DESIGNING A PROTOTYPE VORTEX INDUCEDVIBRATIONS BASED HYDROELECTRICITY GENERATING SYSTEM

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Degree of Master of Science

Department of Electrical Engineering

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Abstract

With the inevitable concerns on energy crisis and environmental pollution, various types of alternative energy resources such as, hydro, wind, solar, tidal, wave, etc.,havebeen harnessed using various novel technologies. Among all of them vortex induced vibrations (VIV) based hydro energy has identified as one of the most favorable source of energy, which has a betterpotential and the most environmentally benign forms of electricity generation.

Vortex induced vibrations is a technique, which makes linear motions from the water flow.TheVIV based hydro electricity generation system can be operated inlow speed water streams where the turbines cannot be used. Also, the design is cost effective compared to other renewable energy sources.

This research presentsdesigning and implementation of a prototype VIV based hydroelectricity generation technique. The results of the study indicate the capability of generatingelectricity using the VIV based hydro system,and its applicability in low speed streams in Sri Lanka. The VIV based hydroelectricity generation can be identified asone of the mosteffective renewable energy sources for Sri Lanka.

Keywords:*Alternative energy source,Hydro electricity generator,Hydro kinetic energy, Linear generator,Low speed flow,Renewable Energy, Vortex Induced Vibrations, VIV.*

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W.H.M.P.M.Warakaulla

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List of Abbreviations

Abbreviation	**Description**
CFD	Computational Fluid Dynamics
EPRI	Electric Power Research Institute
MREL	Marine Renewable Energy Laboratory
VIV	Vortex Induced Vibrations
VIVHEGS	Vortex Induced Vibrations based Hydro Electricity Generating System

CHAPTER 1

INTRODUCTION

The most challenging problem that the world faces today is low-cost sustainable energy generation. Solving the energy challenge requires tapping into all the available sources of energy and development of the technologies that can generate electrical energy at a competitive cost. It is expected that renewable energy generated in environmentally compatible ways will contribute more towards solving the energy challenge. Under this situation the renewable energy has two great advantages compared to fossil fuels. Firstly, the renewable energy resources contributes minimum in greenhouse gas emissions; secondly, the renewable energy will be the future energy when fossil fuels are spent. The renewable energy resources include solar power, tidal power, wind power, hydropower, wave power, geothermal power and so on. From all above existing renewable energy sources, hydro energy can be considered as one of the most suitable solutions for Sri Lanka according to its geographical facts.

1.1 Background

Hydro energy is the most widely used form of renewable energy source to generate electricity in the world. Different technologies, such as: conventional (dams), pumped storage, run-off river, and tide, have been adopted to harness or utilize the energy optimally. Hydrokinetic energy from currents can be harnessed using turbines or watermills. According to marine renewable energy laboratory (MREL), university of michigan[1], turbines require an average speed of 5-7 knots to be financially viable. In Sri Lanka, there are abundant water streams, which cannot be used for hydroelectricity generation due to their low speeds of less than 3 knots. Therefore, researching on utilizing hydrokinetic energy in low speed flows would bring another dimension to hydro technologies in Sri Lanka. However, such technology has to be environmentally compatible, cost competitive, unobtrusive to people, have high energy density, be scalable, manufactureable, robust to loads, and generate grid-dispatchable electricity.

The phenomenon of vortex induced vibrations (VIV) [2] has become the latest technology to utilize hydro energy, and many researches are being carriedrelated to the topic. Rotational and hydraulic generators are not economical and not efficient in recovering a high energy density from low speed water currents. Application of linear generators to harness energy from low speed water currents using the VIV technology requires more investigation.

1.2 Problem Statement

At present, oil, coal and natural gas is supplying nearly 85% of the world's energy supply. Unfortunately, as they are being depleted fast due to over consumption, we are facing a global energy crisis. As a solution, various types of alternative energy sources like wind, nuclear power, sea waves, hydro, geothermal, biomass, etc. are being introduced. Among them, one of the most favorable alternative energy sources is hydropower, which is a good energy carrier among all renewable energy sources.

Sri Lanka has utilized the available full conventionally extractable hydro power potential as there is no further location to build a reservoir. However, there are plenty of water streams flowing to ocean without utilizing their stored energy. Those water streams have low flow speed and therefore, Vortex Induced Vibrations (VIV) technology can be utilized to harness the otherwise wasted energy.

The goal of this project is to investigate the application of the Vortex Induced Vibrations (VIV) technology to extract energy from low speed water currents. Since VIV make a linear motion, a linear generator has to be used to convert that mechanical energy in to electrical energy. It has been concluded in literature [3], [4] that a linear generator is the best means of recovering energy from VIV convertor efficiently. It is reported that the generator experiences high counter electromotive force causing a non-continuous motion throughout the cycle [5]. The stronger the counter electromotive force is from the generator, the more energy can be harnessed from each cycle, but too much force will disrupt the vortex shedding and take energy away from the process. Onsite customization of the electromotive force is the key in the success of the linear generator. A finite element analysis on the linear generator prototype will allow for total customization and scalability for numerous VIV applications[6].

1.3 Objectives and Scope

1.3.1 Objectives

The goal of this project is to find an innovative solution for the energy crisis by utilizing the hydrokinetic energy in low speed water streams.

The specific objectives are:

- To investigate and identify the design aspects of linear generator.
- To design a prototype for vortex induced vibrations (VIV) based hydroelectricity generator**.**

1.3.2 Scope

- Linear Power Generator

In this research, it is intended to design and implement a small scale prototype of VIV based hydroelectricity generator that would be capable to develop as a commercial product later. In the prototype model permanent magnets are used in the linear generator but, when the generator is applied in commercial purpose, it can be replaced by electromagnets. The prototype would be designed and implemented only for demonstrating purpose. Therefore, durability and strength of the design would not be capable of catering commercial purpose conditions. The focus of the research is on electrical characteristics of the generation technology rather than the mechanical characteristics.

- Power Output

Low rated prototype linear generator would be implemented for demonstrating purposes and the correct operation of the prototype generator would be validated using a lighting circuit.

1.4 Research Methodology

1. Conduct a survey on VIV systems.
2. Identify the required conditions of the water flows to build a vortex hydroelectricity generating system.
3. Locate a suitable site for implementing a prototype of vortex hydroelectricity generating system.
4. Simulate the water flow by using computational fluid dynamics (CFD) analyzing software in order to identify the behavior.
5. Design an appropriate prototype for the water flow at the selected location.
6. Implement the prototype.
7. Fine-tuning the system by identifying the issues arising during the operation.

1.6 Required Resources

- Appropriate water flow with adequate qualities
- Suitable CFD analysis software
- A cylinder of low density high strength material
- Hardware components to build supportive structure
- Permanent magnets
- Copper wires
- Dielectric materials
- Electronic accessories
- Tools and equipment
- Laboratory measuring instruments

1.7 Budget

Table 1.1: Budget

Activity	Budget (LKR)
Implementing the prototype	10,000
Payments for laboratory test equipment	5,000
Total	15,000

CHAPTER 3

ENERGY HARNESS SYSTEM ANDGENERATOR DESIGN

3.1 Pre-feasibility Study

The Vortex Induced Vibrations (VIV) is a modern technology to harness the hydro energyfrom water streams, which has been a popular topic in global research forgenerating electricity[7] - [3]. In this research, it was attempted to apply the VIV technology in Sri Lanka for the first time, whereit necessitated conducting apre-feasibilitystudy. Therefore,river, Gingaga was selected and the water flow speed was measured using a propeller current meter, under the guidance of hydrology gaugestation at Baddegama, Sri Lanka.Figure 3.1gives a schematic of a propeller current meter.

