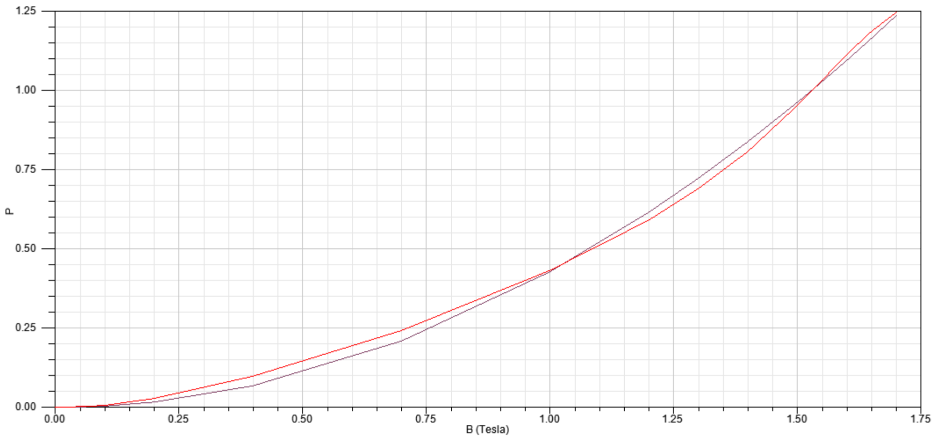

FIGURE 7. B-P loss curve

The detailed description is illustrated in flow chart as shown in Figure 8.

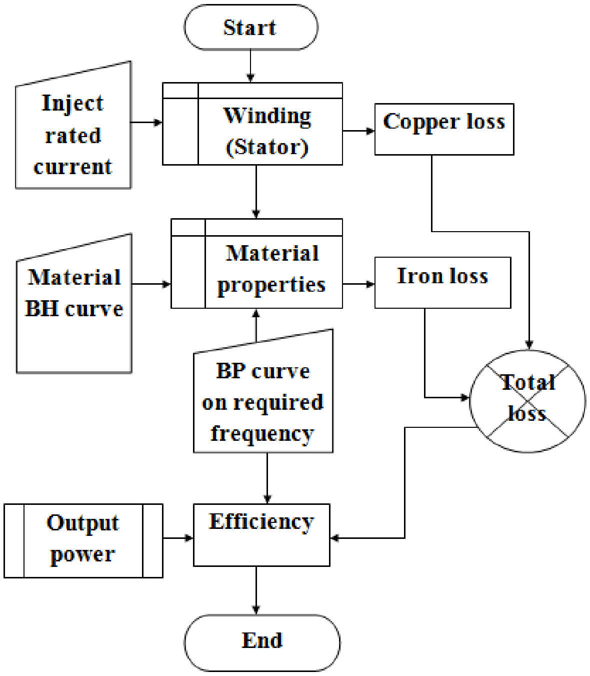

FIGURE 8. Flow chart of detail description

3.4 Gantt Chart

Workflow / tasks	Week																										
	Semester 1														Semester 2													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
Selection of project topic	🟦	🟦																										
Preliminary research work		🟦	🟦	🟦	🟦	🟦																						
Submission of extended proposal						🟨																						
Review of concept							🟦	🟦	🟦																			
Proposal defense								🟦	🟦																			
Project work continues										🟦	🟦	🟦																
Submission of interim draft report													🟨															
Submission of interim report														🟨														
Refine Methodology															🟦	🟦	🟦											
Simulation & Results																		🟦	🟦	🟦	🟦							
Submission of progress report																						🟨						
Preparation of technical paper																							🟦	🟦	🟦	🟦		
ELECTREX																									🟨			
Draft Final Report																											🟨	
Final refinery work																											🟦	🟦
Final Report & Technical Paper																												🟨

3.5 Scheduled Activities

Time allocated	Task
Week 1 - 6	Literature survey
Week 7 - 9	Selection of suitable electrical generator for wave energy converter
Week 10 - 12	Detailed study of linear generator for offshore wave energy converter
Week 13 - 17	Finite element analysis (FEA) study and model development
Week 18 - 20	Electromagnetic characteristic prediction; induced-EMF, flux-linkage, open-circuit magnetic flux distribution, and magnetic flux density
Week 21 - 22	Total losses (copper loss & iron loss) determination
Week 23 - 24	Efficiency analysis
Week 25 - 28	Thesis writing

3.6 Project Key Milestones

Literature review

- Detailed study of linear generator for offshore wave energy converter.
- Refine manipulating variables on generator's electrical energy output which is feasible for simulation

Identify Parameter of interest

- Associate the parameters of interest consist of induce voltage and power losses with manipulating variables such as type of stator winding (concentrated & distributed) and type of generator’s core (air & iron).

