Wave Energy Prospects in Bangladesh

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DECLARATION OF CANDIDATES

It is hereby declared that this thesis or any part of it has not been submitted elsewhere for the award of any degree or diploma.

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DEDICATION

We would like to dedicate the thesis book to our respective family and the late son of Dr. Md. Hamidur Rahman sir.

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ABSTRACT

This thesis book intends to present the wave energy prospects of Bangladesh by displaying a **Wave Energy Converter (WEC)** prototype. The prototype is a variant of Point Absorber where the generator is a **Permanent Magnet Linear Generator (PMLG)**. The generator is operated in a wave generation facility to investigate the outcomes. The generator parameters are thus frequently optimized using the facility. The generator outputs were recorded throughout to obtain a linear generator characteristic. This characteristic and design aspects are examined to propose a possible outcome and feasibility in the real scenario.

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CHAPTER 1

1.1 Introduction

1.1.1 Energy

Energy is the capacity of doing work. It can exist in different types of potential, kinetic, thermal, electrical, chemical, atomic, or other. In addition, there is heat and function— that is, power in moving from one body to another. Energy is always marked by its definition after it has been transferred. Therefore, heat transmitted can be converted into thermal energy, while work done can manifest itself as mechanical energy.

Motion is correlated with all forms of energy. For example, if any body is in motion, it has kinetic energy. Although at rest, a tensioned system such as a bow or spring has the potential to create motion; due to its structure, it contains potential energy. Likewise, nuclear power is potential fuel because it comes from the subatomic particle structure in an atom's nucleus.

Energy can not be created or destroyed, but it can only be converted from one form to another. This rule is known as energy conservation or thermodynamics ' first law. For example, when a box falls down a hill, the box's potential energy from being high up on the slope is converted into kinetic energy, energy of motion. As the box slows by friction to a halt, the kinetic energy from the movement of the box is converted into thermal energy heating the box and the slope.

Energy can be converted in different ways from one form to another. For example, accessible mechanical or electrical energy is produced by many types of devices, including heat engines, generators, batteries, fuel cells, and magnetohydrodynamic systems.

Energy is expressed in joules in the International Unit System (SI). One joule is equal to the work performed over a one-meter distance by a one-newton force.[1]

1.1.2 Energy Sources

Energy sources can be labeled as renewable and non-renewable As people use energy in their homes, electricity is usually produced from burning coal or natural gas, a nuclear reaction, or a river-side hydroelectric plant, to name only a few. The energy source is petroleum (gasoline) refined from crude oil and may include fuel ethanol provided by growing and processing corn. Coal, natural gas, nuclear, hydropower, coal, and ethanol are referred to as sources of energy.

Energy sources are divided into two groups:

- Renewable (an energy source that can be easily replenished)

- Nonrenewable (an energy source that cannot be easily replenished)

Renewable and nonrenewable energy sources can be used as primary energy sources to produce useful energy such as heat or used to produce secondary energy sources such as electricity.

1.1.3 Renewable energy

There are five main renewable energy sources:

- Solar energy from the sun
- Geothermal energy from heat inside the earth
- Wind energy
- Biomass from plants
- Wave Energy from flowing water

1.2.3 Nonrenewable energy

Most of the energy consumed in the United States is from nonrenewable energy sources:

- Petroleum products
- Hydrocarbon gas liquids
- Natural gas
- Coal
- Nuclear energy

Crude oil, natural gas, and coal are considered fossil fuels because they have been formed over millions of years by energy from the core of the earth and rock and soil stress on the remains (or fossils) of dead plants and creatures like microscopic diatoms. Most of the petroleum products purchased in the United States are made from crude oil, but it is also possible to make petroleum fuels from natural gas and coal.

Nuclear energy is produced from uranium, a non-renewable energy source whose atoms are split (through a nuclear fission process) to generate heat and, eventually, electricity.

The chart below shows the energy sources used in the United States. In 2018, nonrenewable energy sources accounted for about 90% of U.S. energy consumption. Biomass, which includes wood, biofuels, and biomass waste, is the largest renewable energy source, and it accounted for about 45% of all renewable energy consumption and nearly 5% of total U.S. energy consumption.[2]

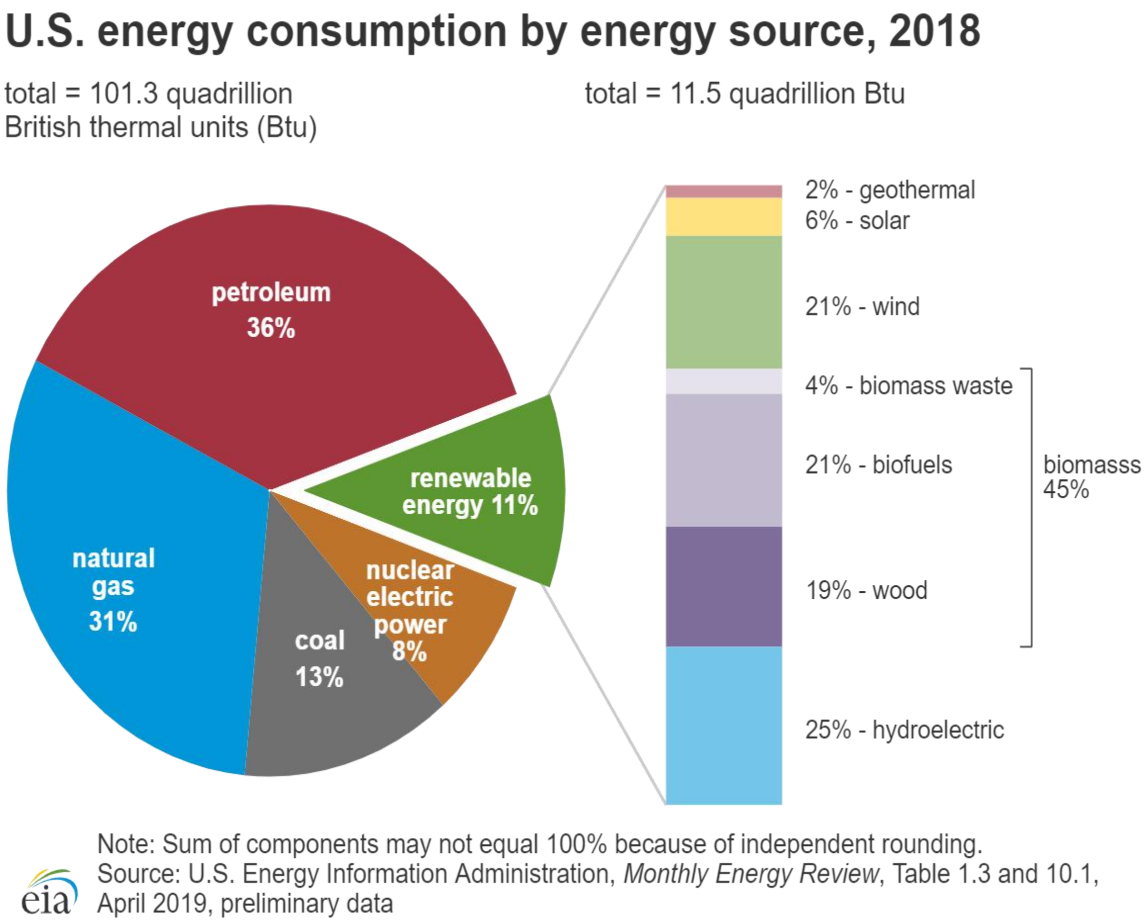


Figure 1: U.S. energy consumption, 2018.

1.1.4 Renewable Energy

Renewable energy is energy produced from sources that are not depleting or replenishable within the lifetime of a human being. Wind, solar, geothermal, biomass and hydropower are the most common examples. It compares with non-renewable sources like fossil fuels.

The bulk of renewable energy is directly or indirectly derived from the wind. Using solar technology, sunlight can be collected directly. The heat of the sun powers winds that are produced by turbines. Plants often rely on the sun to grow and it is possible to use their stored energy for bio-energy. Not all sources of renewable energy depend on sunlight. Geothermal energy, for example, uses the internal heat of the Sun, tidal energy relies on the moon's gravitational pull, and hydropower relies on water flow.

Renewable energy accounts for 13.5% of the world's total energy supply, and 22% of the world's electricity. [3]

Renewable energy systems are a major topic when discussing the globe's energy future for two main reasons:

1. Renewable energy systems provide energy from sources that will never deplete.

2. Renewable energy systems produce less greenhouse gas emissions than fossil fuel energy systems. [4]

Although renewable energy systems are better for the environment and generate fewer carbon than traditional sources of energy, many of these sources still face difficulties in large-scale implementation, including, but not limited to, technical obstacles, high start-up capital costs, and intermittent challenges. [5]

It is important to note that in all situations the words ' renewable energy," green energy' and' clean energy' are not interchangeable; for example, a' clean' coal plant is simply a coal plant with technology for reducing emissions. The coal plant itself is not yet a source of' renewable energy.' Green energy' is a form of renewable energy with low or zero emissions and low environmental impacts on structures like land and water.[6]

1.1.5 Types of Renewable Energy

➢ Solar

Solar energy is derived by capturing radiant energy from sunlight and converting it into heat, electricity, or hot water. Photovoltaic (PV) systems can convert direct sunlight into electricity through the use of solar cells.

The practical endlessness of sunshine is one of the advantages of solar energy. There is an unlimited supply of solar energy with the equipment to exploit it, which means it could make fossil fuels obsolete. They are also helping to improve public health and environmental standards by focusing on solar energy rather than fossil fuels. Solar energy can also lower energy costs in the long term and reduce the energy bills in the short term. Several national, state and federal governments often promote solar energy investment by offering rebates or tax credits.

Although solar energy will save you money in the long run, it tends to be a significant upfront cost and is an unrealistic expenses for most households.

Figure 2: Solar Energy[6]

For personal homes, homeowners also need to have the ample sunlight and space to arrange their solar panels, which limits who can realistically adopt this technology at the individual level.

➢ Wind

By using turbines, wind farms harness the power of wind stream and turn it into electricity. Various forms of systems are used to harness wind energy, and each differs. Commercial wind powered generation systems are capable of powering several different organizations, while single-wind turbines are used to helpsupport pre-existing energy organizations. One type is wind farms on a utility scale, which are purchased by contract or wholesale. Wind energy is theoretically a type of solar energy. The phenomenon we call "wind" is caused by the temperature differences in the atmosphere combined with the Earth's rotation and the planet's geography.[7]

Wind energy is a clean energy source, which means that it doesn’t pollute the air like other forms of energy.

Figure 3: Wind Energy[8]

Wind energy doesn't produce carbon dioxide, or release any harmful products that can cause environmental degradation or negatively affect human health like smog, acid rain, or other heat-trapping gases.[8] Investment in wind energy technology can also open up new avenues for jobs and job training, as the turbines on farms need to be serviced and maintained to keep running.

➢ Biomass Energy

Biomass is the most important source for energy productions supplied by agriculture. Effective harnessing of bio-energy can energize entire rural milieu in a country like Bangladesh where nature offers various types of biomass. This energy is also available in the form of biodegradable waste, which is the rejected component of available biomass [9]. Biomass energy refers to fuels made from plants and animal wastes. The Biomass resource is, organic matter in which the energy of sunlight is stored in chemical bonds. When the bonds between carbon, hydrogen and oxygen molecules are broken by digestion, combustion (or) decomposition these substances release stored energy. Biomass energy is generated when organic matter is converted to Energy. In alcohol fermentation, the starch in organic matter is converted to sugar by heating. This sugar is then fermented and finally ethanol is distiller and then blended with another fuel. An aerobic digestion converts biomass, especially waste product such as municipal solid waste and market waste.

➢ Wave Energy

The ocean can produce two types of energy: thermal and mechanical. Ocean thermal energy relies on warm water surface temperatures to generate energy through a variety of different systems. Ocean mechanical energy uses the ebbs and flows of the tides to generate energy, which is created by the earth's rotation and gravity from the moon.

Figure 4: Wave Energy[10]

Unlike other forms of renewable energy, wave energy is predictable and it's easy to estimate the amount of energy that will be produced. Instead of relying on varying factors, such as sun and wind, wave energy is much more consistent. This type of renewable energy is also abundant, the most populated cities tend to be near oceans and harbors, making it easier to harness this energy for the local population. The potential of wave energy is an astounding as yet untapped energy resource with an estimated ability to produce 2640 TWh/yr.[10]

➢ Geothermal Energy

Geothermal heat is heat trapped under the Earth's crust from Earth's formation 4.5 billion years ago and from radioactive decline. Large amounts of this heat often escape naturally, often all at once, resulting in common phenomena including volcanic eruptions and geysers. The energy can be produced by using steam that comes from the heated water flowing below the surface, which then rises to the top and can be used to drive a turbine.

Geothermal energy is not as common as other types of renewable energy sources, but it has a significant potential for energy supply. Since it can be built underground, it leaves very little footprint on land. Geothermal energy is naturally replenished and therefore does not run a risk of depleting (on a human timescale).

Cost plays a major factor when it comes to disadvantages of geothermal energy. Not only is it costly to build the infrastructure, but another major concern is its vulnerability to earthquakes in certain regions of the world.

Figure 5: Geothermal Energy[11]

1.2 Wave Energy

In this article, the wave relates to wind producing ocean waves. As such, solar energy is primarily concentrated. The sun shines on the earth and heats up the air, resulting in variations of energy being the engines pushing the winds. It moves power from the sun to and concentrates in the wind. Waves are produced when the wind blows over a stretch of water.

Some of the energy in the air is transferred in the waves, and once again focus the energy that originally came from the sun. It starts with small pressure difference on the ocean surface, due to turbulence in the wind,

That create small irregularities or small waves on the ocean surface, Resonance between the vertical wind pressure and these small waves, together with sheer stress due to higher wind speeds at the crests compared to the troughs then acts upon the waves and makes them grow. When they are big enough process take over, the friction of the wind on the water and the pressure difference created by the sheltering effect of the lee side of the wave compared to the wind side of the wave to continue to grow. Energy is continually transferred from the winds to the waves throughout all of these processes. The size that they ultimately reach depends on three things; the wind speed, the length of time during which the wind blows, and the distance of water over which the wind is blowing, the fetch.[11]

Wave energy is a renewable energy by storing the energy that waves naturally produce. Waves also get their energy from the wind which moves over the surface of the sea and can transmit their energy with little loss over long distances; wave energy is considered an important tool for renewable energy.

There is tremendous energy potential in the intermittent and oscillating stream of wave energy in oceans–kinetic energy as it is called –and if harnessed could provide a significant addition to a clean energy network. The wave energy is measured and estimated by the height of the wave, the frequency, the size, and the water density. Although most wave technologies are designed to be mounted close to the surface of the ocean, they can be used in nearshore, inland or offshore locations depending on the location.

In deep water where the water depth is larger than half the wavelength, the wave energy flux is[a]

$$P = \frac{\rho g^2}{64\pi} H_{m0}^2 T_e \approx \left(0.5 \frac{\mathrm{kW}}{\mathrm{m}^3 \cdot \mathrm{s}}\right) H_{m0}^2\ T_e,$$

With P the wave energy flux per unit of wave-crest length, Hm_0 the significant wave height, T_e the wave energy period, ρ the water density and g the acceleration by gravity. The above formula states that wave power is proportional to the wave energy period and to the square of the wave height. When the significant wave height is given in metres, and the wave period in seconds, the result is the wave power in kilowatts (kW) per metre of wavefront length.

Example: Consider moderate ocean swells, in deep water, a few km off a coastline, with a wave height of 3 m and a wave energy period of 8 s. Using the formula to solve for power, we get[a]

$$P \approx 0.5 \frac{\mathrm{kW}}{\mathrm{m}^3 \cdot \mathrm{s}} (3 \cdot \mathrm{m})^2 (8 \cdot \mathrm{s}) \approx 36 \frac{\mathrm{kW}}{\mathrm{m}},$$

Meaning there are 36 kilowatts of power potential per meter of wave crest.

In major storms, the largest waves offshore are about 15 meters high and have a period of about 15 seconds. According to the above formula, such waves carry about 1.7 MW of power across each metre of wavefront.