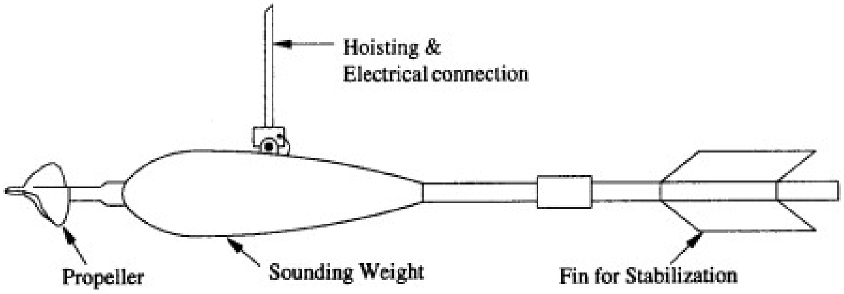

Figure 3.1: Propeller current meter[17]

The velocity of a river is not constant from bank to bank or from the bed to thesurface. Therefore, a number of velocity measurements must be made at differentdepths at intervals across the river. Depending on the depth, more velocity measurementsare made along vertical. Therefore, they the cross section of the river was divided into several sections and the flow speedswere measured. The measurements were taken at 1 feet above the bottom and 1feet below the surface of the stream for each section. Then the mean speed was calculated according to a pre-defined mathematical model used by the hydrology gaugestation.

According to details provided by the hydrology gaugestation, the average speed of the Gingaga at Baddegamaarea is in a range of 0.5ms^{-1}to1.2ms^{-1}.A conventional hydro turbine cannot be used under such low speeds of water flow. However,VIV technology can be utilized inthis type of low speed water streams to produce electricity [3]-[7].

According to the results of the pre-feasibility study, the up-lift force on the cylinderunder water flow speeds in a range of 0.5ms^{-1}- 1.2ms^{-1}needed be analyzed.

3.2 CFD analysis

The forces thatoccur due to the vortex induced vibrations were analyzed through simulations and the Solid Works premium 2013 simulationsoftware was used in the study.Using the simulation studies, parameters of the cylinder were optimized for optimum outputpower.

As discussed in Section 2.1.4, the Reynolds numbershould be in the range of 40 <Re <10^{5}to achieve a usable up liftforce. According to the equation(2.1),Reynolds number depends onfree stream velocity, characteristic length andkinematic viscosity. Therefore, in the simulation,it is necessary to make the following assumptions:

i. The vortex energy harnessing system is operated at 25^{0}C
ii. The flow speed of the water stream is considered as 1ms^{-1}(as per the pre-feasibility study).

The kinematic viscosity, $\boldsymbol{\mu}$ is a constant for a particular temperature, and at 25^{0}C, it is 8.9×10^{-7}m^{2}s^{-1}. By using the equation (2.1), and considering the constraint, 40 <Re <10^5,to achieve a usable up liftforce:

$$40 < \frac{1 \times L}{8.9 \times 10^{-7}}$$

$$L > 3.56 \times 10^{-5}\ m$$

And,

$$10^5 > \frac{1 \times L}{8.9 \times 10^{-7}}$$

$$L < 8.9 \times 10^{-2}\ m$$

Therefore,it can be seen that the characteristic length of the cylinder should be withinthe range of $3.56 \times 10^{-5} m < L < 8.9 \times 10^{-2}\ m$. Then,the CFD simulationswere performed with several characteristic lengths, which are in this range to observe an optimum point.

3.2.1 Analysis of diameter (characteristic length) of the cylinder

In this section, the forces are analyzed by varying the diameter of the cylinder keepingthe length at 1m. Figure 3.2 to Figure 3.5 illustrate the variation of lift forces under cylinder diameters (characteristic lengths) of 1 cm, 3 cm, 5 cm and 7 cm respectively. Results indicate that the lift force is increasing with the increasing cylinder diameter.