Design & simulate

- Proceed with designing air cored linear generator with two different coil windings as iron cored generator introduce unwanted cogging force to device.
- Both device share similar design parameters and oscillate at same speed 1.5m/s.

Refine & Evaluate the results

- Refine the analysis by increasing the number of element in mesh plot.
- The efficiency of both devices are evaluated. The computation of induced voltage and power losses in devices are generated through the evaluation of FEA software.

CHAPTER 4

RESULTS AND DISCUSSION

The methodology of linear generator was described in chapter 3, this chapter presents the obtained results by finite element analysis. In order to analyze selected linear generator, the existing generator [23] is compared and also analyzed as shown in Figure 9. This linear generator has concentrated winding in stator. The finite element analysis shows that the selected linear generator offers higher efficiency as shown in Figure 9.

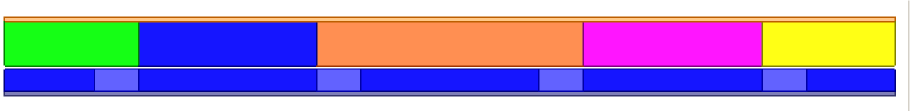

FIGURE 9: Existing generator with concentrated winding

The induced emf can be written as

$$E = \frac{2\,\pi}{\sqrt{2}} f\, N_{ph} \varphi_m$$

Where f is the electrical frequency, N_{ph} is the number of coil turns in series per phase and φ_m is the flux per pole linked by the phase winding.

4.1 Finite Element Simulation and Results:

The finite element analysis is determined of selected linear generator. Initially, the original mesh is analyzed which is very wide and scattered throughout the machine parts. Afterwards, open circuit magnetic flux is determined which also shows that flux lines are not smooth and then flux density is determined which also shows same characteristics as shown in Figure 10.

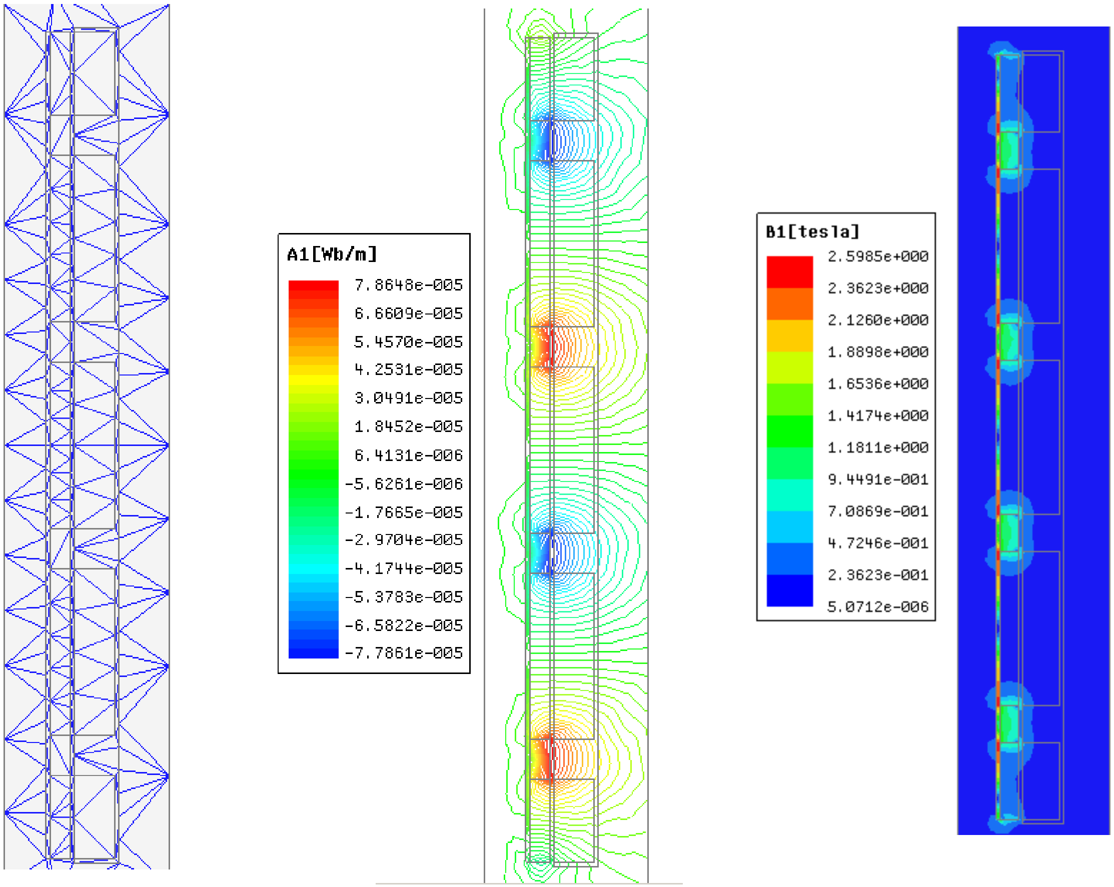

FIGURE 10: Initial mesh, flux line and flux density

Figure 11 shows the refined version which is more narrower in mesh and flux line are smooth.