An effective wave power device captures as much as possible of the wave energy flux. As a result, the waves will be of lower height in the region behind the wave power device.

1.2.1 Why Wave Energy?

Using waves as a source of renewable energy offers significant advantages over other methods of energy generation including the following:

- Sea waves offer the highest energy density among renewable energy sources [12]. Waves are generated by winds, which in turn are generated by solar energy. Solar energy intensity of typically 0.1– 0.3kW/m2 horizontal surface is converted to an average power flow intensity of 2–3kW/m2 of a vertical plane perpendicular to the direction of wave propagation just below the water surface [4].
- 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.
- It is reported that wave power devices can generate power up to 90 per cent of the time, Compared to ~20–30 per cent for wind and solar power devices [5, 6].

1.3 Literature review

Ocean waves are a huge, largely untapped energy resource, and the potential for extracting energy from waves is considerable. Research in this area is driven by the need to meet renewable energy targets, but is relatively immature compared to other renewable energy technologies. This review introduces the general status of wave energy and evaluates the device types that represent current **wave energy converter (WEC)** technology, particularly focusing on work being undertaken within the countries with wave energy access. The possible power take-off systems are identified, followed by a consideration of some of the control strategies to enhance the efficiency of point absorber-type WECs. The possible solution chosen here is **Permanent Magnet Linear Generator (PMLG).** There is a lack of convergence on the best method of extracting energy from the waves and, although previous innovation has generally focused on the concept and design of the primary interface, questions arise concerning how best to optimize the powertrain. The **PMLG** characteristic is obtained using a prototype and a generation facility. Though the characteristic defines a lot about the generation outcome in ideal cases but has the constraint of having operational precision. The outcomes of the operation are finely examined and optimized to have a good clearance over the predicted values. The prototype here shows a conversion rate which is more than half of the developed and installed mechanisms. The conversion rate is mainly poor due to mechanical efficiency of the setup and configuration of the buoy. Multiple buoy installation along with highly efficient gear mechanism could have resulted in a great outcome. However this book tries to facilitate a good perspective and operational background for future developments in this area of research.

1.4 Thesis objectives

The main objective of the thesis can be concluded as to find out the Wave Energy aspects of Bangladesh. Nevertheless it could be quantized as:

- To create a positive impression about the huge Wave Energy resources of Bangladesh.
- To look through the suitable Wave Energy conversion method.
- To develop a theoretical feasibility analysis.
- To design and operate a prototype to predict the outcome.
- To examine the prototype outcome and propose a real life model.

1.5 Thesis organization

This thesis is intended to show an operational view of Wave Energy potential, it's importance and aspects in Bangladesh:

- In **chapter 2**, different types of Wave Energy Converters are described. The type includes Wave activated bodies, Oscillating Water columns, Overtopping devices and Point Absorber.
- In **chapter 3**, the basics, design and advantages of a **Linear Generator** is put on favor of the Point Absorber.
- In **chapter 4**, a prototype of Linear Generator is designed and described as **Permanent Magnet Linear Generator (PMLG).**
- In **chapter 5,** the outputs of the prototype is studied and made comparison with the real life scenario.
- In **chapter 6,** the conclusion is made on the thesis which ends with the future work plans.

CHAPTER 2

2.1 Types of Wave Energy Converters

Wave power devices are generally categorized by the method used to capture or harness the energy of the waves, by location and by the power take-off system. Locations are shoreline, nearshore and offshore. Types of power take-off include: hydraulic ram, elastomeric hose pump, pump-to-shore, hydroelectric turbine, air turbine,[12] and linear electrical generator. When evaluating wave energy as a technology type, it is important to distinguish between the four most common approaches: point absorber buoys, Wave Activated bodies, oscillating water columns, and overtopping devices.

2.1.1 Wave Activated Bodies

Wave activated bodies (WABs) are devices with moving elements that are directly activated by the cyclic oscillation of the waves. Power is extracted by converting the kinetic energy of these displacing parts into electric current. One example of such a WAB, is made by a single floater connected to a linear magnetic generator fixed to the seafloor. In other cases, only parts of the body are fully immersed and dragged by the orbital movements of the water. In order to maximally exploit this resource, the moving compounds need to be small in comparison to the wavelength and preferably they are placed half a wavelength apart. For these reasons, wave activated bodies are usually very compact and light. The main disadvantage of this type of wave energy converters is the high cost of the power generator needed to convert the irregular oscillatory flux into electricity.

The "DEXA", developed and patented by DEXA Wave Energy ApS [13], is an illustrative example of a WAB. The device consists of two hinged catamarans that pivot relative to the other (Fig. 1). The resulting oscillatory flux at the hinge, is harnessed by means of a water-based low pressure power transmission that restrains angular oscillations. Flux generation is optimized by placing the floaters of each catamaran half a wavelength apart. A scaled prototype (dimensions 44x16.2m[14]). placed in the Danish part of the North Sea should generate 160 kW (Martinelli et al., 2009[15]). Full-scale models are thought to be able to generate up to 250 kW. [13]

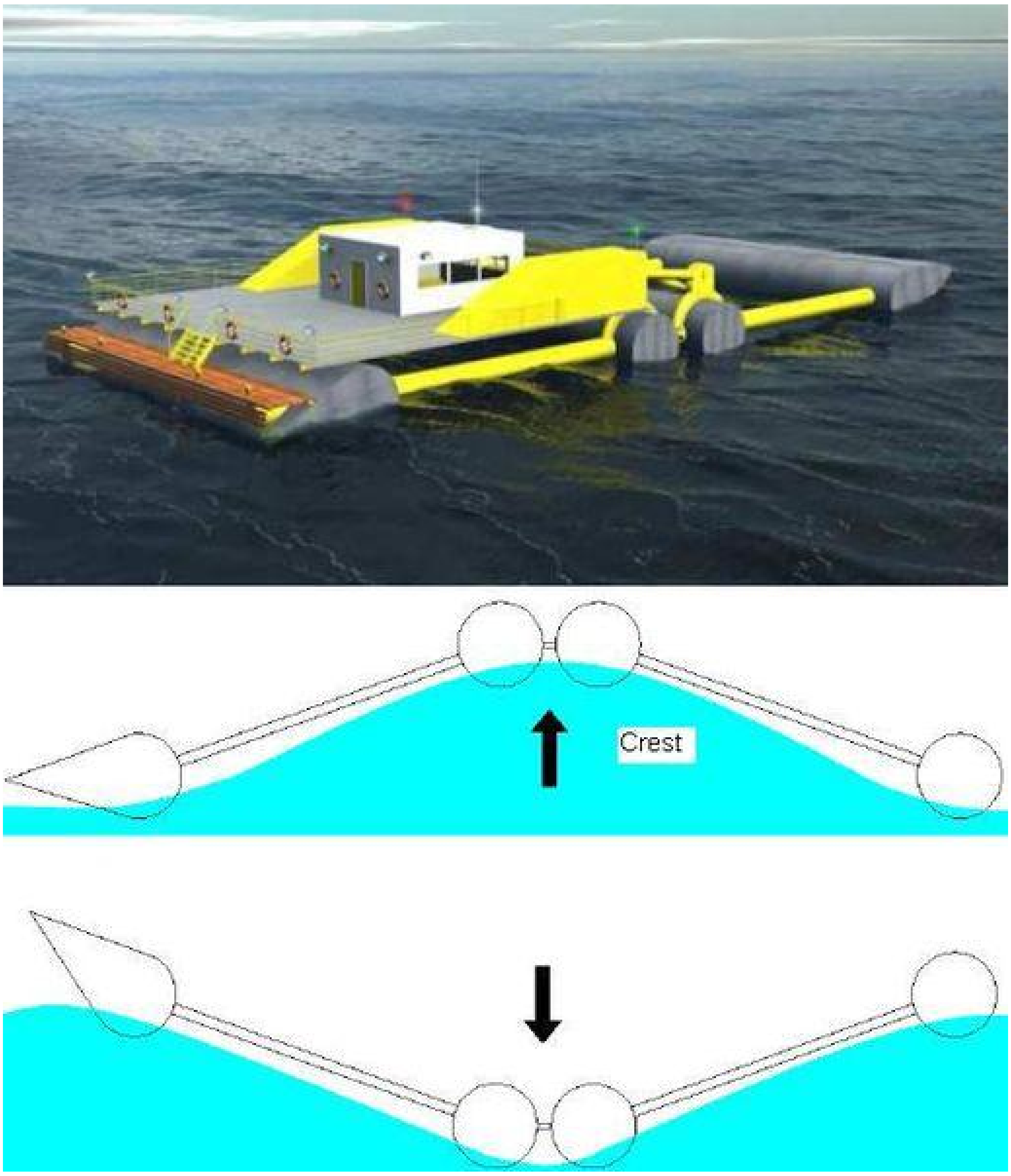


Figure 6: DEXA concept [16]

2.1.2 Oscillating Water Columns

The functioning of the oscillating water columns (OWCs) is very similar to that of a wind turbine, being based on the principle of wave induced air pressurization. The device is set upon a closed air chamber, which is placed above the water. The passage of waves changes the water level within the closed housing and the rising and falling water level increases and decreases the air pressure within the housing introducing a bidirectional air flow. By placing a turbine on top of this chamber air will pass in and out of it with the changing air pressure levels. There are two options to separate the bi-directional flow: a Wells turbine to create suction or alternatively, pressure generating valves (Kofoed and Frigaard, 2008[17]). OWC devices can be moored offshore or be placed on the shoreline where waves break.

An example of an offshore OWC is the "Sperboy", developed and patented by Embley Energy LTD [18]. It is circular in plane and therefore invariant to wave direction (Fig. 2). Its size varies according to the target sea conditions at the deployment site but maximum dimensions are set at 30m diameter, 50m height and 35m draft. Up to 450 kW mean annual output can be obtained from this concept. An inshore example is the resonant wave energy converter "REWEC-3", created by the Università degli Studi "Mediterranea" di Reggio Calabria (Fig. 2). It operates much like conventional concrete caisson breakwaters but here, each caisson is fitted with a Wells turbine. Efficiency of these devices is generally considered to be high (Boccotti, 2003[19][20]).

Figure 7: Different concepts of oscillating water columns - Sperboy (above) and REWEC-3 (below) [21]

2.1.3 Overtopping Devices

Another type of Wave energy converter is the overtopping device, which works much like a hydroelectric dam. The "Wave Dragon" created by Wave Dragon ApS[22] is an example of an offshore overtopping device (Fig. 3). Its floating arms focus waves onto a slope from which the wave overtops into a reservoir. The resulting difference in water elevation between the reservoir and the mean sea level then drives low-head hydro turbines. Proposed optimal size design of 260m width and 150m length will produce 4 MW. In wave climates above 33 kW/m, this technology is expected to be economically competitive with offshore wind power in the near future. After a combined cost saving and power efficiency increase, the power price will eventually be in line with costs of fossil fuel generation (Christensen et al., 2005[23]).

Near shore, OVTs can be installed in front of or as part of caisson breakwaters. The Norwegian company WAVEnergy[24] is developing an integrated multi level overtopping device named the "SeaWave Slot-Cone Generator (SSG)" (Fig. 3). The SSG has the advantage of harvesting wave energy in several reservoirs placed above eachother, resulting in high hydraulic efficiency. The reservoir capacity smooths out the irregularity of incoming waves, providing a regular electricity output to the grid. Additionally, with the turbine shaft and the gates controlling the water flow, SSG is built as a robust concrete structure with few moving parts in the mechanical system. This most likely makes it a low maintenance, durable system. Other SSG designs can be deployed onshore or offshore.

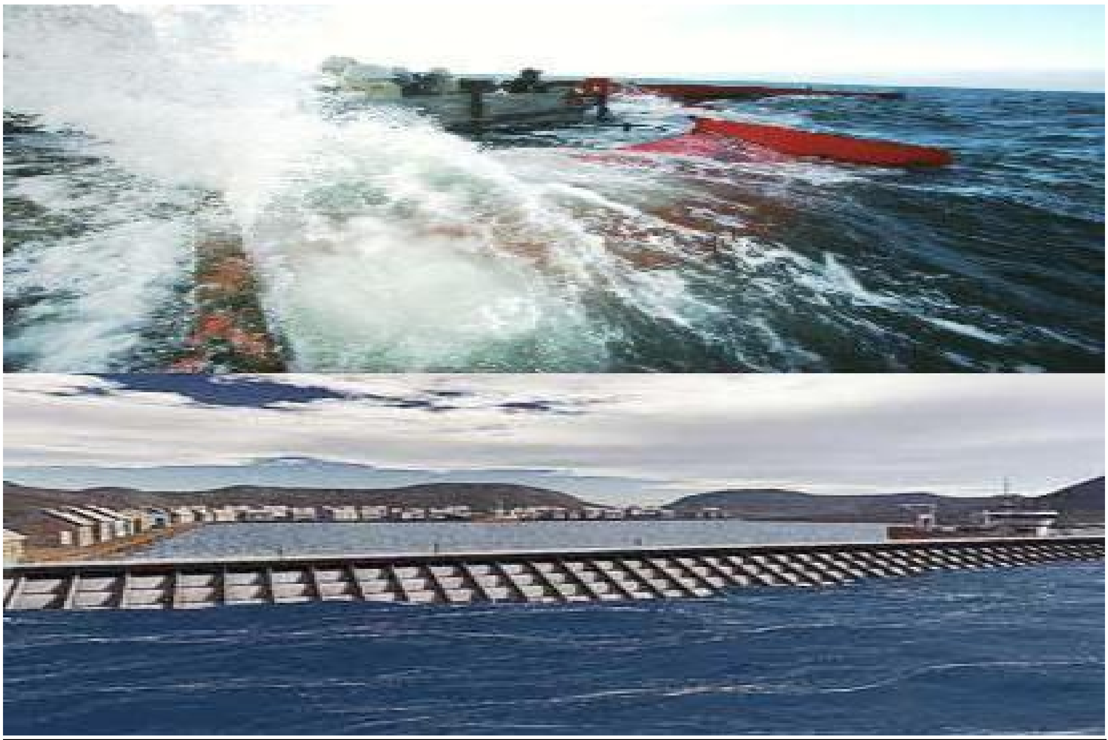


Figure 8: Different overtopping devices - Wave Dragon (Above) and SSG (below)[25]

2.1.4 Point absorbers and Attenuator Buoys

Point absorber are buoy-type WECs that harvest incoming wave-energy from all directions. They're placed offshore at or near the ocean surface. A vertically submerged floater absorbs wave energy which is converted by a piston or linear generator into electricity. One such a point absorber WEC is the FO3 concept developed by Norwegian entrepreneur Fred Olsen. It consists of several (12 or 21) heaving floaters attached to a 36 by 36 meter rig (Fig. 4). By means of a hydraulic system, the vertical motion is converted into a rotational movement that drives the hydraulic motor. This motor in turn powers the generator that can produce up to 2.52 MW (Leirbukt and Tubaas, 2006[26]).

Comparable, the attenuator type WEC "Wave Star", developed by Wave Star ApS[27], has a number of floaters on movable arms (Fig. 4). The energy of the motion of the arms is again captured in a common hydraulic line and converted into electric current. Most noticeably, being able to raise the entire installation along its pillars, this system has a high endurance for rough storm conditions. So far, this method has not been deployed at full scale. A 1:2 scaled installation has been built at Hanstholm which turns out 600 kW. However, production is thought to be scale-able up to 6 MW (Bjerrum, 2008[28]). A major benefit of these types of exploitation is the minimal contact with water, placing any delicate machinery and electrics out of reach of any corrosion or physical forcing of the waves.

Figure 9: The FO3 point absorber (above) and the Wave Star attenuator (below)[29]

2.2 Project Background

The fantastic development in science and science nowadays has allowed us to harness strength from renewable sources. The focus on producing electrical energy from renewable sources is as soon as again an important region of research with global interest being drawn to climate alternate and the rising level of CO2 [1]. Therefore, lots attention is paid to wave energy nowadays. Using waves as a source of renewable power has grew to be quintessential after the oil disaster in 1970's. Figure 1.1 suggests the renewable electricity consumption round the world.