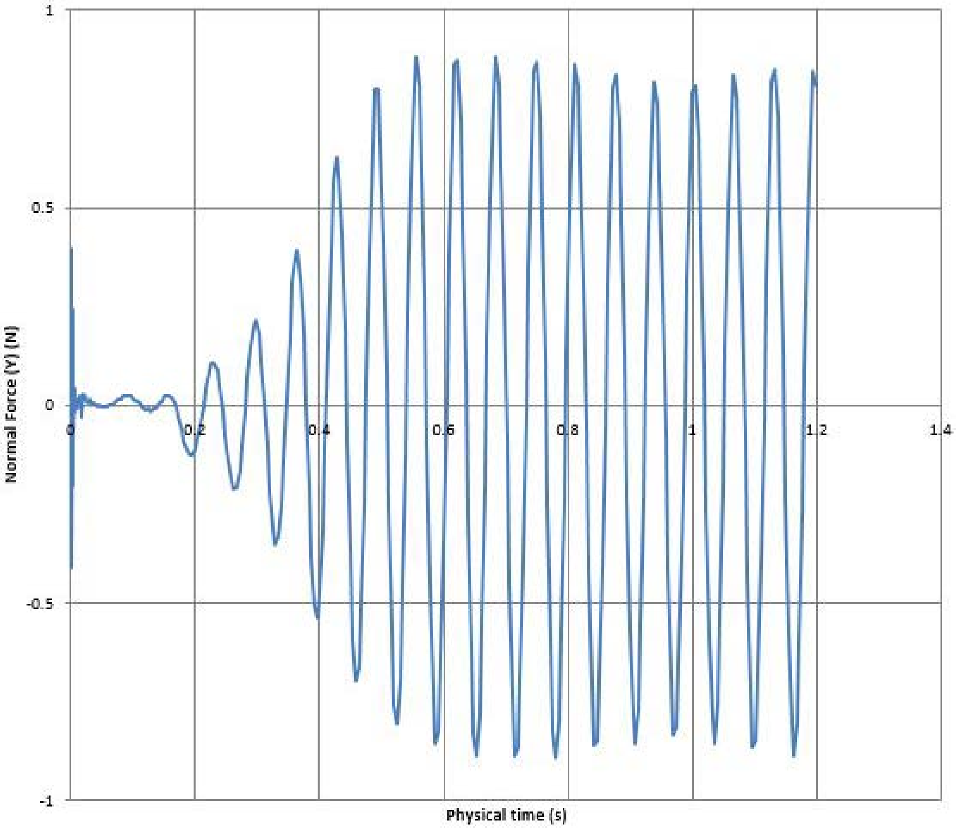

Figure 3.2: Lift force analysis for 1cm diameter and 1m length

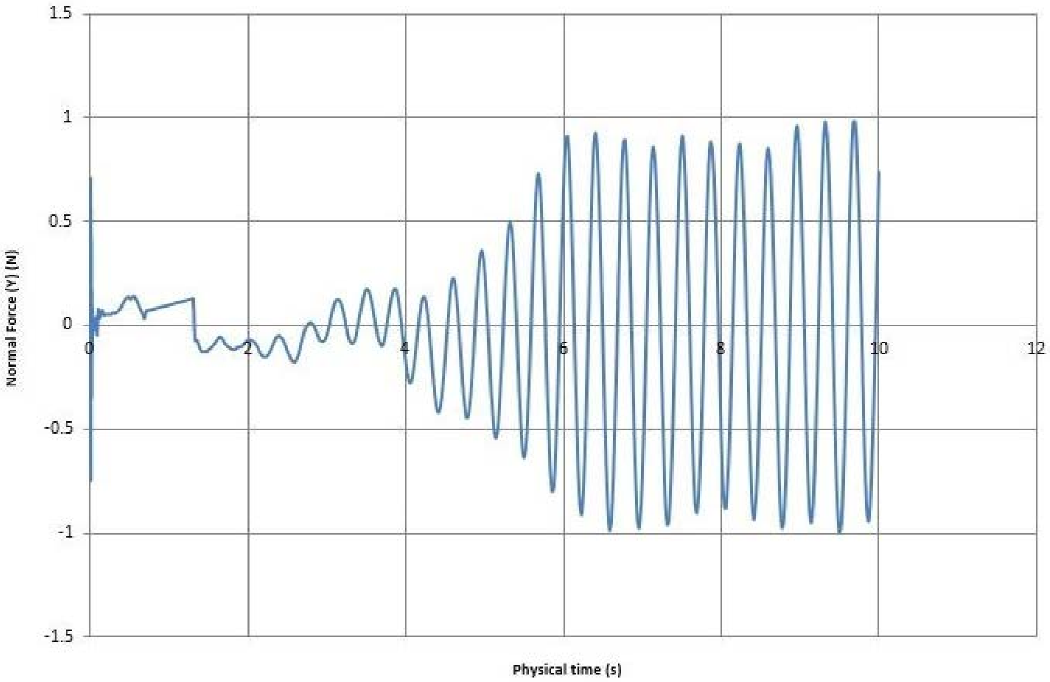

Figure 3.3: Lift force analysis for 3cm diameter and 1m length

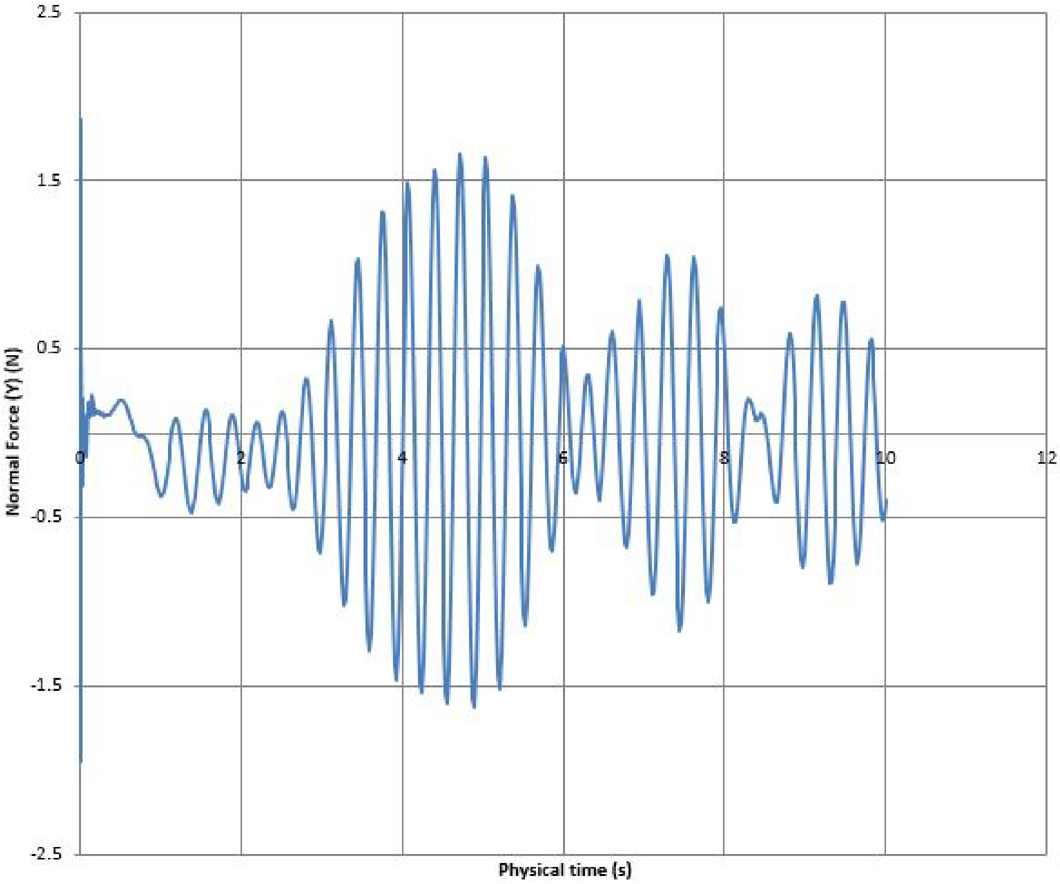

Figure 3.4:Lift force analysis for 5cm diameter and 1m length

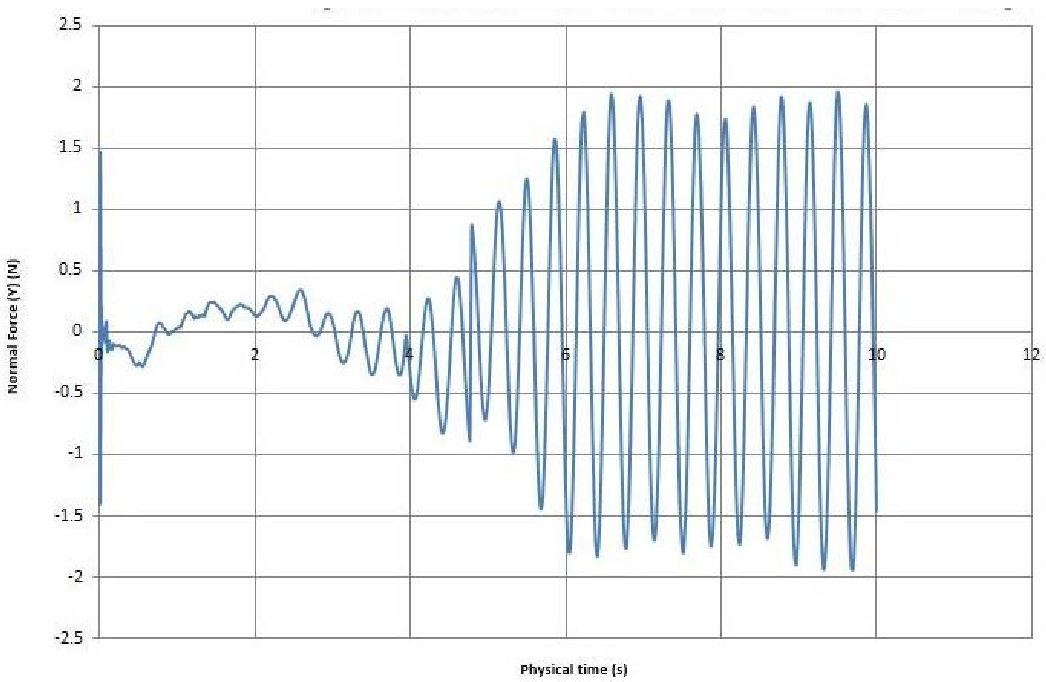

Figure 3.5: Lift force analysis for 7cm diameter and 1m length

When we consider the maximum characteristic length of 8.9×10^{-2}m, then Re = 10^{5}. However,itneed be noted that 1ms^{-1} is an average value of flow speed ofwater. Therefore,in case if the flow-speed ofwater exceeds1ms^{-1}, then the Reynolds number will be greaterthan its maximum value of 10^{5}. Therefore, the characteristic length was selected tobe a middle value like 5×10^{-2} m, which provides relatively maximum uplift force for a 1m cylinder length in a 1ms^{-1}flow speed.

3.2.2 Analysis of length of the cylinder

In this section the forces are analyzed, by varying the length of the cylinder keepingthe diameter at 5cm.