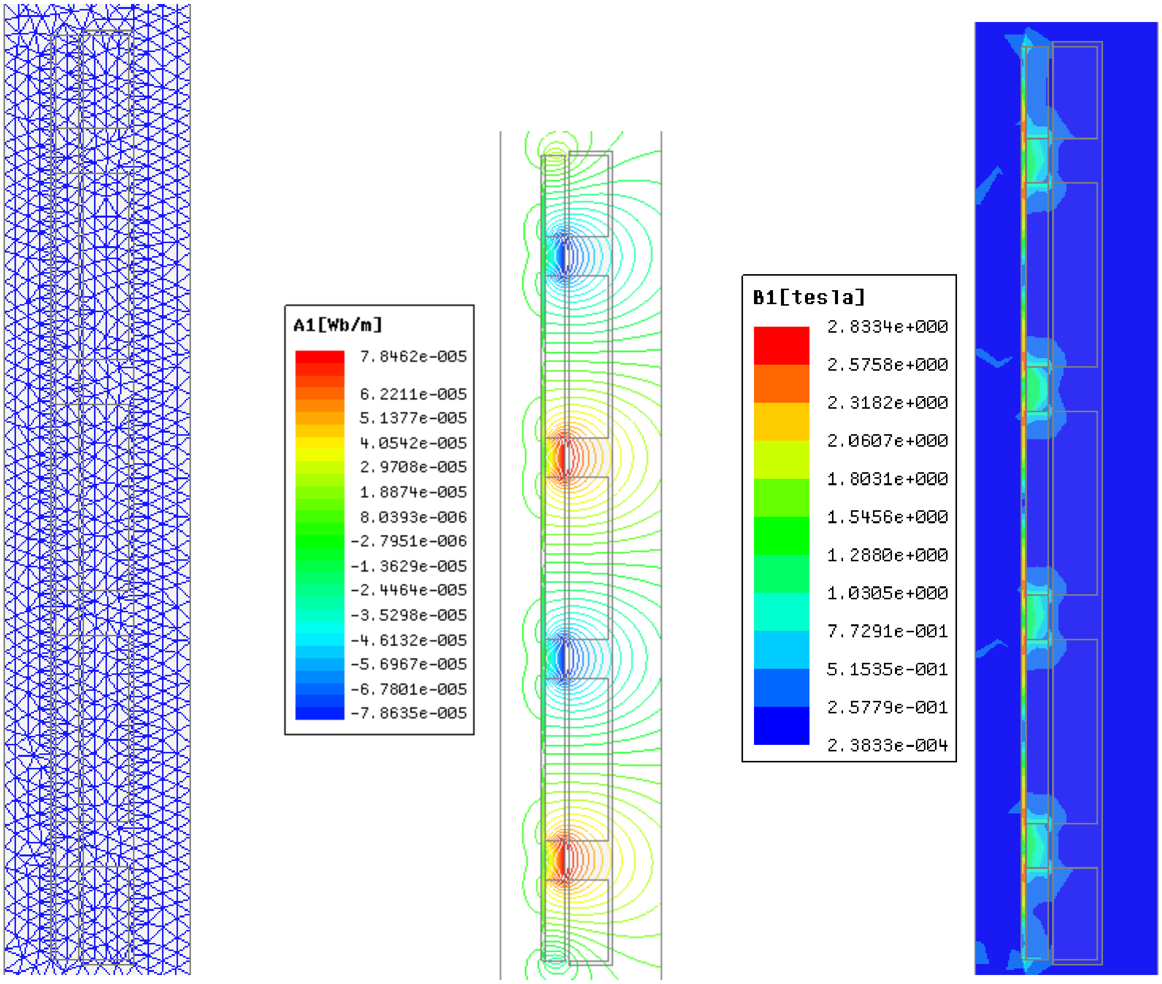

FIGURE 11: Refined mesh, flux line and flux density

Dynamic Performance:

The dynamic performance is also called time-varying performance. It is determined on the velocity on which translator is reciprocating. The induced emf and flux linkage generated in winding is shown below.