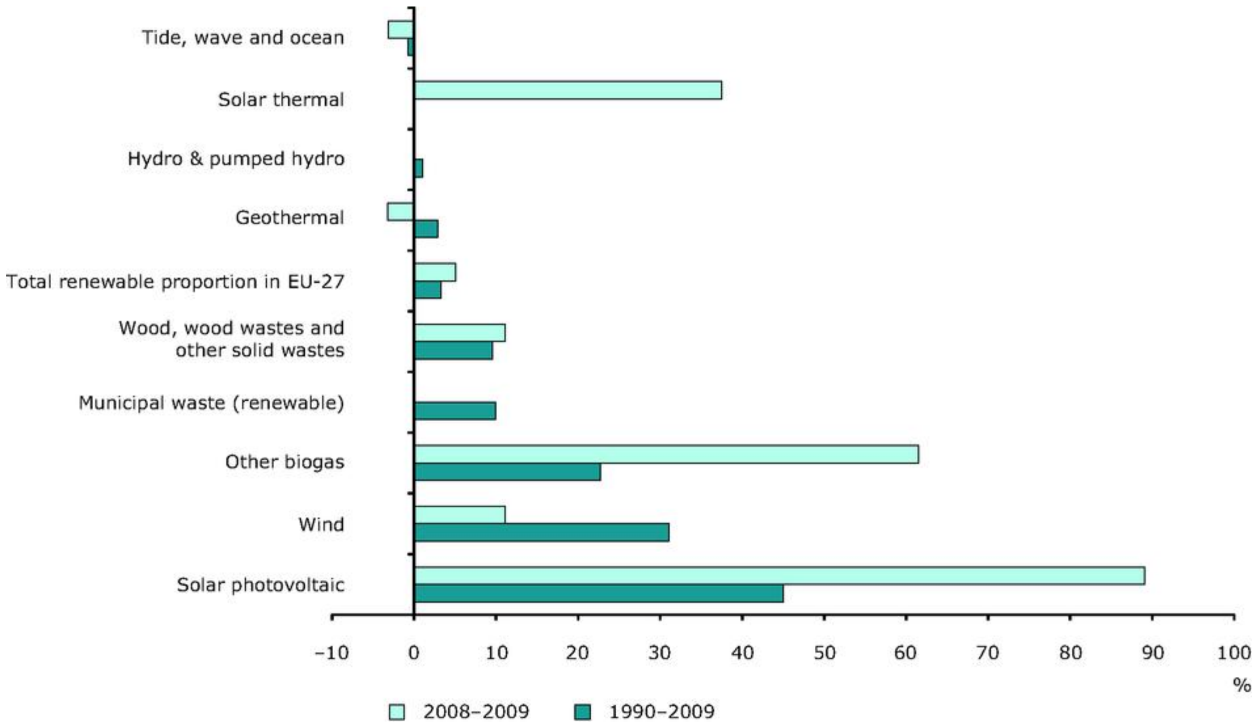


Figure 10: Average annual growth rates of renewable energy in electricity consumption (EU-27) for 1990-2009 and 2008-2009(EEA, 2012) [1].

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

Air stress differences between the upwind and the lee facet of a wave crest as nicely as friction on the water surface by way of wind, will make the water to go into the shear stress motives the increase of the waves as proven in Figure 1.2. Wave strength is believed to preserve a splendid achievable for extracting strength from as ocean waves are large and they have generally untapped electricity resource.

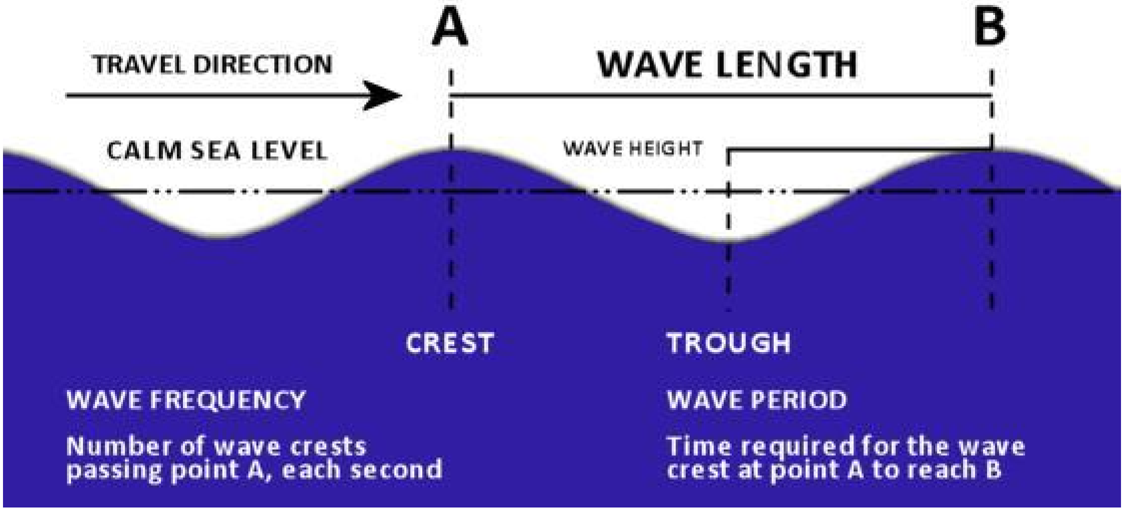
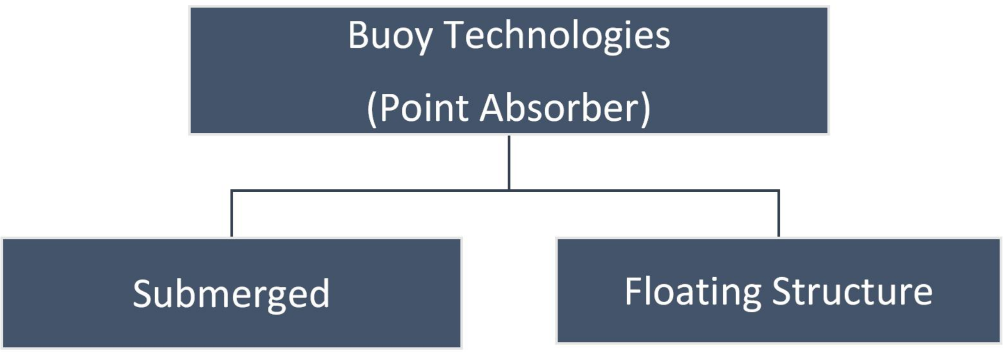


Figure 11: Wave forming [2].

2.3 After background study

Buoy Technology Wave Energy Conversion (BTWEC) is used to harvest electricity from all the instructions at one factor and additionally called as point absorber. It is an offshore system positioned close to the ocean floor [13]. According to H. Khalid et al. [13], the BTWEC can be categorized into two principal classes namely submerged and floating buoy applied sciences as proven in Figure 2.5.



CHAPTER 3

3.1 Linear Generator

Since this linear generator will be designed for fishermen to gain from it, the most appropriate WEC that can be used is the Buoy Technologies Wave Energy Converter Technologies. To be specified, Floating Buoy Technologies (FBT) will be used to achieve the objective. Since the plan of the linear generator has to compromise withsmall scale factor, mobile, less expensive and high effectivity and low-cost, this technique or technique has been identified as the best. Figure 11 suggests the floating buoy machine with the linear generator. There are a number of solutions for placing the linear generator WEC factors and Figure 12 is showing the instance of placement.

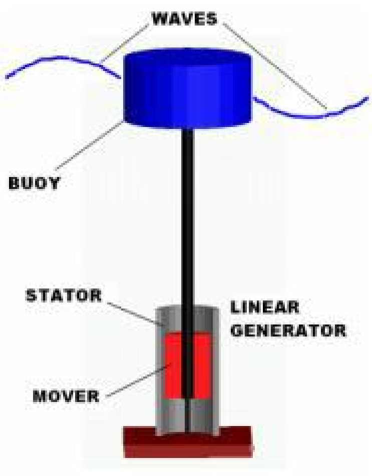


Figure 12: Floating buoy system with the linear generator [18]

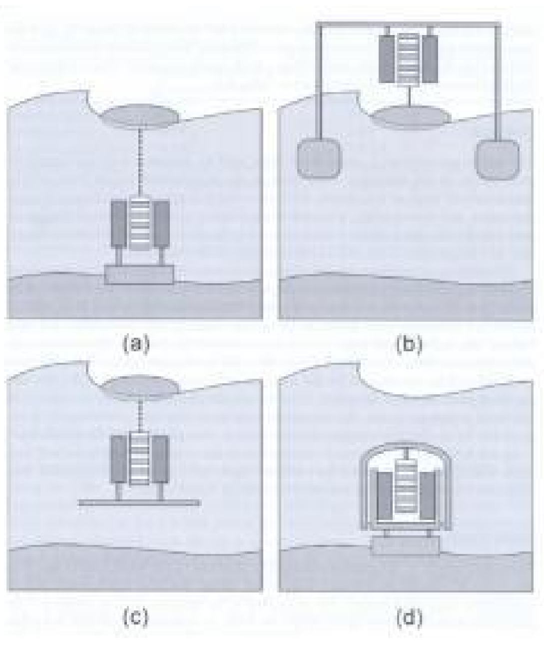


Figure 12: Various solutions for placing the linear generator WEC components [19]

3.1.1 Linear generator vs. rotary generator

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

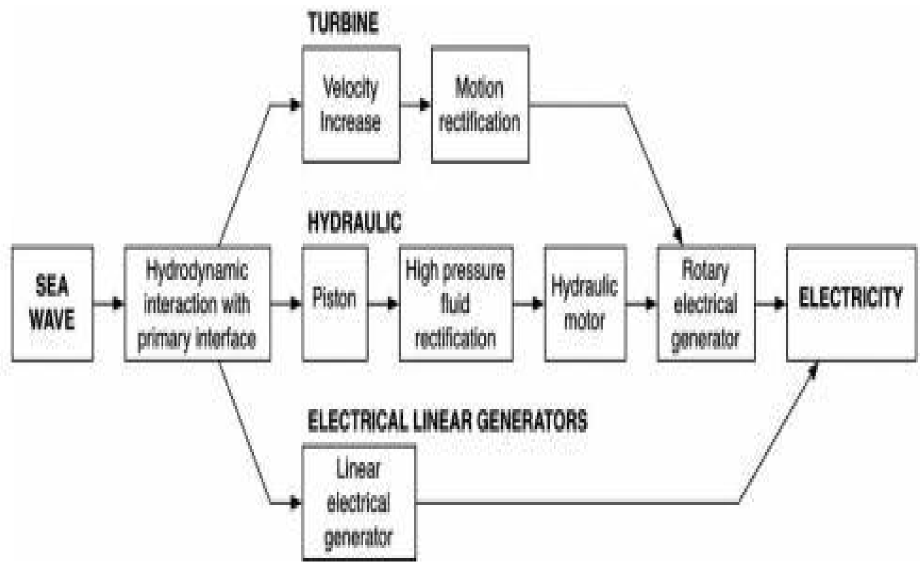


Figure 13: Power take off mechanisms using linear and rotary electrical generator [1].

3.1.2 Linear generator type

Linear generator is a system that converts mechanical power to electrical electricity and it moves or slides alongside one course which can be x-axis or y-axis. There are many kinds of linear generator that can be used for wave energy conversions such as induction generator, synchronous generator, direct present day generator, and everlasting magnet generator. Each kind of generator has its own blessings and drawbacks. In order to show a wonderful comparison between the generators, Table 2.2 is tabulated in term of performance and feasibility for wave strength conversion.

3.1.3 Comparison between the types of generators

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

3.1.4 Tubular vs. Planar linear generators

A result of excessive performances at low pace and a easy structure, implying a excessive reliability is critical for a linear generator to be compatible with WEC. According to Oprea et. al [19] advanced bearing gadget is needed in non-tubular constructions to compensate the excessive magnetic forces in the everyday direction. Figure 2.13 indicates the planar and tubular kind permanent magnet machine.

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

The core and the spacers are viewed to be realized by means of using pure iron with nonlinear B-H curve. Magnetic flux paths are produced by iron poles whilst ring magnets on cylindrical mover are axially magnetized. Usually hallbach array magnets or radial magnets are more often than not used in such machines. Table 2.3 indicates the gain and feasible applications of a tubular type of a linear generator.

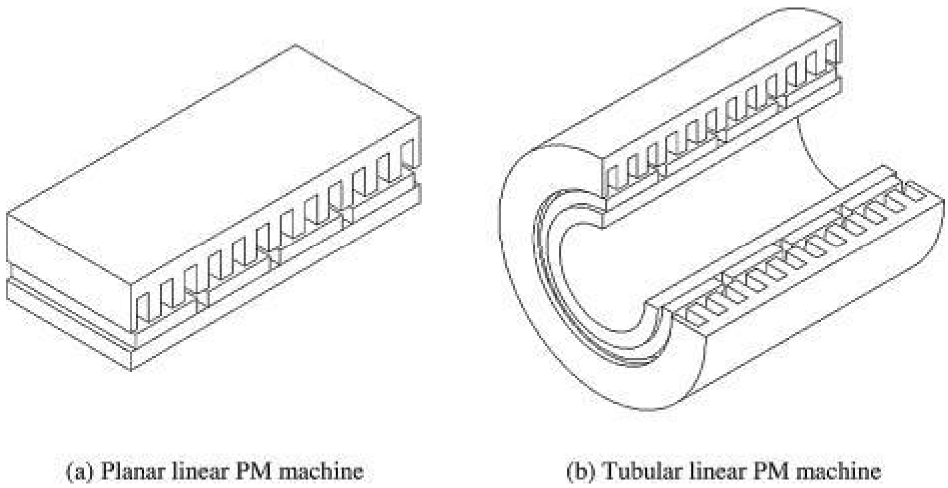


Figure 14: Linear machines. [20]

3.1.5 Advantages of a tubular type of a linear generator

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

3.1.6 Air core vs. Iron core stator

Iron core stators are typically excessive cost, heavy and extra resources is required to install, stabilize and maintain. Iron core additionally suffers from cogging torque which is a resulting torque from the interaction between the everlasting magnet of the rotor and stator slots of the permanent magnet. This torque is also knows as no-current torque. Cogging torque is an undesirable issue for the operation of iron-core electric generators. It is mainly outstanding at decrease speeds the place windings on either the rotor or stator become worn or defective, surprisingly knowledgeable technicians are-required to conduct restore or maintenance.

The heavy weight and unwieldiness of conventional iron-core stators also often require the use of machinery or teams of technicians to conduct even routine maintenance.

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

3.1.7 Selection of moving part

The magnet volume wished to generate the area of a moving coil desktop is a great deal increased than moving magnet generator which produce equal output and efficiency. Since magnets are via some distance the highest priced constituent of either type, transferring coil functions are relevant for price insensitive applications. Advantage of the moving coil kind is absence of radial forces, open circuit axial forces, and torques on the shifting coil. Such outcomes are very essential in linear machines. Radial forces can weigh down fuel bearings or even oil bearings and lead to lossy operation or failure. Moving iron used to be rotationally unstable in its air gap. If tilted, it tended to tilt further and close the gap, performing like a negative torsion spring with such a excessive spring constant that it defeated all tries at stabilization by way of better initial alignment and larger mechanical rigidity. Moving magnet gives extra efficiency. In this design, the linear generator will be have the magnet shifting as an alternative of coil or core shifting primarily based on practical concerns.