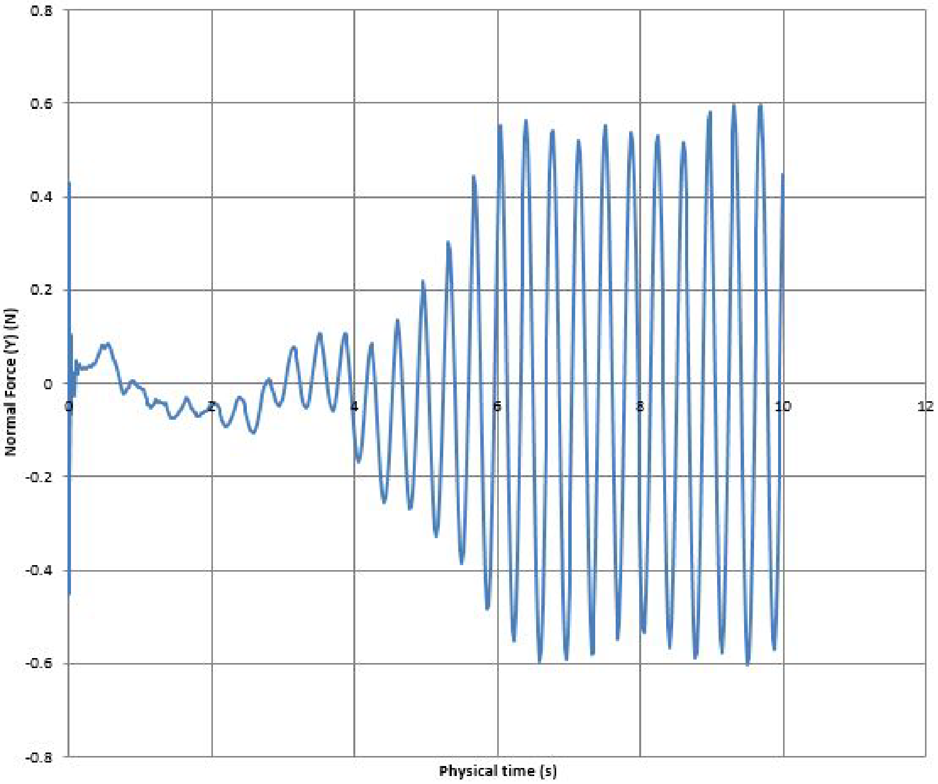

Figure 3.6:Lift force analysis for 5cm Diameter and 30cm length

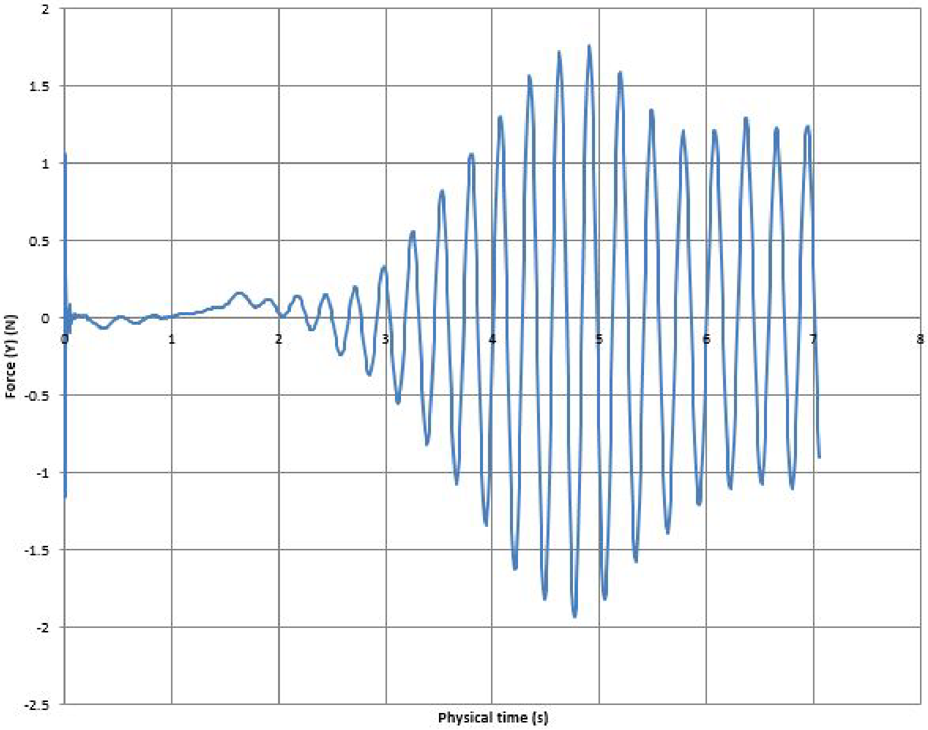

Figure 3.7: Lift force analysis for 5cm Diameter and 60cm length

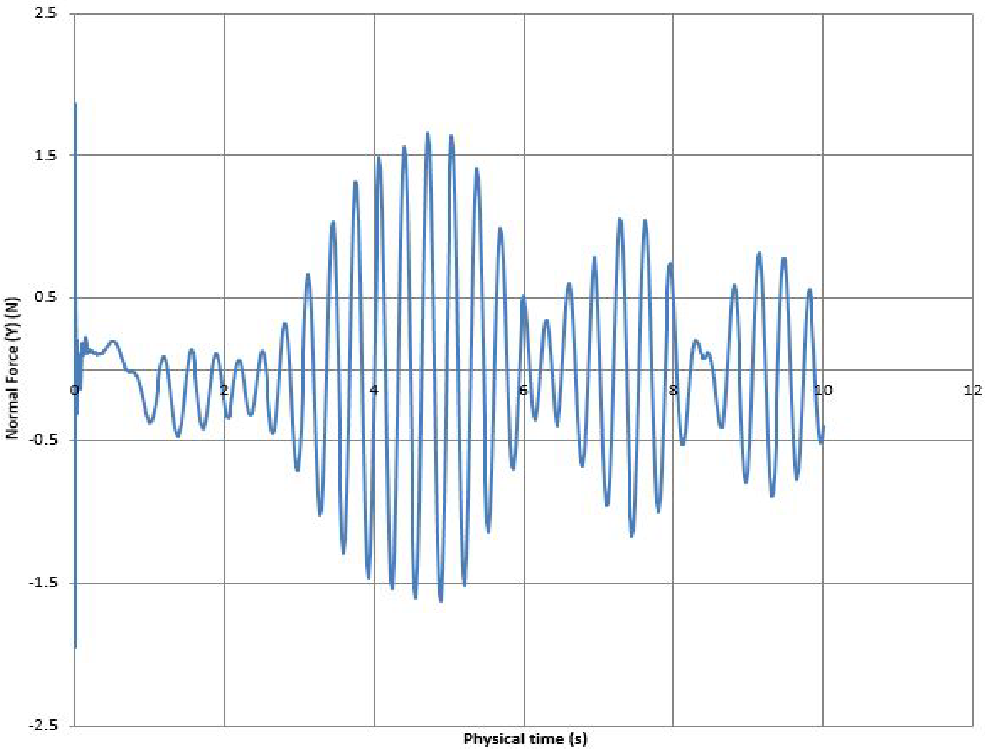

Figure 3.8: Lift force analysis for 5cm Diameter and 1m length

Variation of the lift forces on a 5 cm cylinder having 30 cm, 60 cm and 1 m lengths were illustrated in the Figures 3.6 to 3.8. The results indicate thatthe lift forces are decreasing with the decreasing cylinder length.Therefore,it can be concluded thata cylinder with a diameter of 5cm and a length of 1 m will givea relatively maximumlift force.A maxim cylinder length of 1 mis selected to be used considering the limitations caused by the water stream and the design.