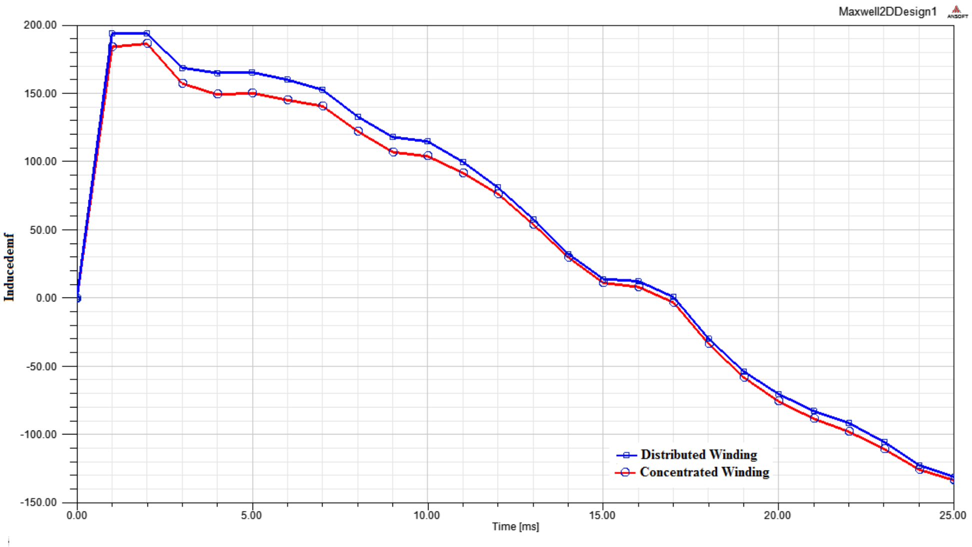

FIGURE 12: induced emf in winding

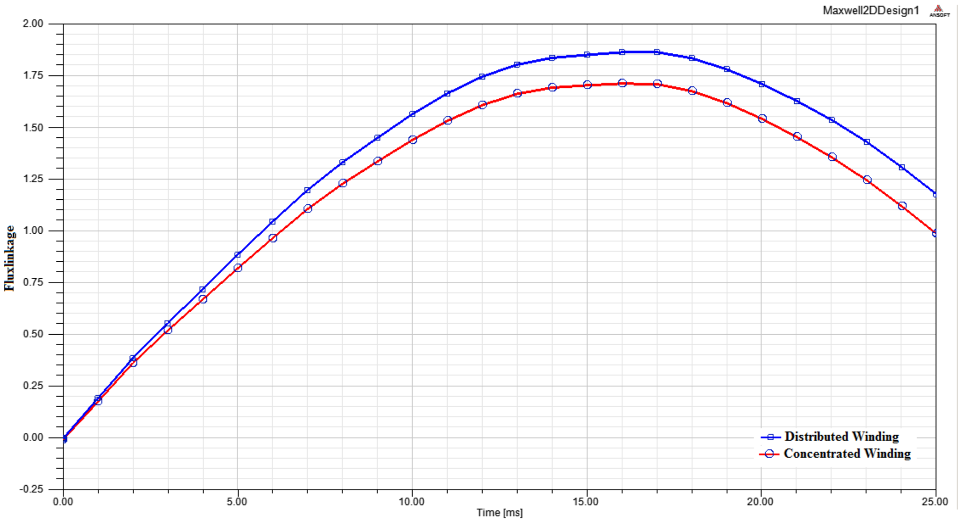

FIGURE 13: flux linkage in winding

Efficiency Analysis:

The efficiency is analyzed based on the method described in chapter 3. The obtained results are presented in below Table 2 which shows that selected linear generator has higher performance as compared to conventional linear generator.

Electromagnetic quantity	Concentrated Winding	Distributed Winding
Induced-EMF	109.3170 Volts	**115.1361 Volts**
Flux-linkage	1.3170 Wb	**1.4464 Wb**
Copper loss (watts)	8.8632 Rated current (0.45 A)	**7.575** **Rated current (0.4 A)**
Iron-loss (mW)	75.3643 mW Rated current (0.45 A)	**75.5754 mW** **Rated current (0.4 A)**
Efficiency (%)	84.94	**86.84**

TABLE 2. Overall results

CHAPTER 5

CONCLUSION AND RECOMMENDATION

This thesis has presented a direct drive linear generator which is a best choice in several aspects such as; simplified system, lowest maintenance and unavailability of mechanical interconnected parts. The linear generator with permanent magnet configuration is chosen because it eliminates the requirement of additional supply for field winding. The selected linear generator is equipped with distributed winding configuration which has several advantages as compared to conventional generators with concentrated winding configuration such as; higher electromagnetic characteristics and improved efficiency. The finite element analysis has been done to predict electromagnetic performance and to evaluate efficiency of selected linear generator. The induced-emf, flux linkage, flux density, mesh plot, flux plot and flux density plot are presented. The efficiency calculation based on core loss and iron loss evaluation has been presented. The selected linear generator is compared with conventional linear generator which shows that selected linear generator has higher performance as compared to conventional linear generator. As a future work, the linear generator can be analyzed further in terms of optimization to obtain accurate performance.

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