3.2 Magnet configuration

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

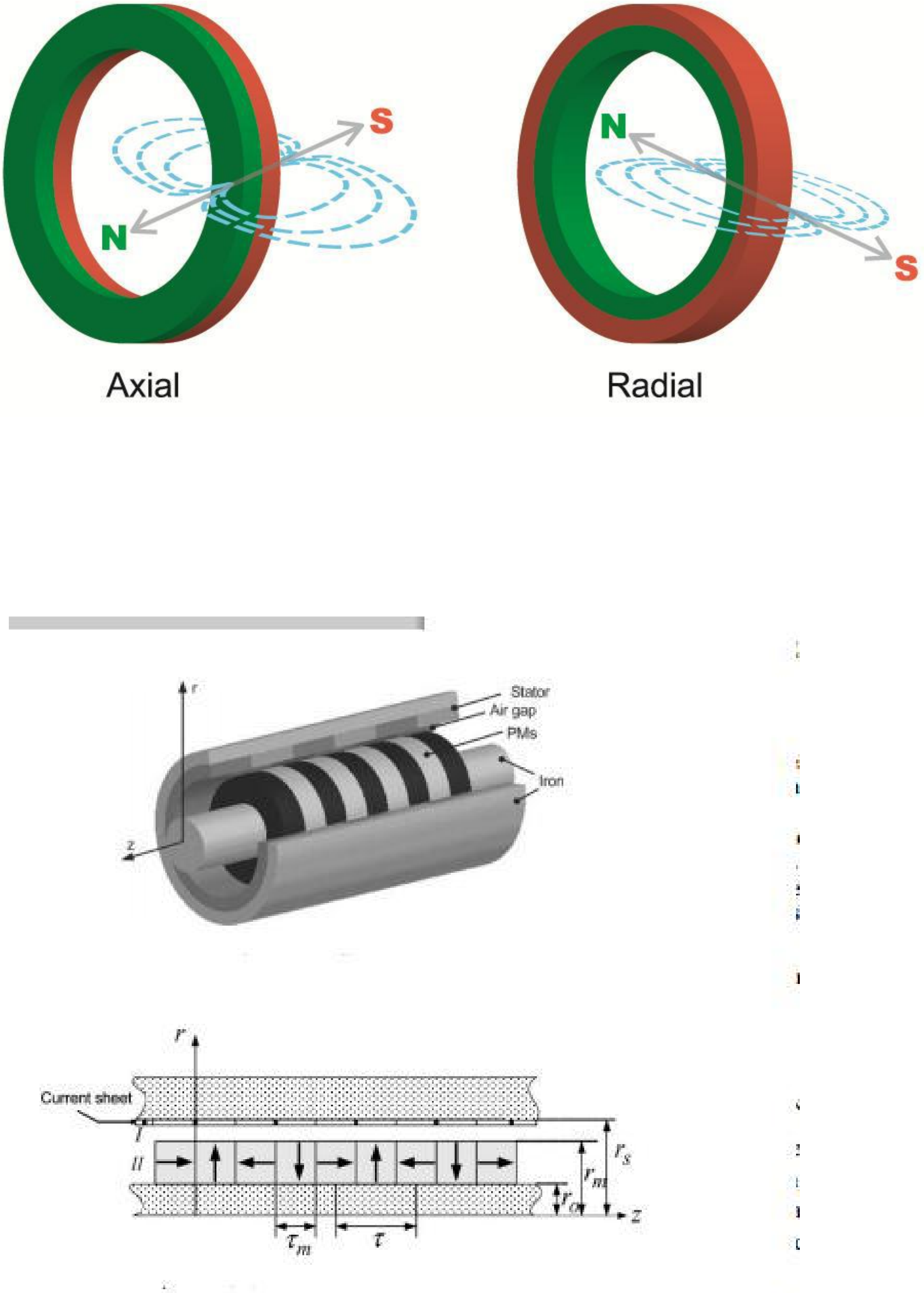


Figure15: Radial, Axial and Hallbach type of magnet arrangement [20]

CHAPTER 4

4.1 Basic Design

Our design for the wave energy converter is a Tubular Permanent Magnet Linear Generator (TPMLG) . For generator design the required components include

- A permanent magnet
- Magnet casing
- Universal joint
- Stator
- Buoy

And the wave generation facility includes

- Wave generator
- Water container

4.1.1 Permanent magnet

The permanent magnet used for our design is a rare earth magnet namely Neodymium N35. It is one of the most powerful magnets ever produced. It exerts very strong pull force compared to other magnetic materials. A neodymium magnet (also known as NdFeB, NIB or Neo magnet), the most widely used type of rare earth magnet, is a permanent magnet made of an alloy of neodymium, iron and boron to form the crystalline tetragonic structure of $Nd_2Fe_{14}B$. Neodymium magnets, produced independently in 1982 by General Motors and Sumitomo Special Metals, are the strongest type of permanent magnet available commercially. These are also classified into two subcategories due to different production processes, namely sintered NdFeB magnets and bonded NdFeB magnets. In many applications in modern products, they have replaced other types of magnets that require strong permanent magnets, such as motors in cordless tools, hard disk drives and magnetic fasteners.

Neodymium is a steel which is ferromagnetic (more particularly it indicates antiferromagnetic properties), which means that like iron it can be magnetized to come to be a magnet, but its Curie temperature (the temperature above which its ferromagnetism disappears) is 19 K (−254.2 °C; −425.5 °F), so in pure structure its magnetism only appears at extraordinarily low temperatures.[9] However, compounds of neodymium with transition metals such as iron can have Curie temperatures well above room temperature, and these are used to make neodymium magnets.The power of neodymium magnets is due to countless factors. The most necessary is that the tetragonal $Nd_2Fe_{14}B$ crystal shape has relatively high uniaxial magnetocrystalline anisotropy ($H_A \approx 7$ T – magnetic field electricity H in devices of A/m versus magnetic moment in A·m2).[10][3] This means a crystal of the fabric preferentially magnetizes along a specific crystal axis, however is very hard to magnetize in other directions. Like different magnets, the neodymium magnet alloy is composed of microcrystalline grains which are aligned in a effective magnetic discipline all through manufacture so their magnetic axes all factor in the equal direction. The resistance of the crystal lattice to turning its course of magnetization gives the compound a very high coercivity, or resistance to being demagnetized.

The neodymium atom also can have a large magnetic dipole moment due to the fact it has four unpaired electrons in its electron shape as adversarial to (on average) three in iron. In a magnet it is the unpaired electrons, aligned so they spin in the identical direction, which generate the magnetic field. This gives the $Nd_2Fe_{14}B$ compound a excessive saturation magnetization ($J_s \approx 1.6$ T or sixteen kG) and a remnant magnetization of typically 1.3 teslas. Therefore, as the maximum energy density is proportional to J_s^2, this magnetic section has the doable for storing large quantities of magnetic power ($BH_{max} \approx 512$ kJ/m3 or 64 MG·Oe). This magnetic strength value is about 18 times greater than "ordinary" ferrite magnets by way of volume, and 12 times through mass. This magnetic electricity property is higher in NdFeB alloys than in samarium cobalt (SmCo) magnets, which were the first type of rare-earth magnet to be commercialized. In practice, the magnetic properties of neodymium magnets rely on the alloy composition, microstructure, and manufacturing approach employed.The $Nd_2Fe_{14}B$ crystal structure can be described as alternating layers of iron atoms and a neodymium-boron compound. The diamagnetic boron atoms do no longer make contributions without delay to the magnetism, however enhance cohesion by using strong covalent bonding. The notably low rare earth content material (12% with the aid of volume) and the relative abundance of neodymium and iron in contrast with samarium and cobalt makes neodymium magnets lower in rate than samarium-cobalt magnets.

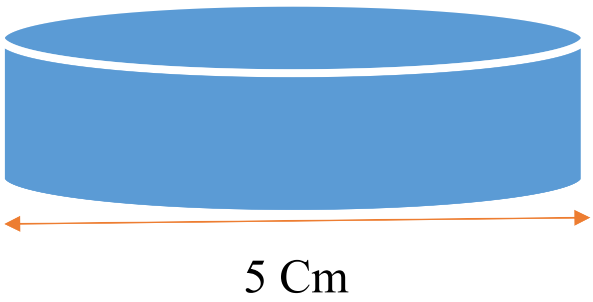


Figure 16: Permanent Magnet

Magnet parameters:

Parameters	Value
Name	Neodymium N35 Magnet
Operating temperature	80^0C
Surface	Nickel Plating
Dipole moment	26.8 Am^2
Diameter	5 cm
Height	2 cm

4.1.2 Magnet casing

3D printed diamagnetic casing was used to couple the magnet with a non magnetic universal joint.

Figure 17: 3D Printed Magnet Casing

Casing Parameters:

Parameters	Value
Material	PLA
Inner diameter	5 cm
Outer diameter	5.2 cm
Inner height	2 cm
Total height	2.2 cm

4.1.3 Universal Joint

An established joint is a joint or coupling connecting inflexible rods whose axes are inclined to every other, and is often used in shafts that transmit rotary motion. It consists of a pair of hinges placed close together, oriented at 90° to each other, connected by way of a cross shaft. The time-honored joint is not a constant-velocity joint.

We used a hollow stainless steel rod for our universal joint mechanism. It provides good connectivity and offers less weight. Also because of being made of stainless steel it won't get rusty.

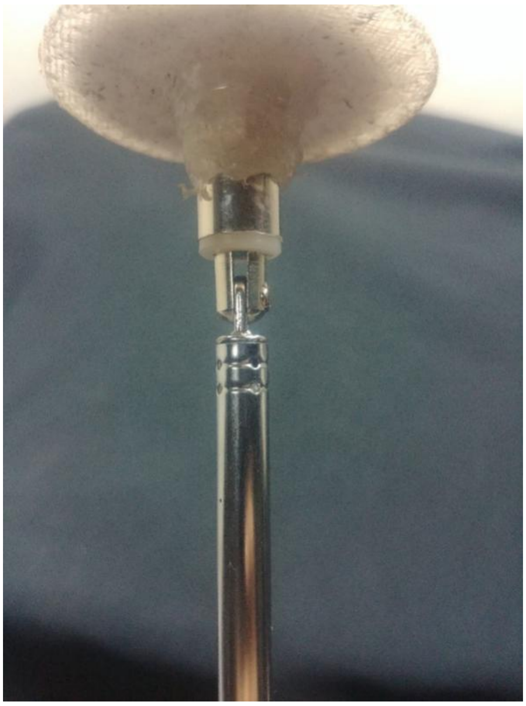


Figure 18: Universal Joint

Universal joint-shaft parameters:

Parameters	Value
Material	Stainless steel
Length	10 cm
diameter	6.5 mm

4.1.4 Stator

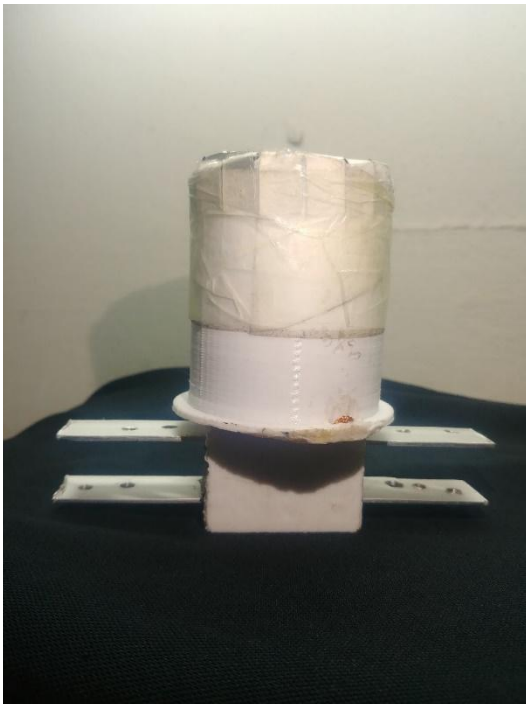
The stator is the stationary section of a rotary system, observed in electric powered generators, electric motors, sirens, mud motors or biological rotors. Energy flows thru a stator to or from the rotating factor of the system. In an electric motor, the stator affords a rotating magnetic area that drives the rotating armature; in a generator, the stator converts the rotating magnetic subject to electric powered current. In fluid powered devices, the stator courses the go with the flow of fluid to or from the rotating phase of the system.

Depending on the configuration of a spinning electromotive gadget the stator might also act as the discipline magnet, interacting with the armature to create motion, or it may additionally act as the armature, receiving its influence from moving subject coils on the rotor. The first DC generators (known as dynamos) and DC motors put the field coils on the stator, and the electricity generation or motive reaction coils on the rotor. This is integral due to the fact a constantly moving electricity change regarded as the commutator is wanted to preserve the subject efficaciously aligned throughout the spinning rotor. The commutator need to turn out to be large and greater robust as the current increases.

An AC alternator is able to produce electricity across a couple of high-current strength technology coils connected in parallel, eliminating the want for the commutator. Placing the area coils on the rotor lets in for an inexpensive slip ring mechanism to switch high-voltage, low cutting-edge power to the rotating area coil.

4.1.4 (a) Stator Casing

For the stator a 3D printed cylindrical casing was used to provide support for the winding.



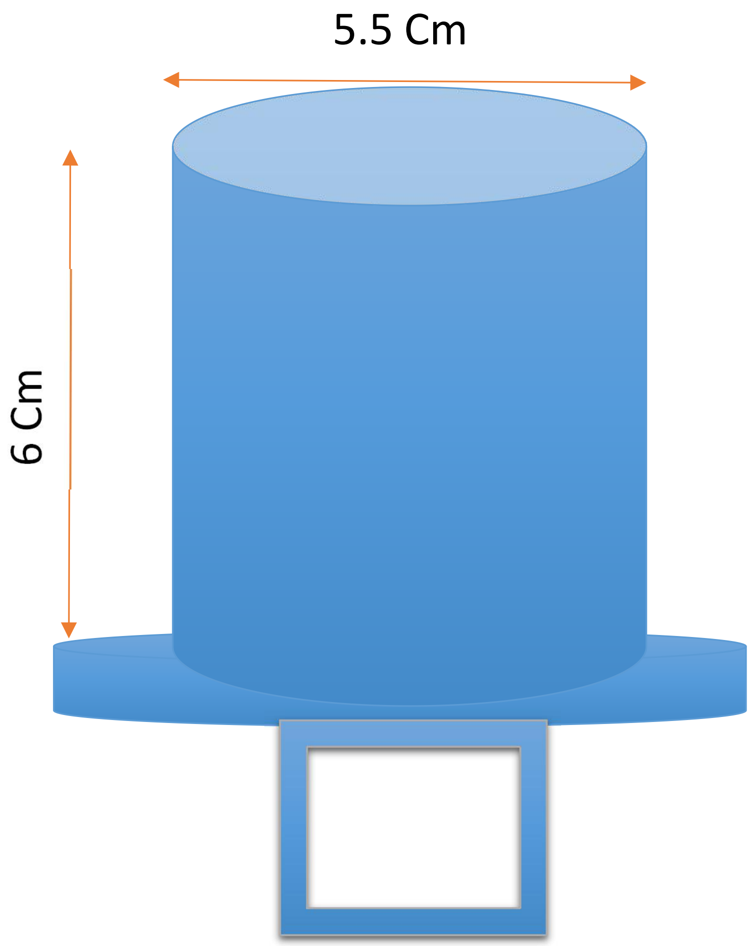


Figure 19: Stator Casing

Stator Casing Parameters:

Parameters	Value
Material	PLA
Inner diameter	5.2 cm
Outer diameter	5.5 cm
Height	6 cm

4.1.4 (b) Stator winding

In electrical engineering, coil winding is the manufacture of electromagnetic coils. Coils are used as components of circuits,and to provide the magnetic field of motors, transformers, and generators, and in the manufacture of loudspeakers and microphones. The shape and dimensions of a winding are designed to fulfill the particular purpose. Parameters such as inductance, Q factor, insulation strength, and strength of the desired magnetic field greatly influence the design of coil windings.