3.2.3 Vortex shedding frequency calculation

The vortex shedding frequency can be found by equation (2.2).

Let, the strouhal number = 0.21[9],

$$St_v = \frac{f_s L}{U}$$

$$0.21 = \frac{f_s \times 5 \times 10^{-2}}{1}$$

$$f_s = 4.2\ Hz$$

3.3 Energy Harness System

3.3.1 Designing of cylinder parameters

- **Diameter**

The speed of the flow indirectly related with the diameter of the cylinder as mentioned in section 3.2.1. Though the consideration is an average value as 1 ms^{-1}, it can be varied among 0.5ms^{-1} to 1.2ms^{-1}. Inrainy seasons these values can be exceeded. So therefore considering all limitations andallowable conditions, decided that the characteristic length (diameter) shouldbe $5x10^{-2}$ m which provides a relatively maximum uplift force according to the analysis data in section 3.2.1.

- **Length of the cylinder**

As the length of the cylinder increases lift force also increases. Propose amaximum length of 1 m to the cylinder as this energy harness system is designed for low speed small water streams since the width has limitations and to makethe system design easy and in a low cost range.

- **Material of the cylinder**

The material of the cylinder does not affect to the lift forces hence it onlydepends on the geometry of the cylinder[9]. When harnessing energy the totalsystems weight need to take in to account as the fluctuating force frequencyshould be nearly same as the natural frequency of the total system[7]-[4]. Naturalfrequency of the system varies with the weight of the system which consistcylinder, springs, moving magnets of the electrical system. Proposed to usea smooth surfaced light weight material to cylinder as many other weights willbe added to the total system.

3.3.2 Designing of damping spring

According to the design, the system with the cylinder is mounted with a spring inorder to make a continuous oscillatory motion of the cylinder. So it is necessary to decidethe spring constant which should be used to the design.

According to the equation (3.1) which regards with simple harmonic motion,[18]

$$m\ddot{y}(t) + c\dot{y}(t) + ky(t) = F(t) \tag{3.1}$$

Where,

$\boldsymbol{m}$ - Total mass of the system $\boldsymbol{k}$ - Spring constant

$\boldsymbol{y}$ - Amplitude of the motion $\boldsymbol{F}$ - External forces

$\boldsymbol{c}$ - Coefficient of Damping

At this stage it can be assume that there is no any external forces on the system.

So therefore,

$$F(t) = 0$$

Then the solution of aboveequation (3.1) can be expressed as,

$$y = A\cos(\omega t) + B\sin(\omega t) \tag{3.2}$$

So we can calculate the amplitude of the simple harmonic motion of the cylinder. Furthermore there is another equation which related with spring constant as given by (3.3).

$$\omega = \sqrt{\frac{k}{m}} \tag{3.3}$$

Where, $\boldsymbol{\omega}$ - Angular frequency of the motion ($\omega = 2\pi f$)

Then according to the above equation (3.3), we can calculate the spring constant.

3.4 Linear Generator

Generator, being the stage which converts mechanical energy to electrical form, playsa major role in this system. Based on the literature review[4]-[14], theoretical knowledge andpracticed experience, the design and construction of commercialpurpose generatorshould be precise and both time consuming and expensive. Yet, in this conceptualproduct it needs to design a generator with a minimumpossible cost.

Also, linear motion characteristics accompanied by the mechanical system highlysuggests that a linear type generator would be more suitable over a rotary type. Thisreduces the additional mechanical losses due to conversion of linear motion to rotarywhile increasing the simplicity of design and construction of the generator. Moreover,this increases the efficiency of the whole system by reducing mechanical losses andeffectively transforming the mechanical energy to electrical form directly at the pointof harnessing[4].

The generator consists of two main parts, the translator and the stator while beinga simple implementation of Faradays law of electromagnetic induction. Here, therole of ferromagnetic core and yoke has been left as a future implementation.

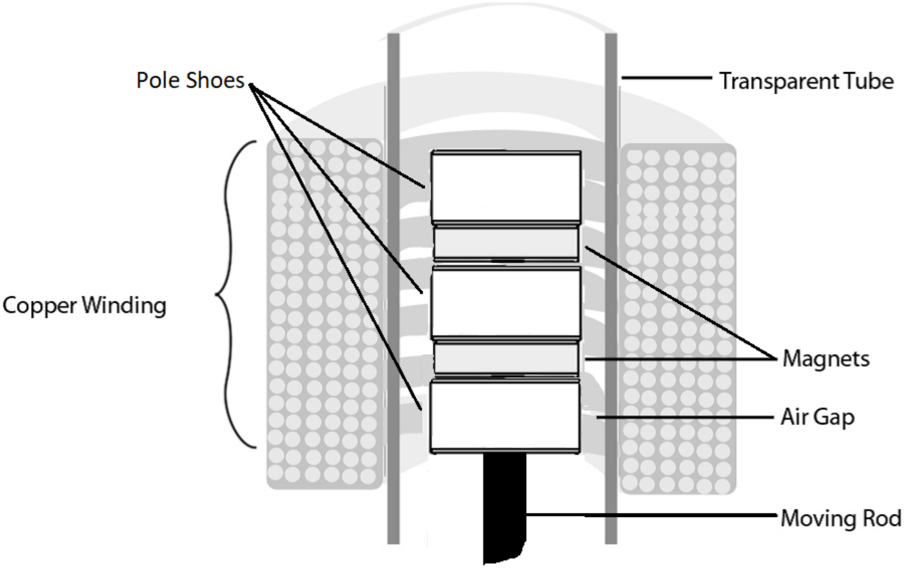

Figure 3.9: Schematic diagram of a cross section of the generator

Figure 3.9 shows a simple schematic diagram of a cross section of the generator.Here the translator moves in vertical direction while the stator being fixed relatively.Since there is no core used, the air gap would be the only medium of flux guidance.And a transparent hollow cylinder is used to hold the winding on purpose so thatthe magnet motion can be seen clearly and the necessary adjustments can be madeaccordingly with testing. According to the literature review three phase generatorhas many advantages compared to single phase[14]. Yet, considering the complexity ofconstructing a ferromagnetic core, it was decided to use a single phase generator overthree phase generator.

3.4.1 Designing of linear generator

In such a situation with more parameters to be concerned, different priorities will be considered in different optimal designs. Here, much attention has paid on efficiencyand the economic cost. Tests on mechanical structure alone without generator, suggestthat the linear displacement of the cylinder is limited to an average of 4cm. Sothe magnet arrangement and magnets were chosen depending on this distance, suchthat a higher flux variation is experienced within this displacement. Also the remanenceand price were considered.

Finally, commercially available 20 mm diameter and 10 mm height twoN52 neodymium magnets were coupled and the vertical flux density variation along thevertical and horizontal axis was measured in air medium and graphed in order tohave a clear idea about flux paths. Figure 3.10 shows the Flux density variation of magnets in horizontal direction and Figure 3.11 shows the Flux density variation of magnets in vertical direction.

Since the generator to be designed is air cored, the flux density variation wouldmatch the variation same as shown in Figure 3.11.