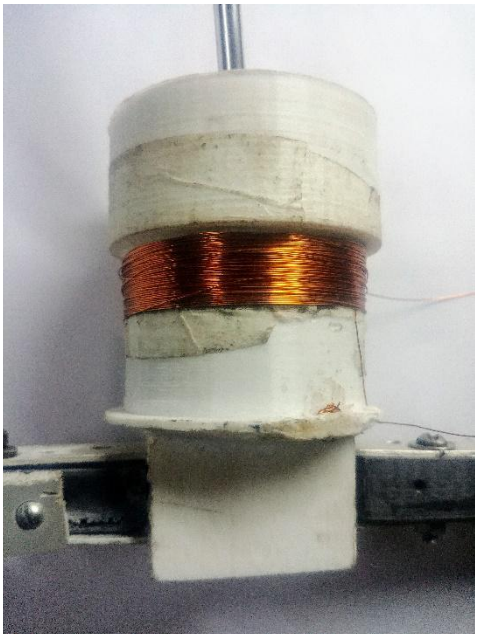


Figure 20: Stator

Coil winding can be structured into several groups regarding the type and geometry of the wound coil. Mass production of electromagnetic coils relies on automated machinery.

Efficient coils minimize the materials and volume required for a given purpose. The ratio of the area of electrical conductors, to the provided winding space is called "fill factor". Since round wires will always have some gap, and wires also have some space required for insulation between turns and between layers, the fill factor is always smaller than one. To achieve higher fill factors, rectangular or flat wire can be used.

Dense packing of wires reduces air space, and is said to have a high fill factor. This increases the efficiency of the electrical device and an improved heat conductivity of the winding. For best packing of round wires on a multi-layer winding, the wires in the upper layer are in the grooves of the lower layer for at least 300 degrees of the coil circumference. The wires occupy a dense package which is called “orthocyclic winding”. The opposite of this would be a random wire structure within the winding space, which is called “wild winding.” Owing to the fact that a round wire will create air gaps that are not electrically used, the fill factor is always smaller than one. In order to achieve higher fill factors, rectangular or flat wire can be used. This can be wound on flat or upright.

❖ *Ortho cyclic winding*

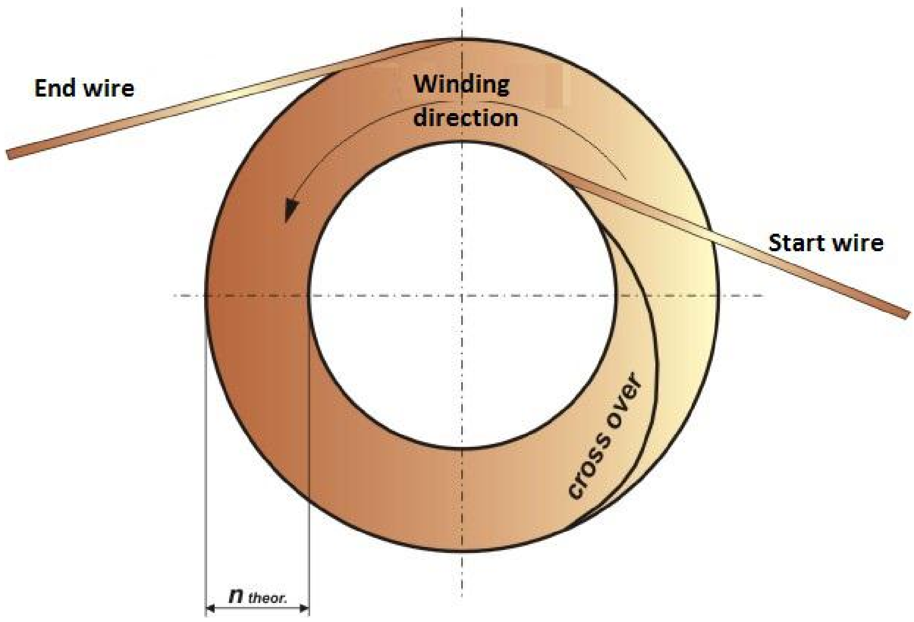
For our stator we used ***Ortho cyclic winding***.

The wires are placed helically in every layer. Owing to the direction of movement from layer to layer changing between right-hand and left-hand, the wires cross and locate themselves within the gap of the layer underneath. A wire guiding of the lower layer is not existent. If the number of layers exceeds a certain limit the structured cannot be maintained and a wild winding is created. This can be prevented with the use of a separate layer insulation, which is needed anyway when the voltage difference between the layers exceeds the voltage strength of the copper wire insulation. This type of winding structure creates an optimal fill factor (90.7%) for round wires. The windings of the upper layer need to be placed into the grooves provided by the lower layer.

The best volume use is found when the winding is parallel to the coil flange for most of its circumference. When the winding has been placed around the coil body it will meet with the previous positioned wire and needs to make a step with the size of the wire gauge. This movement is called winding step. The winding step can occupy an area of up to 60 degree of the coil circumference for round coil bobbins and takes one side of rectangular coil bobbins. The area of the winding step is dependent on the wire gauge and coil bobbin geometry.

If the winding step cannot be executed properly then the self-guiding ability of the wire is lost and a wild winding is produced. Overall, the first intruding wire mainly determines the location and quality of the winding step. It should be recognized that the wire needs to enter in a possibly flat angle into the winding space. That way an unnecessary bending of the wire is being avoided and the needs space for the second winding step is minimized. For Ortho cyclic wound coils, the winding step areas is always located at the area of wire entering the winding space and is being continued in helical form against the winding direction.

As a consequence a bigger winding width of the coil, leads to a bigger winding step area along the circumference of the coil. The created offset leads to a different position of the layer step, from the first to the second layer, in comparison to the wire entry. This behavior repeats itself with every layer which leads to a spiral shaped crossover section at the side of the winding. Owing to the fact that wires are crossing within the crossover section the resulting winding height is increased. As a result, Ortho cyclic wound coils with a round coil ground are never circular in the cross over section, but the radial moving winding and layer step creates a hump shape. Experience has shown that, depending on the winding width, coil and wire diameter, the crossover section is about 5 to 10 percent higher than the regular winding height.



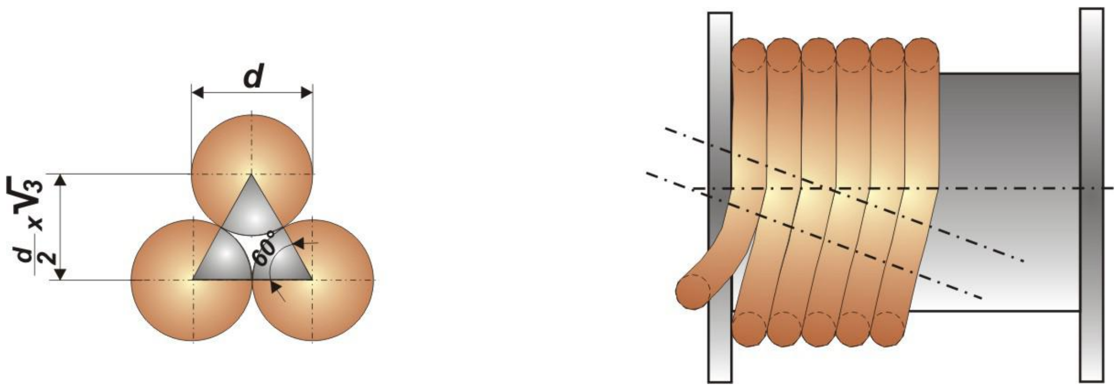


Figure 21: Stator Winding [Source: Wikipedia]

4.1.5 Buoy

A buoy is a floating device that can have many purposes. It can be stationary or allowed to drift with ocean currents.

For this project the buoy is a floating plastic vessel connected to the shaft of the Linear generator through another bigger shaft to provide greater movement and stability.

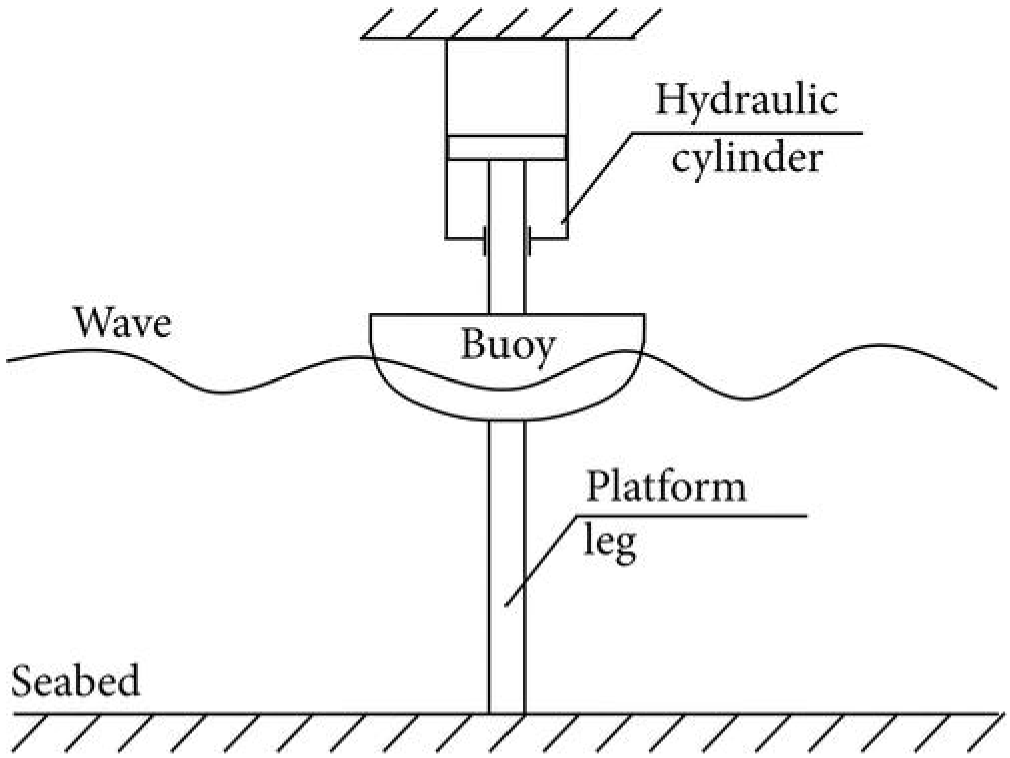


Figure 22: Typical buoy setup for Linear Generators (Source: Wikipedia)

Figure 23: Cylindrical Shaped Plastic Buoy

Buoy parameters:

Parameters	Value
Material	Plastic Bottle
Shape	Cylindrical
Length	24 cm
diameter	7 cm

4.2 Experimental setup

The setup or wave generation facility includes

- **Wave generator**
- **Water Container**

Figure 24: Experimental Setup

4.3 Methodology

For a loop of wire in a magnetic field, the magnetic flux Φ_B is defined for any surface Σ whose boundary is the given loop. Since the wire loop may be moving, we write $\Sigma(t)$ for the surface. The magnetic flux is the surface integral:

$$\Phi_B = \iint_{\Sigma(t)} \mathbf{B}(t) \cdot \mathrm{d}\mathbf{A}$$

where d**A** is an element of surface area of the moving surface $\Sigma(t)$, **B** is the magnetic field, and **B**·d**A** is a vector dot product representing the element of flux through d**A**. In more visual terms, the magnetic flux through the wire loop is proportional to the number of magnetic flux lines that pass through the loop

When the flux changes—because **B** changes, or because the wire loop is moved or deformed, or both—Faraday's law of induction says that the wire loop acquires an EMF, E, defined as the energy available from a unit charge that has travelled once around the wire loop. (Note that different textbooks may give different definitions. The set of equations used throughout the text was chosen to be compatible with the special relativity theory.) Equivalently, it is the voltage that would be measured by cutting the wire to create an open circuit, and attaching a voltmeter to the leads.

Faraday's law states that the EMF is also given by the rate of change of the magnetic flux:

$$\mathcal{E} = -\frac{\mathrm{d}\Phi_B}{\mathrm{d}t}$$

Where $\mathcal{E}$ is the electromotive force (EMF) and Φ_B is the magnetic flux.

The direction of the electromotive force is given by Lenz's law.

For a tightly wound coil of wire, composed of *N* identical turns, each with the same Φ_B, Faraday's law of induction states that,

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

Where N is the number of turns of wire and Φ_B is the magnetic flux through a single loop.

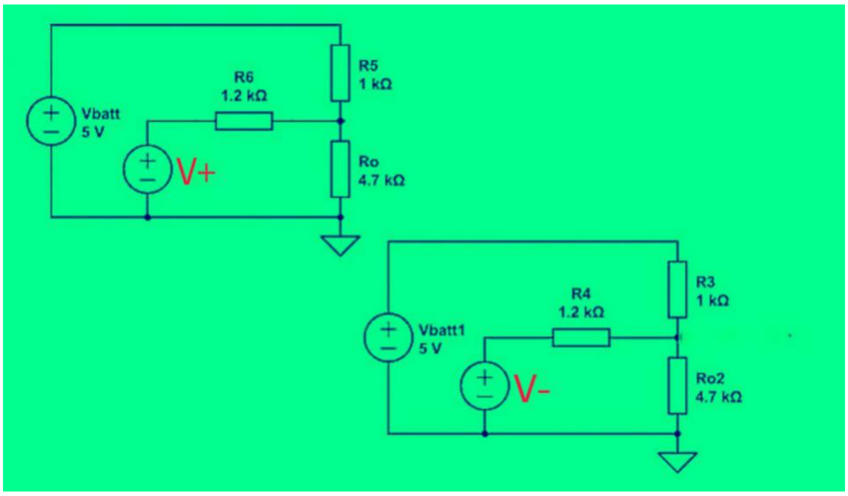
CHAPTER 5

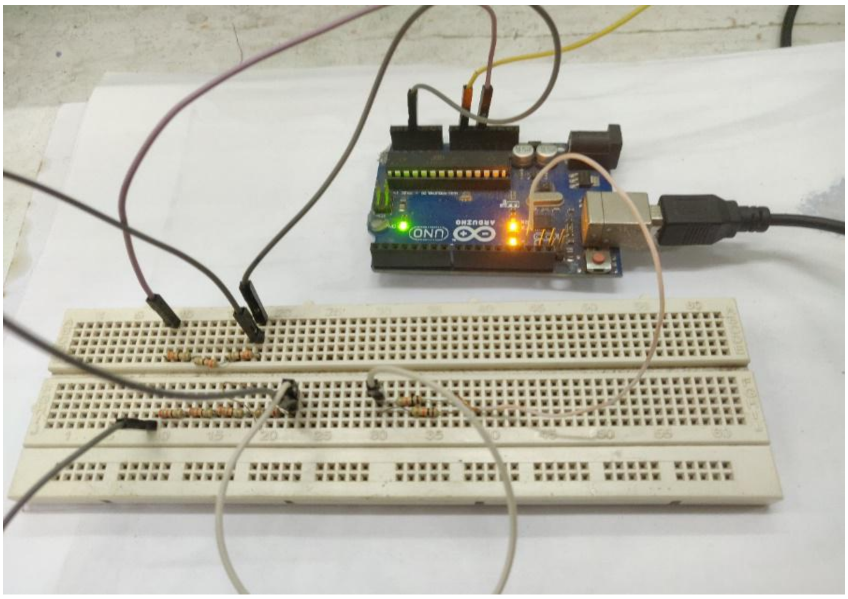
5.1 Output

For getting the output as Voltage Vs time we used an **AC Voltmeter circuit** which needs the following devices and electrical setup:

- ARDUINO UNO
- Laptop
- Breadboard
- Jumper wire
- Registors

5.1.1 Circuit





5.1.2 Hardware Setup

An ARDUINO UNO was confined with the designed circuit which was actually working as a potentiometer. In order to get the satisfactory results of millivolt range from the experiment this sort of voltmeter was used. Three (3) 330 Ω resistors were used as series connection to build the 1kΩ; a 220Ω and three (3) 330Ω resistors were also used as series connection to build 1.2kΩ resistance. These two branches were kept in parallel with another branch of 5kΩ resistance which comprised with two (2) 10kΩ resistors in parallel. This potentiometer provides a small range of voltage measurement having maximum of -6V to +6V.

The potentiometer wiper (middle terminal) connected to analog pin 3 of ARDUINO UNO and outside leads to ground and constant +5V that has been provided by the ARDUINO itself.

5.1.3 ARDUINO code for AC Voltmeter

sketch_nov09a §

```
int analogPin = A3; // potentiometer wiper (middle terminal) connected to analog pin 3
                    // outside leads to ground and +5V
float val = 0;  // variable to store the value read

void setup() {
  Serial.begin(9600);           //  setup serial
}

void loop() {
  val = analogRead(analogPin);
  val=((val*5000)/1024)-2500 ;// read the input pin
  Serial.println(val);
  // debug value
}
```

5.1.4 Software Details

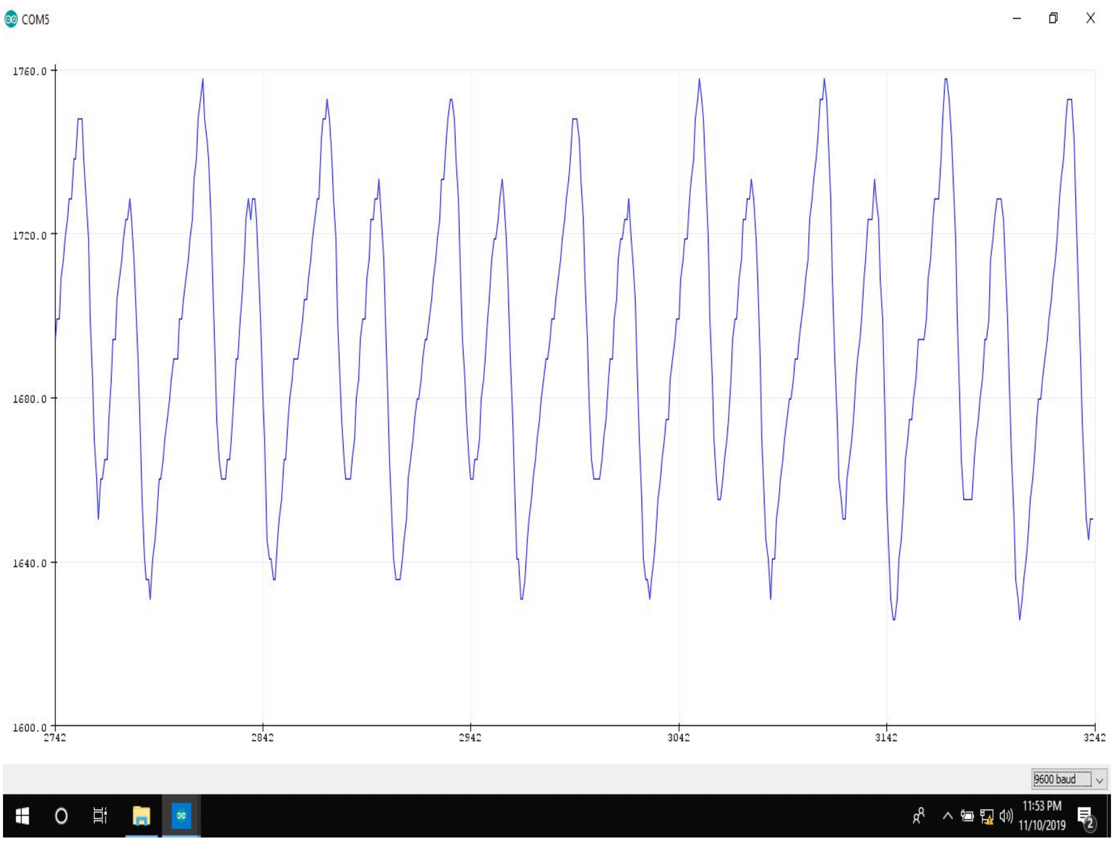
ARDUINO IDE app dealt with the voltmeter software application which provided the clear peak to peak voltage reading to the computer display through the serial plotter option.

Here, Maximum 5V might be produced from initial estimation although millivolt range was used for practical experimental issue. The bit rate of ARDUINO UNO mechanism was 10 bits/s. The smallest segment would be the ($5*1000/2^{10}$) or (5000/1024) equals to 4.88 mV which can be called as accuracy specifications of voltage measurement. Additionally, the baud rate was 9600.

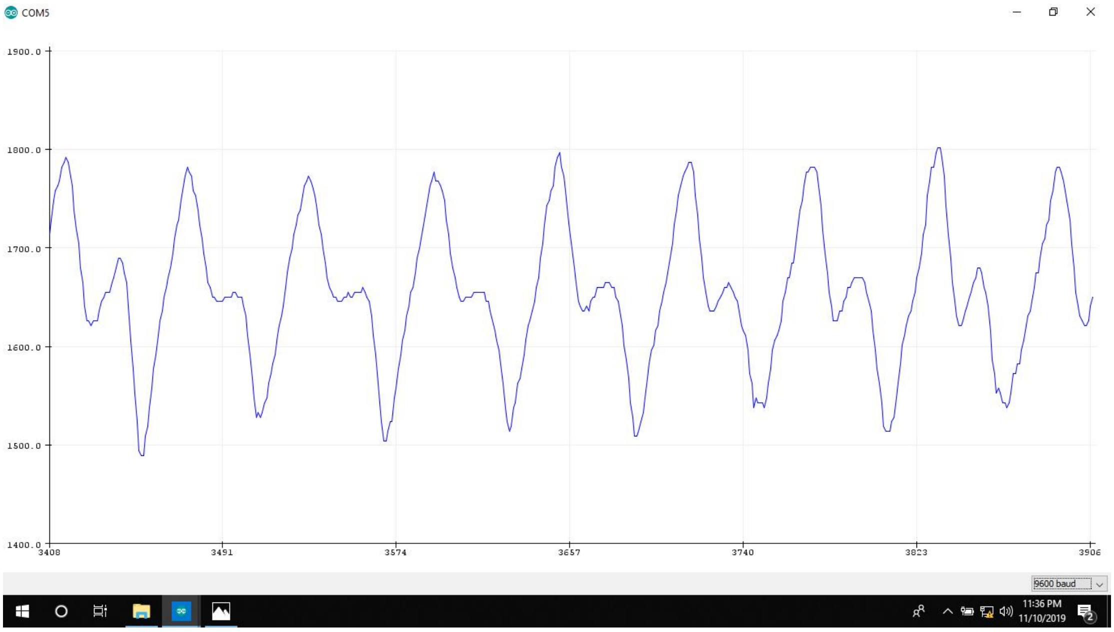
At serial plotter window, X and Y axis indicated the Time(mS) and Voltage(mV) respectively. While the generator was working in full swing a continuous mV Vs mS curve has been produced which clarify the voltage generation from the alternator under no load condition.