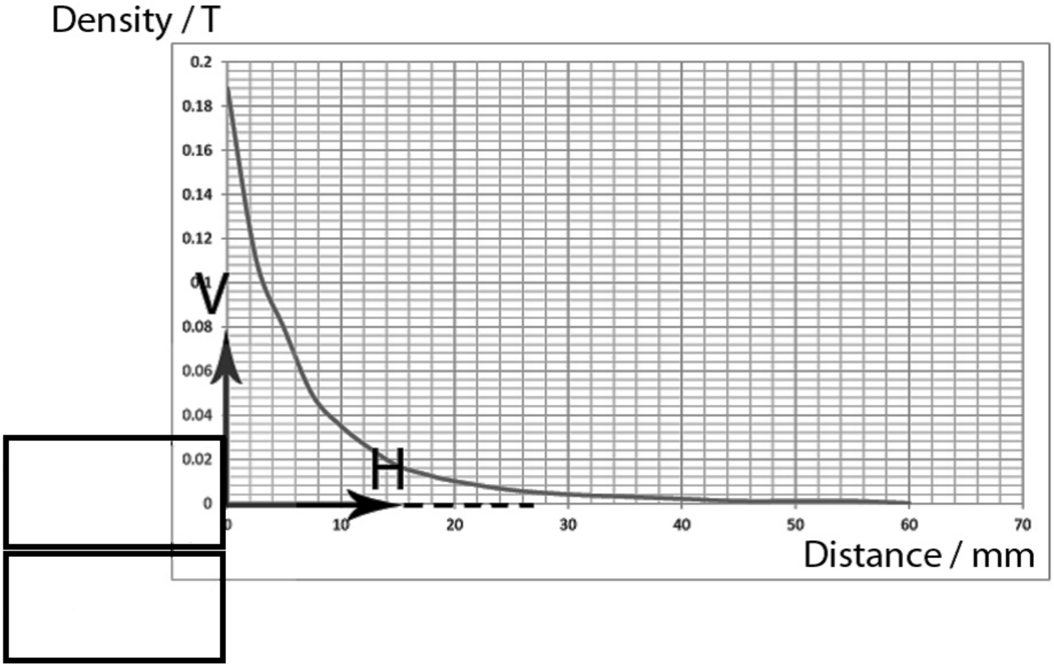

Figure 3.10:Flux density variation of magnets in horizontal direction

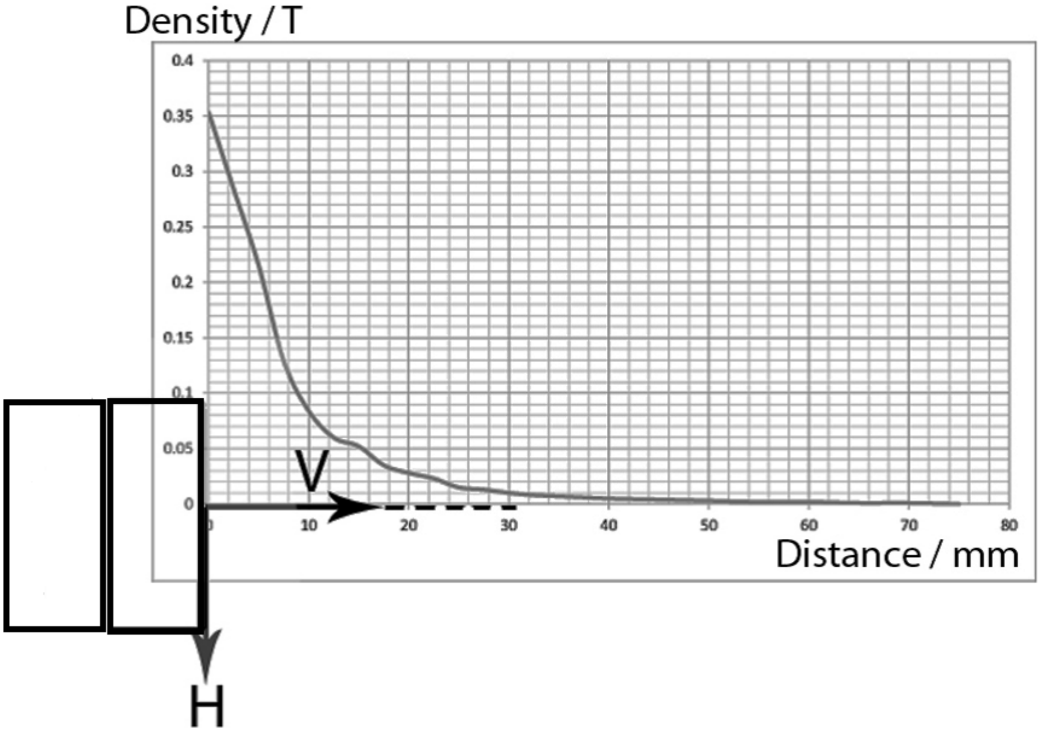

Figure 3.11: Flux density variation of magnets in vertical direction

The gap between magnets and winding was chosen to be 5 mm due to mechanicalconstraints. This gap is composed of 2mm air gap and 3mm plastic material.

The effective flux density end at a distance about 17.5 mm away from the magnetsurface in air medium. And this density shows a distinguish increment at about alength of 10mm away from magnet surface. This marginal distance would be reducedmore due to plastic gap reluctance in the magnetic circuit. Considering these facts,the windings should occupy a radial length of 3.5mm to 5mm maximum. This constraintwould influence on both the number of windings and the copper resistancesof it. However it is expected to have a 2.5V of induced voltage in order to light up the demonstration prototype.

It is assumed that the linear motion is simple harmonic and the magnetic fluxdensity variation follows relationship of the equation (2.17) for the simplicity of calculation.And also the value of $\widehat{\boldsymbol{B}}$ is taken as average of 0.2T, pole width w is taken as 15mm and effective side length of the coil $\boldsymbol{l}$ to be 40mm considering as a worstminimum scenario. The testing of mechanical structure alone has proved that theoscillation movement has an average frequency of 2Hz. Then thelinked flux$\boldsymbol{\lambda}$ in the coil at a time ***t*** would be given by equation (2.18) as described in section 2.2.5,

$$\boldsymbol{\lambda} = \frac{w}{2\Pi} Nl\hat{B} \int_{-\frac{\Pi}{2}}^{\frac{\Pi}{2}} \sin(x - \omega t)\, dx = \frac{w}{\Pi} Nl\hat{B} \sin(\omega t) \qquad (2.18)$$

Here,

$\boldsymbol{w}$ = 1.5×10^{-2}m $\qquad$ $\hat{\boldsymbol{B}}$ = 2.0×10^{-1}T

$\boldsymbol{l}$ = 4.0×10^{-2}m

Then,

$$\boldsymbol{\lambda} = \frac{1.5 \times 10^{-2}}{\Pi} \times N \times 4.0 \times 10^{-2} \times 2.0 \times 10^{-1} \sin(\omega t)$$

$$\boldsymbol{\lambda} = \frac{12 \times 10^{-5}}{\Pi} \times N \sin(\omega t)$$

Further, induced voltage can be given by equation (2.19) as in section 2.2.5,

$$e = -\frac{d\boldsymbol{\lambda}}{dt} = \omega \frac{w}{\Pi} Nl\hat{B} \cos(\omega t) = 2fwNl\hat{B} \cos(2\Pi f t) \qquad (2.19)$$

$$e = 2 \times 2 \times 1.5 \times 10^{-2} \times N \times 4.0 \times 10^{-2} \times 2.0 \times 10^{-1} \cos(2\Pi \times 2t)$$

$$e = 48 \times 10^{-5} N \cos(4\Pi t)$$

Here the number of winding should be decided given the priority for optimizing themaximum flux linkage and minimum copper resistance. As the number of windings(***N***) increase the flux linkage would be maximized according to above equation. Hence the induced voltage would also be increased. Yet, asthe number of windings is increased keeping the total volume of winding constant dueto the limitation of windings occupied radial length mentioned above, the windingcable cross sectional area (***S***) would be reduced. And also the copper resistance ofcore is given by,

$$R = \rho \frac{L}{A} \qquad (3.4)$$

So, resistance of windings (***R***) and number of windings (***N***) have a relationshipsuch that as ***N*** is increased, ***R*** would also be increased. Yet, what is expected is tomaximize ***N***as many as possible while keeping ***R*** very low in order to have a muchvoltage and power efficiently. In order to have a maximum of 2.5V, it is required to have 5208 windings.This is according to the worst case andso many windings in such a smaller space would mean a large amount of resistance,high voltage drop and copper loss. Hence as a tradeoff between induced voltage andcopper loss, value ***N*** is selected to be 4000.