5.1.5 Turnwise voltage Vs time graphs

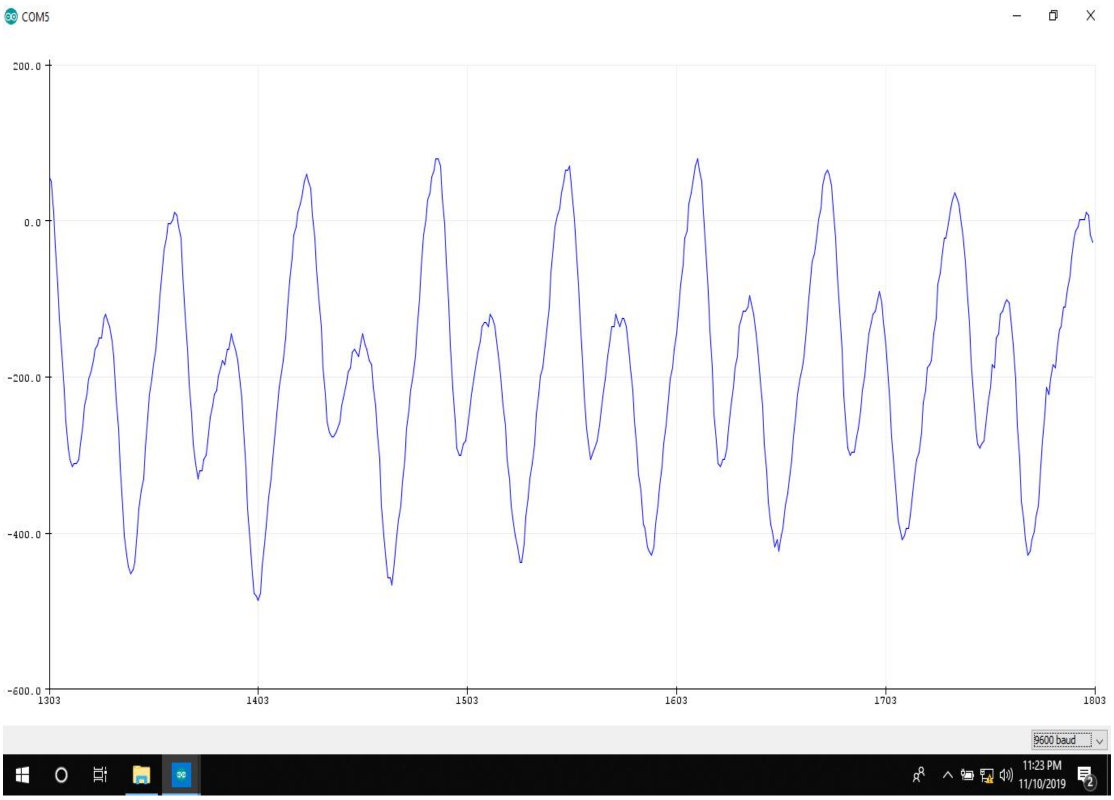
❖ For 100 Turns



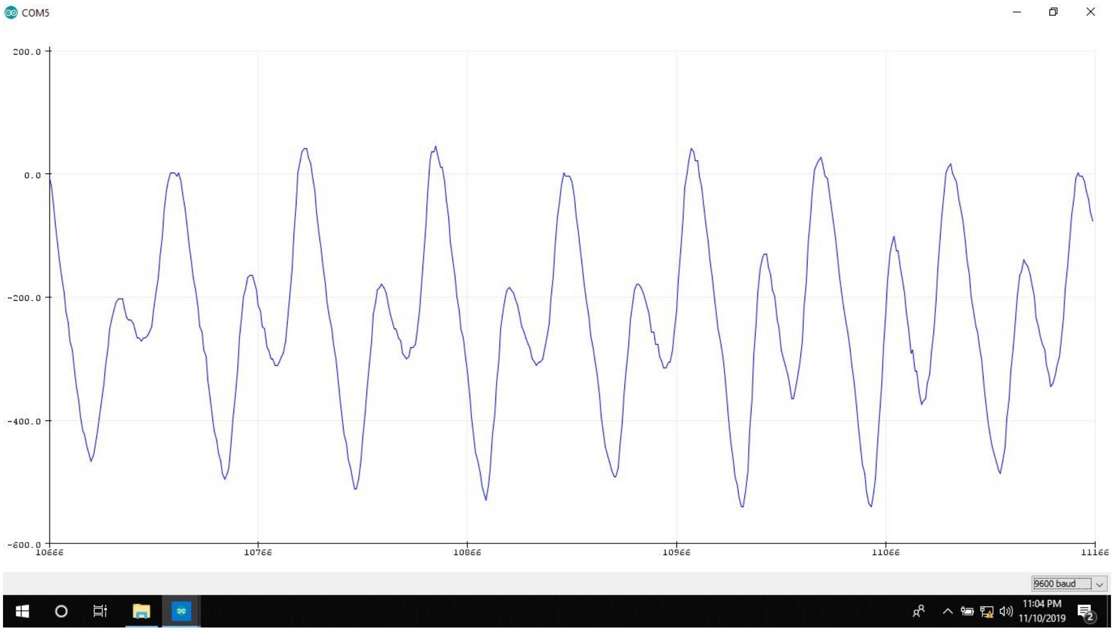
❖ For 200 Turns



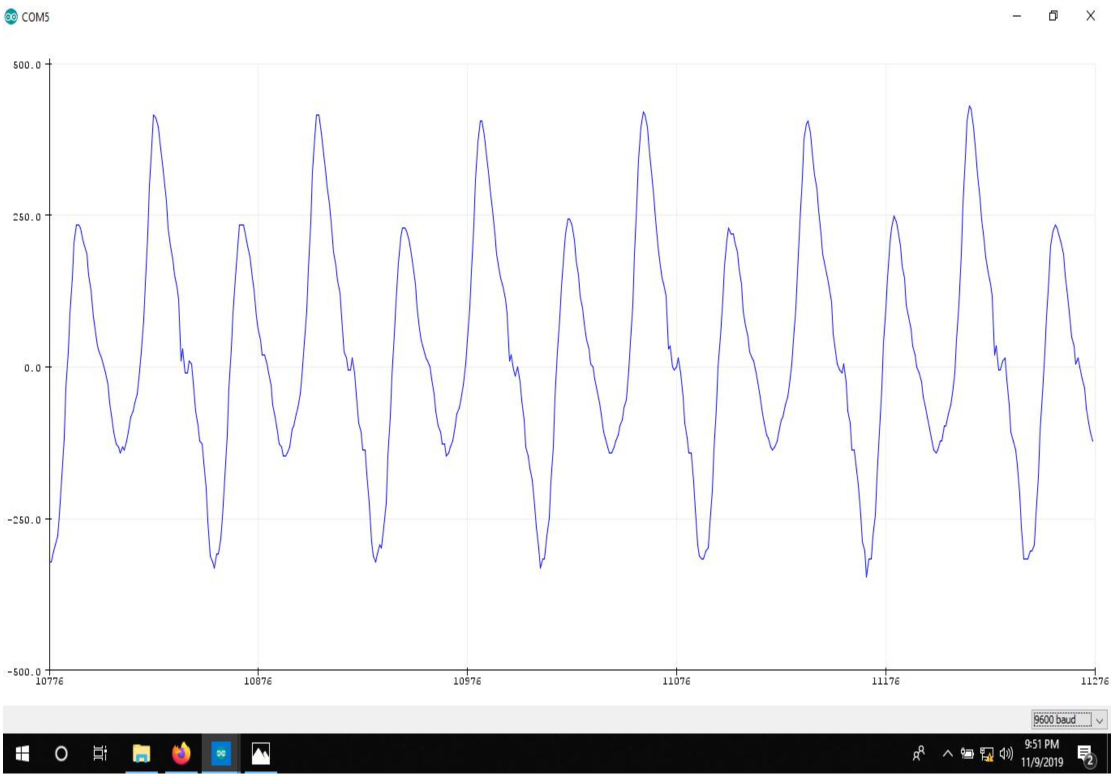
❖ For 300 Turns



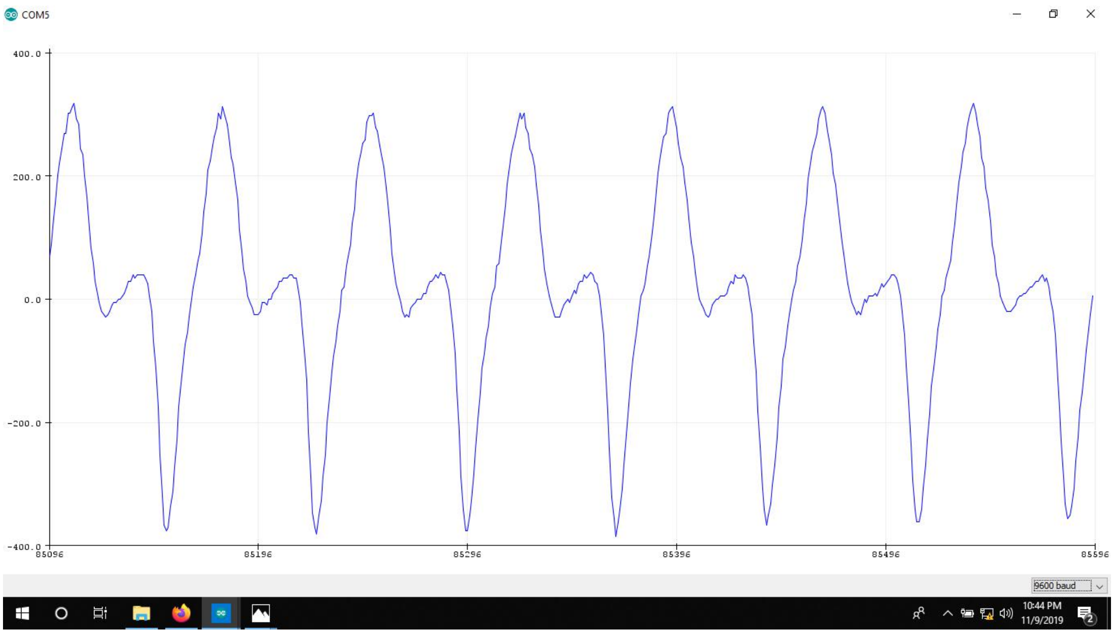
❖ For 400 Turns



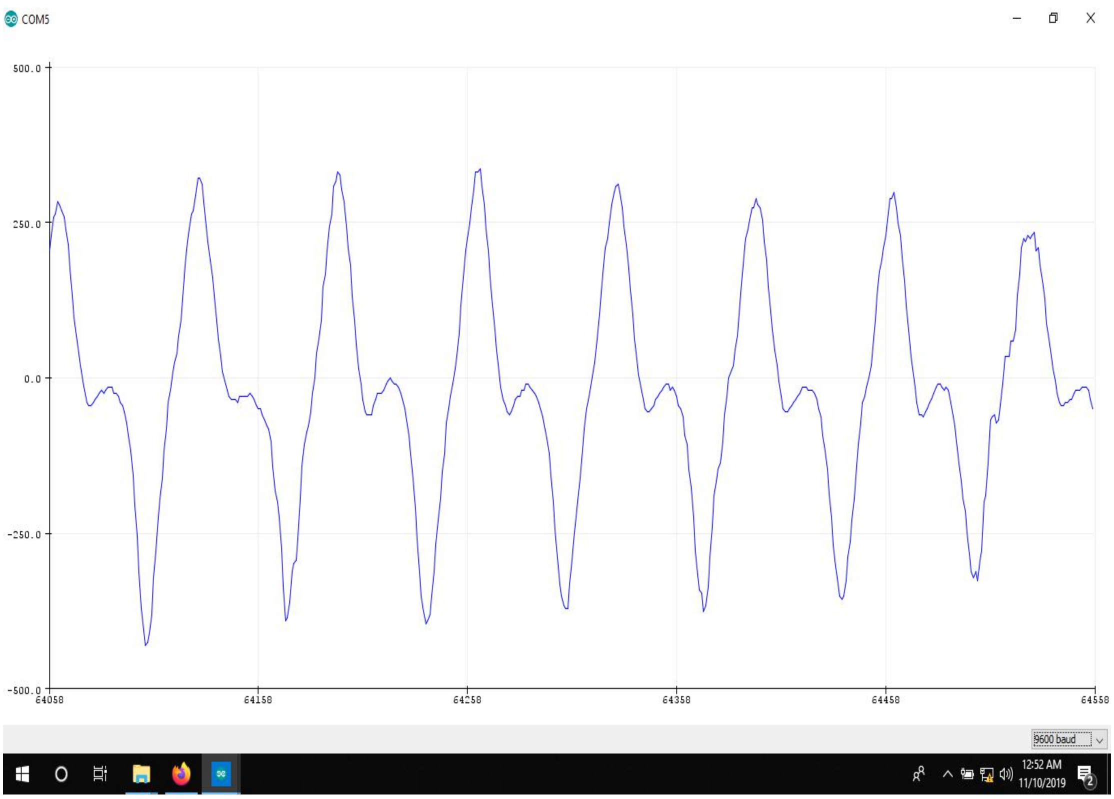
❖ For 500 Turns



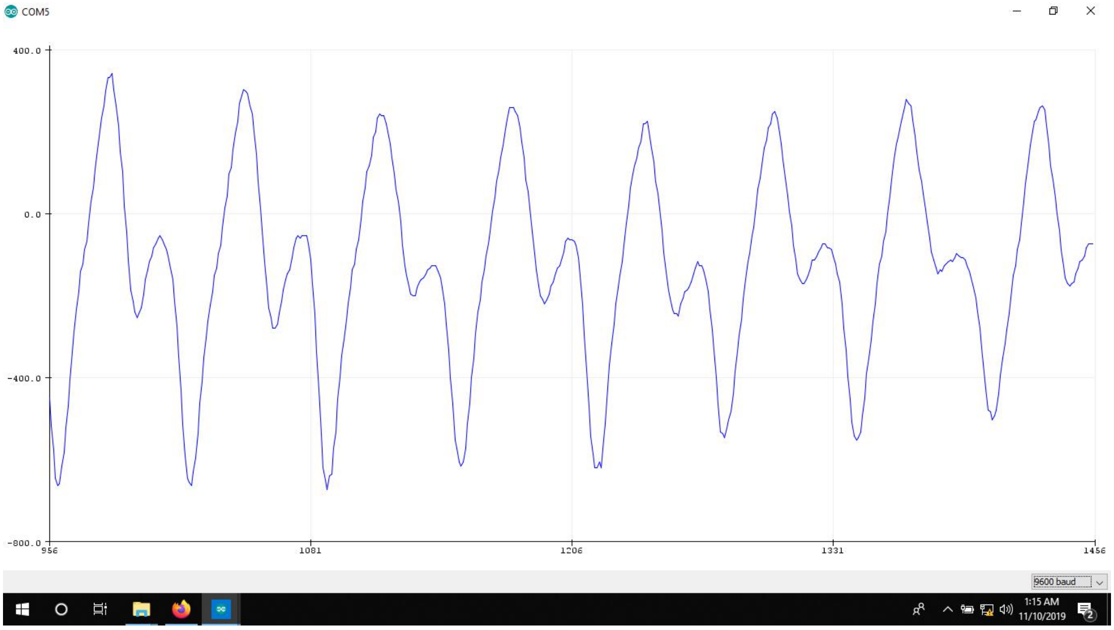
❖ For 600 Turns



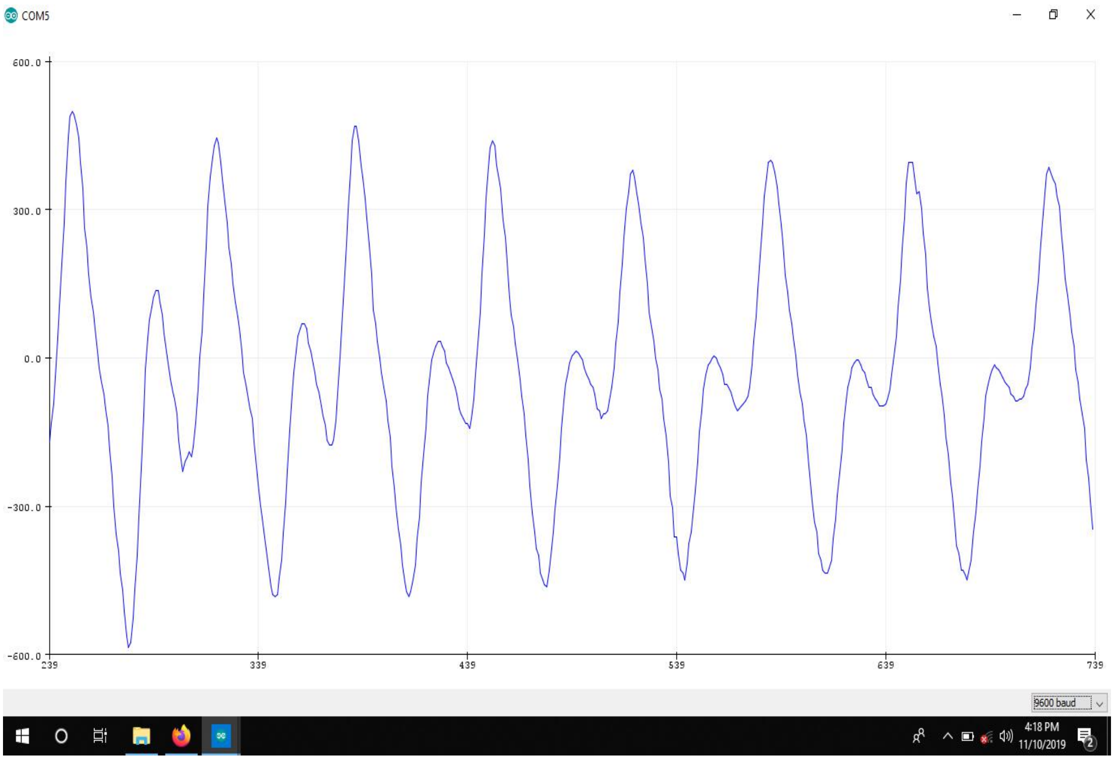
❖ For 700 Turns



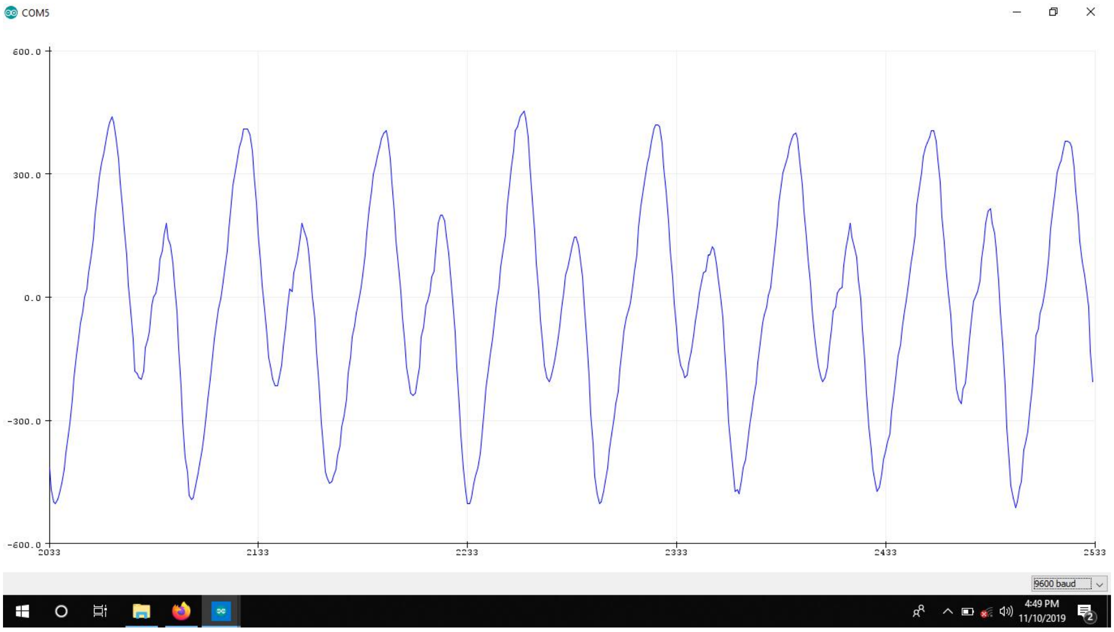
❖ For 800 Turns



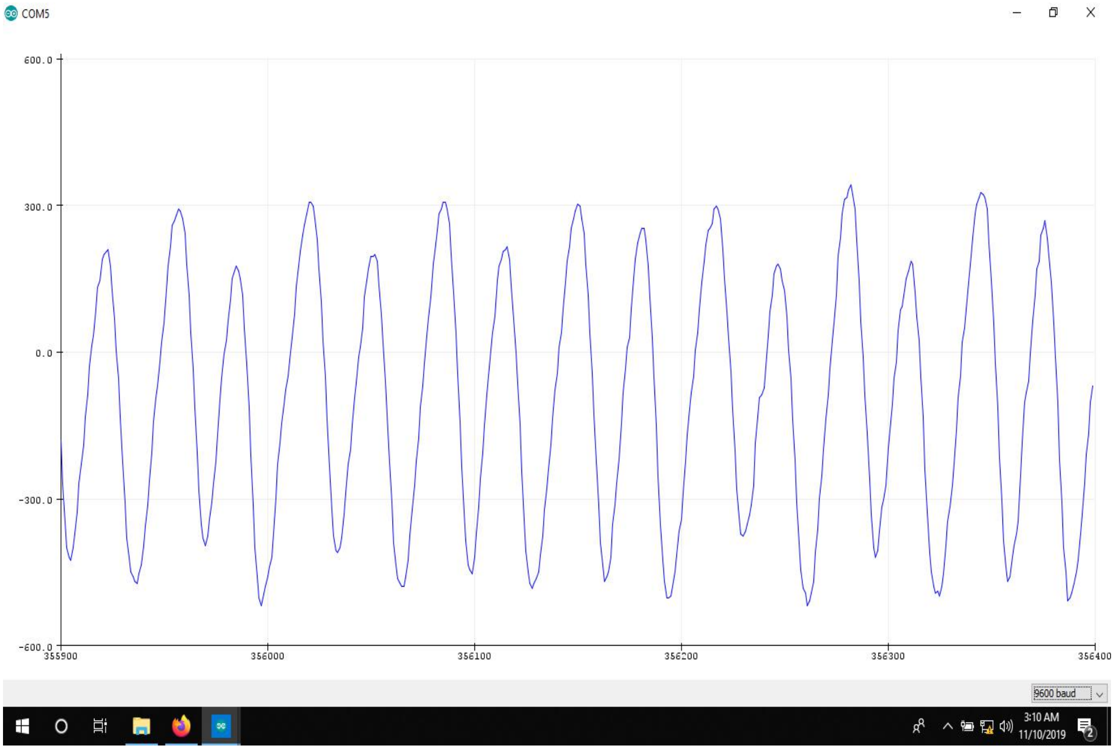
❖ For 900 Turns



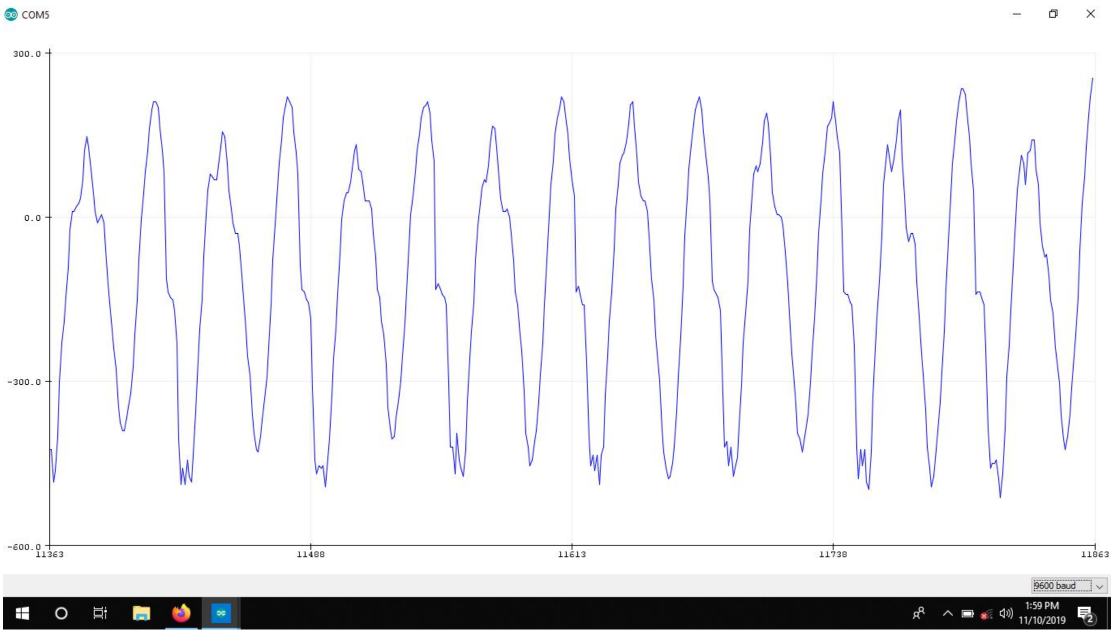
❖ For 1000 Turns



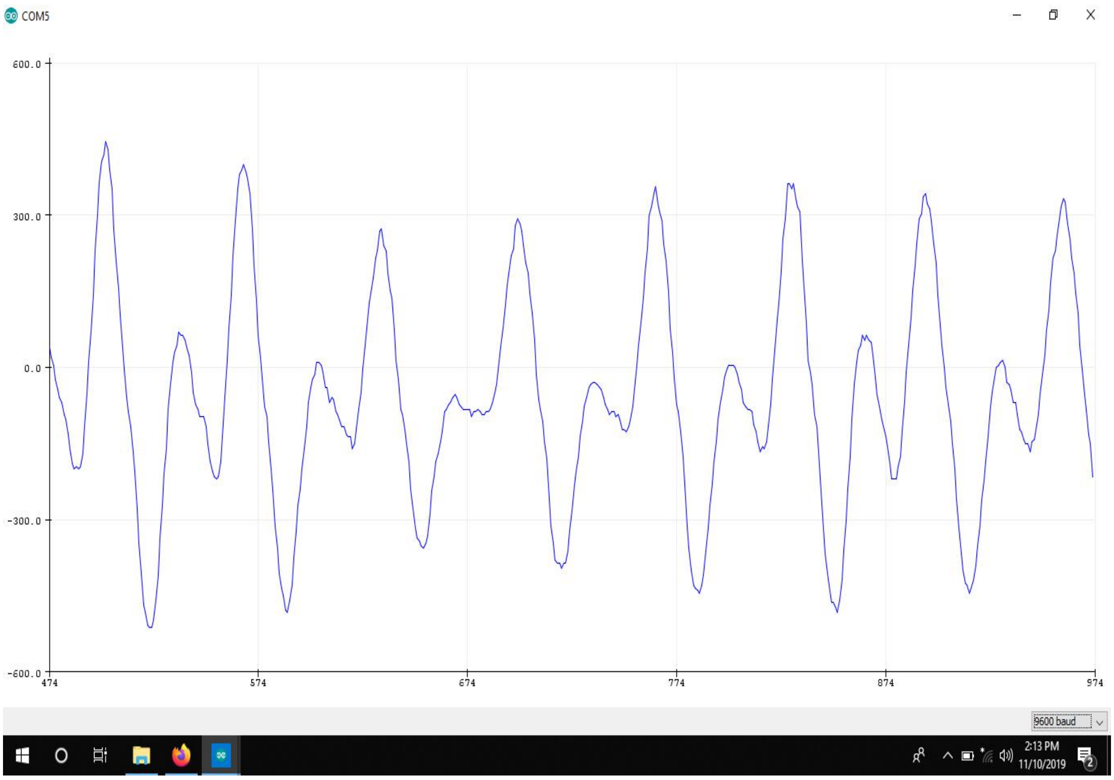
❖ For 1100 Turns



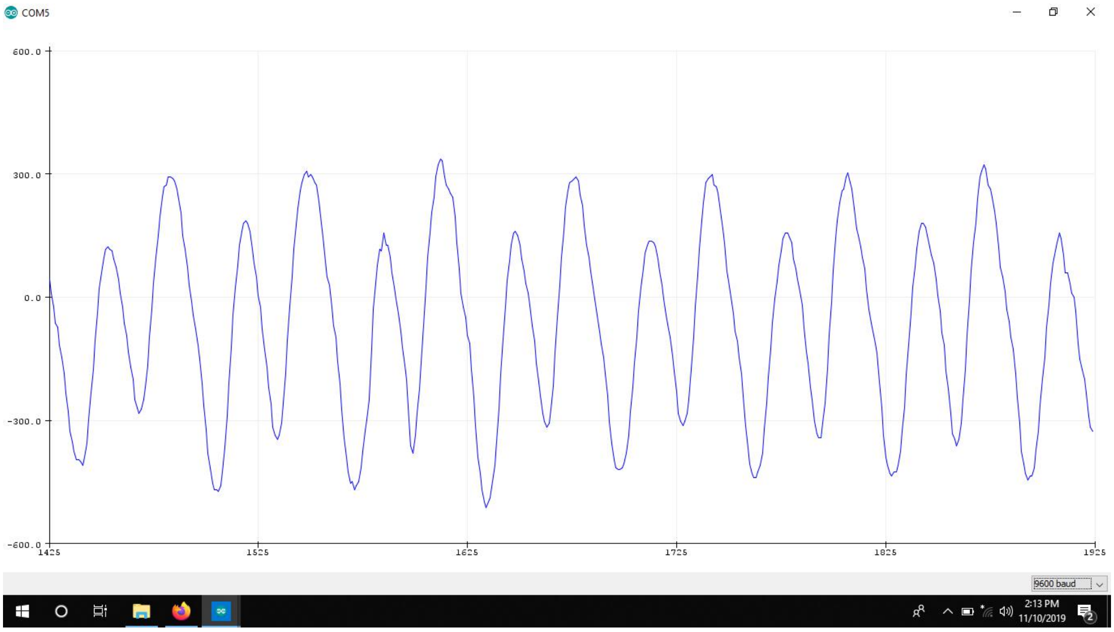
❖ For 1200 Turns



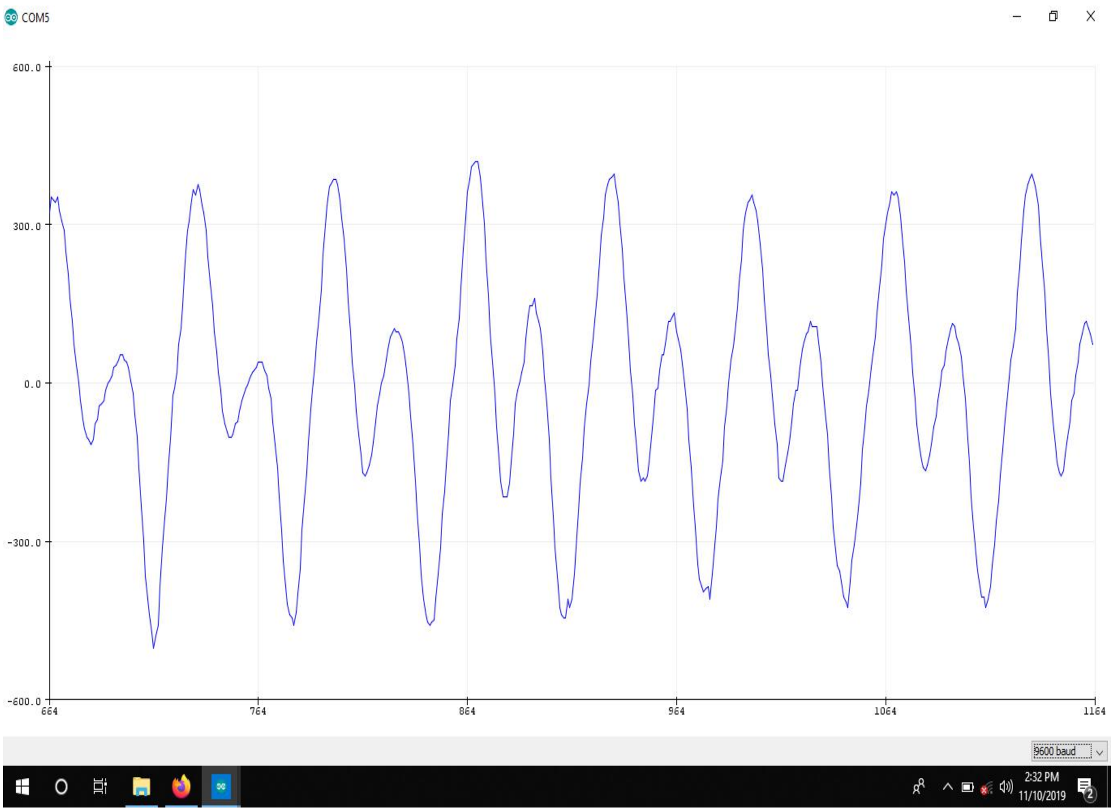
❖ For 1300 Turns



❖ For 1400 Turns

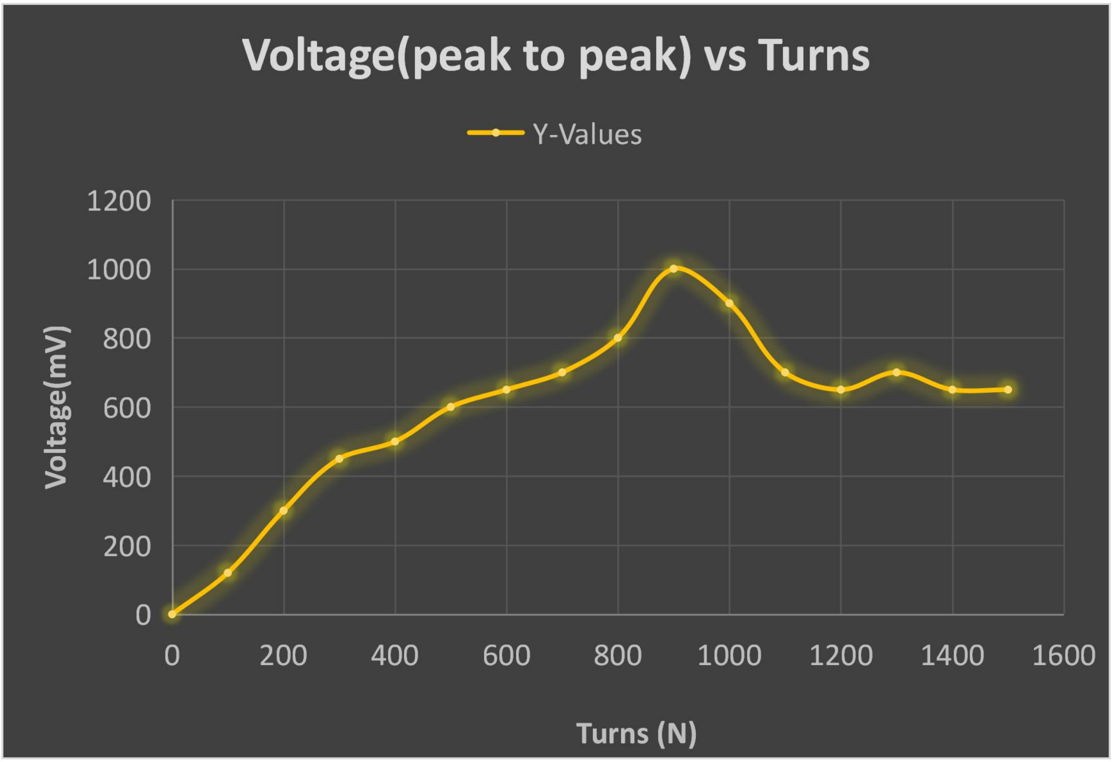


❖ For 1500 Turns



5.1.6 Turnwise peak to peak voltage

Turns	Voltage(mV)
0	0
100	120
200	300
300	450
400	500
500	600
600	650
700	700
800	800
900	1000
1000	900
1100	700
1200	650
1300	700
1400	650
1500	650



This can also be called as Linear generator characteristics.

5.2 Result

In the experiment we got electrical energy (output) from wave energy (input). So, energy has converted two times.

- **Wave energy to Mechanical energy**
- **Mechanical energy to Electrical energy**

5.2.1 Wave Power

The total potential and kinetic energy of an ocean wave [9] can be expressed as

$$E = \frac{1}{2}\rho g A^2$$

wave power can be written as a function of wave height, H.

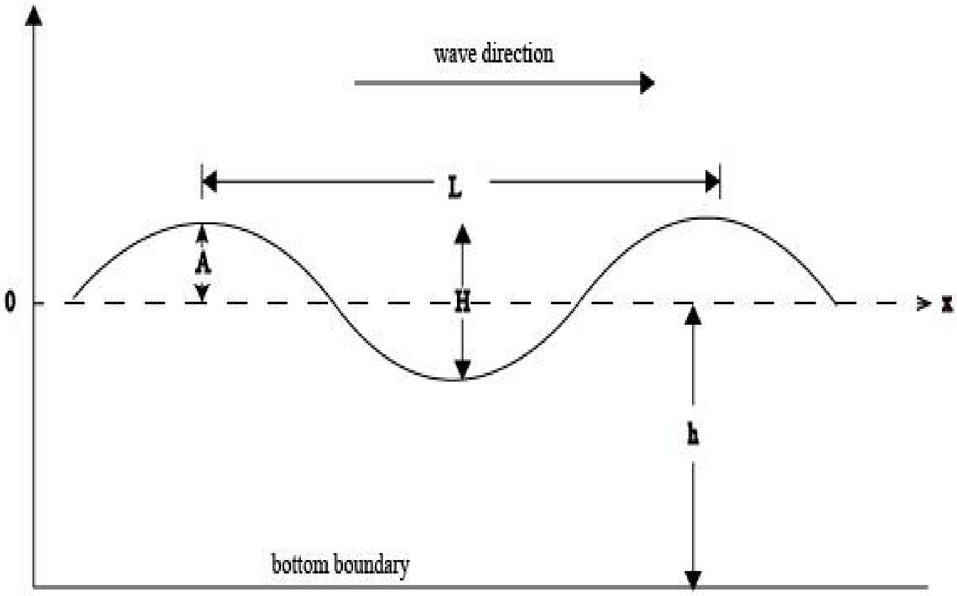


Figure 26: Wave Function

Considering that the wave amplitude is half of the wave height, the wave power becomes,

$$P_w = \frac{\rho g^2 T H^2}{32\pi}$$

Here, for our setup,

T = 30/66 =0.4528 s

H = 6.5 cm = 0.065 m

g = 9.8 ms^{-2}

ρ = 1000 kgm^{-3}

$$P_w = \frac{\rho g^2 T H^2}{32\pi}$$

$$= \underline{0.1865 \text{ W}}$$

5.2.2 Electrical power

Resistance, R = 30 Ω at 900 turns. We will get the maximum Electrical power at 900 turns.

So the electrical power is,

$P_e = VI$

= 1V*(1/30 Ω)

= 0.0333 W

5.2.3 Mechanical Power

Total buoy displacement= 3.25 Cm

Total water height displacement due to wave= 7.5 Cm

Displacement of buoy at one side (positive or negative) from initial position=Total buoy displacement ÷ 2 = 1.625 Cm

Wave amplitude= Total water height displacement ÷ 2 = 3.75 Cm

$\eta_{mechanical}$ = (One side buoy displacement) / (wave amplitude)

= 1.625/3.75

= .433

= 43.3%

Mechanical Power = wave power * $\eta_{mechanical}$

= 0.08075 W

5.2.4 Efficiency

$\eta_{mechanical}$ = 43.3 %

$\eta_{electrical}$ = (electrical output) / (mechanical output)

= (0.0333 W)/(0.08075 W)

= .4124

= 41.24 %

$\eta_{overall}$ = (electrical output) / (wave power)

= (0.0333 W)/(0.1865 W)

= .1787

= **17.87%**

5.3 Saint Martin's scenario

Average wave height at saint martin's island is, H=2.8 m [10]. So the wave power at that location will be,

$$\textbf{Wave power} = \frac{10^3 kgm^{-3} * 9.8ms^{-2} * \frac{30}{66} s * 2.8^2 m^2}{32\,\pi}$$

= 8305 W

= 8.305 kW

If we use our Prototype at Saint martin's island then,

$$\textbf{Electrical power} = \textbf{Wave power} * \eta_{overall}$$

= 8.305 kW * 0.1787

= 1.484 kW

This **1.484 kW** power can be extracted by using a single equivalent unit of our prototype.

CHAPTER 6

6.1 Conclusion

The idea of using the specified criterion for the linear generator is achieved after a thorough study. Through this project a small scale wave energy converter will be used attached closely with a new design of linear generator to produce an efficient power output. The Floating Buoy Technologies will be used as the operating system where the designed new linear generator will be placed as it is small, mobile, inexpensive and efficient power delivery. The design parameters that have been finalized are PMLG tubular type, air-cored stator, moving magnet and radial topology with axial magnet arrangement will be used to in this design. The magnets are tested against two parameters which are EMF distribution and turns distribution. The simulation work and the analysis have been performed and the optimization of design is done in order to achieve the objective. After analyzing the performance of the design it is concluded as a satisfactory one in this relevant area of research.

6.2 Future Work Proposal

The selected prototype can be similarly multiplied and optimized to maximize the performance of the linear generator. The format model has to be analyzed with the same finite factor analysis to find out about the power technology and model efficiency to be in contrast with current linear generators in market.

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