The translator and the stator winding of theconstructed linear generator are shown in Figure 3.12 and Figure 3.13 respectively.

Figure 3.12: Translator of the constructed Linear Generator

Figure 3.13: Stator winding of constructed Linear Generator

The Linear Generator was designed by considering the parameters of mechanical designoutput in order to optimize the mechanical power in to electrical means. TheImplemented two identical generators shown in Figure 3.14 for the demonstration.

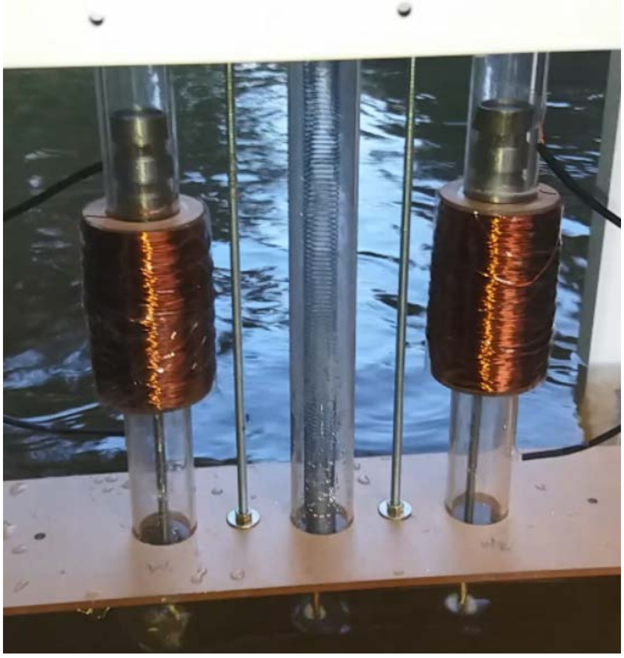

Figure 3.14: Implemented two identical generators

Following figure 3.15 illustrate the design summary for linear generator using a cross sectional schematic diagram of the same.

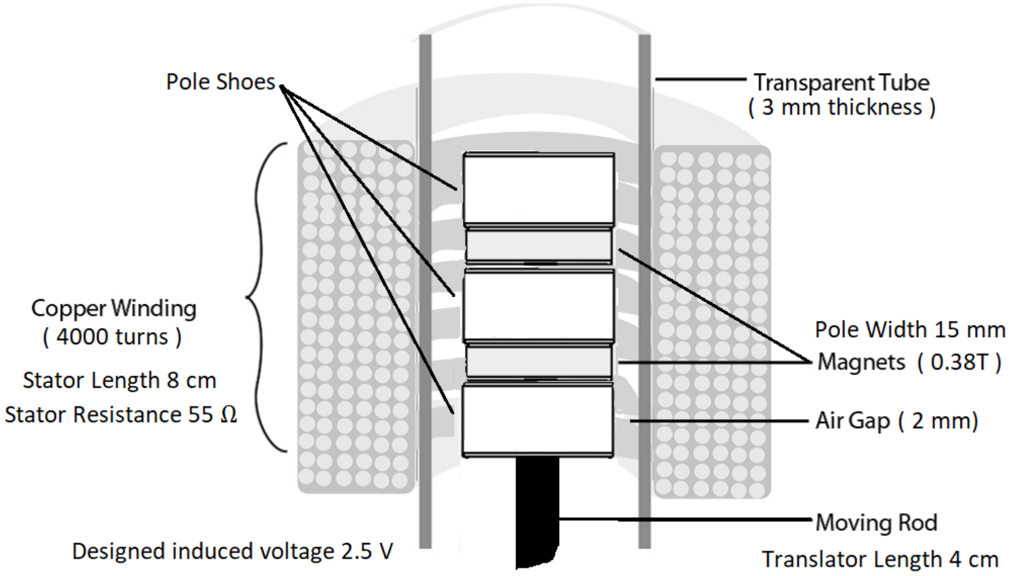

Figure 3.15: Design Summary for linear generator

The specifications of a generator is as following Table 3.1.

Table 3.1 : Generator Parameters

Parameter	**Value**
Remanence	0.38T
No. Of turns	4000
Stator resistance	55Ω
Stator length	8cm
Translator length	4cm
Air gap	2mm
Designed induced voltage	2.5 V
Pole width	15 mm

CHAPTER 4

PROTOTYPE ASSEMBLING AND TESTING

4.1 Prototype Design and Assembling

In order to achieve thegoal of constructing a prototype design to harvest vortexenergy, two design structures were made. It was needed to move from the first design to a second one due tofew of practical difficulties occurred at the prototype level implementations and finally the second structure was chosen as the design for assembly at prototype level.

4.1.1 Mechanical Structure Design - I

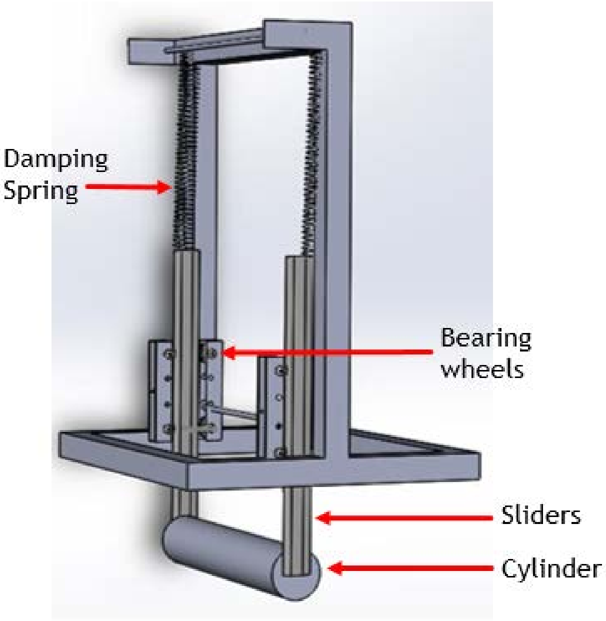

Figure 4.1: Structure Design I

The above Figure 4.1 shows the first design which was made for harvesting vortexenergy and to convert it to mechanical energy. The basic specifications of the system are given below.

- Length of the cylinder- 1m
- Diameter of the cylinder - 5cm

Of course, this is a better design for such system for a power plant of vortex hydro energy. Even though it seems such a way,after assembling of aforesaid design structure,it was observed that there are few issues persist in the structure when it is operating. The majorissue that encountered was the high friction between two sliders and the bearing wheels.To achieve it as a frictionless system is much complicated and it is needed to use highexpensive components. Also it was a design which involve bulky/ heavy construction, consideration of a prototype level implementation. Further, it is very complicated to achieve the stability in water due to the floating of the aforesaid mechanical structure. Therefore it was needed to move to another design structure in order to achieve theresearch ambition under the prototype levelimplementation.

4.1.2 Mechanical Structure Design - II

According to the above mentioned reasons/difficulties,it was designed a simple mechanical structure as design II in ordertoharvest vortex energy by standing on prototype level. The following Figure 4.2 showsthat structure design.

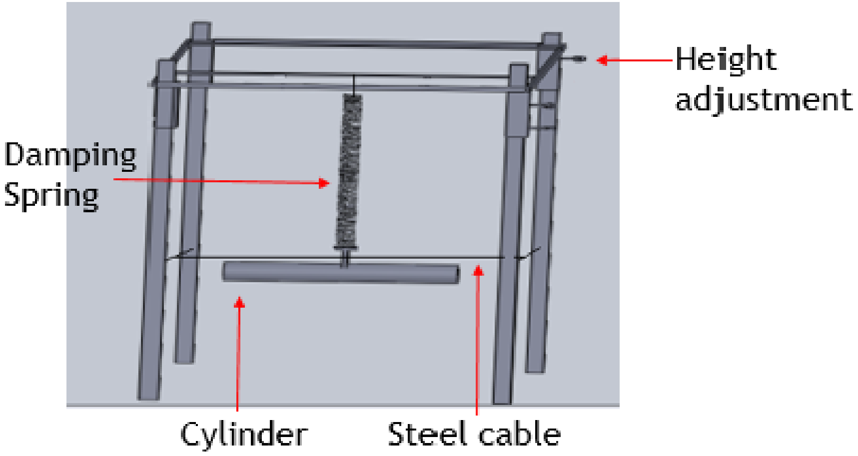

Figure 4.2:Structure Design II

The above shown structure is mounted on a steel frame and it is made with abilityto adjust the height of the system. The cylinder of this system is immersed in thewater and a steel cable has used to balance the drag force occurred on cylinder. And,that cylinder is mounted elastically using a spring damping system along with aneffective energy harness mechanism (damper) attached to it. Further the cylinder in thesystem is constrained to move only in the vertical y-direction.

The basic specifications of the system are given below.

- Length of the cylinder- 30cm
- Diameter of the cylinder - 5cm
- Mass of the cylinder - 1.5kg
- Spring constant - 109 N/m

4.1.3 PrototypeDesign for Assembly

In order to achieve the research ambition as aprototype level implementation, above described design II was selected due to the simplicity of construction together with lower implementation cost.

Following Figure 4.3 shows the finalized prototype level design as a combined view of the mechanical structure design with two identical linear power generators.

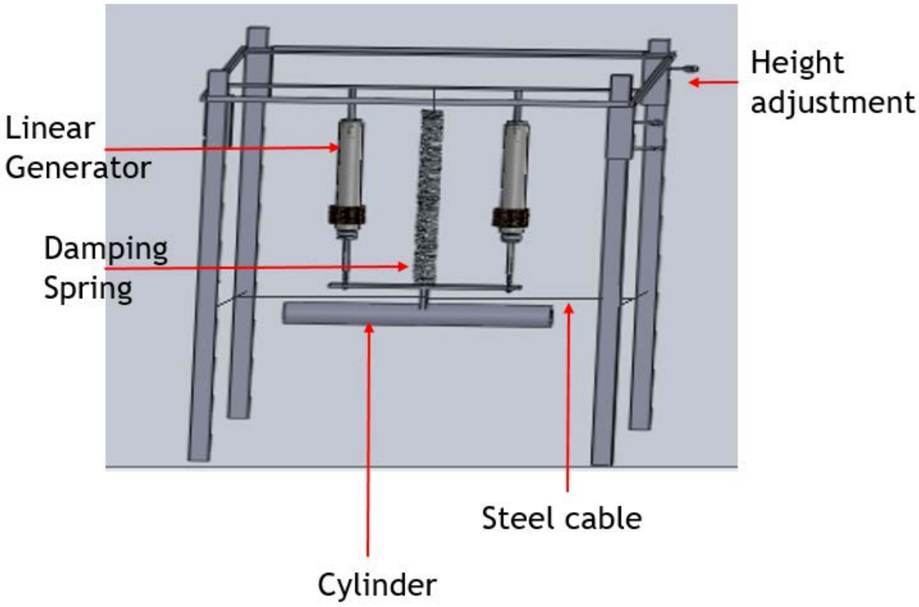

Figure 4.3: Prototype design for assembly

The constructed prototype is shown in Figure 4.4 below as in front and side views.

Figure 4.4: Front and Side view of Constructed Prototype

As separation of the boundary layer begins to take place on the surface of the body, a pressure variation results along the circumference of the cylinder, which causes the cylinder to oscillate. And two linear generators are mounted on cylinder in both sides of spring which convert the mechanical energy to electrical energy. The design/formation of the generator has described at a prior section of this document.

4.2 Testing of the system

After fixing above system the testing was done in a water stream with a water flowspeed of 0.4 ms^{-1}. And it should be mentioned that the water flow speed in theupper layer of the water level is higher than in depth. So it was tested the system byimmersing the cylinder in the upper layer of the water level of the stream.

In thisstage so many experiments were done by changing the parameters such as the lengthof the cylinder, diameter of the cylinder, mass of the cylinder and spring constant.And found optimal design parameters for this prototype design. Finally it wasable to achieve about 4cm amplitude of cylinder vibration as an average from this system.

Furthermore, as per the mechanical system oscillatory input, the electrical output measuredat the linear generator’s stator terminals of each generator was observed as in Figure 4.5.

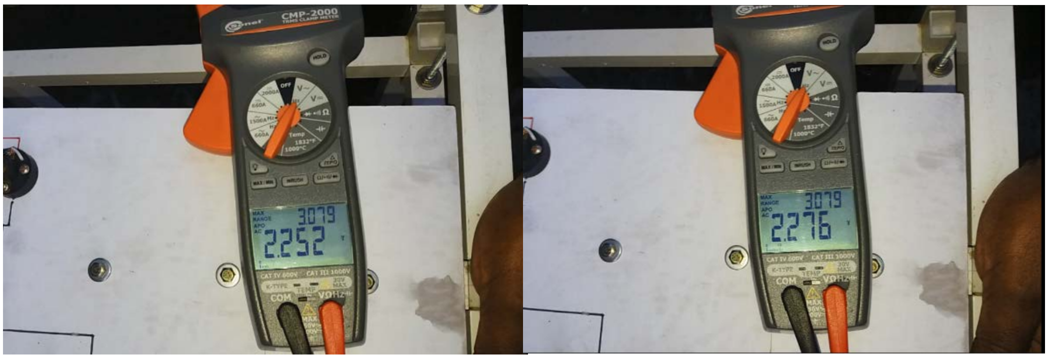

Figure 4.5:Linear generator output

CHAPTER 5

CONCLUSION AND RECOMRNDATIONS

In this research of utilizing vortex hydro energy from a linear generator, it was madetwo mechanical structures for energy harnessing. Experiments were carried out from both thesesystems in a same water stream. According to those experiments the realization was that the first design is not suitable for such prototype design due to its friction and complexityof the design. But it should be mentioned, that system is very suitable for a power plantby reducing the friction and its complexity. The second design is simple and ithelpedto success this concept in prototype level as a low cost implementation.

This vortex hydro energy harnessing system is tested in a water stream withwater flow speed of 0.4 ms^{-1} approximately. Therefore it can be concluded that, thoselow speed water streams around Sri Lanka provide sufficient opportunities for vortexhydro energy utilization. There are plenty of locations in Sri Lanka which are moresuitable for establishment of a vortex hydro energy power plant. However in this case,it is necessaryto consider about the feasibility of construction of a power plant in those locations.And It should mentioned that the springs, natural frequency of cylinder, magnet typeand their strength and the coil winding on the stator, create major effect to the poweroutput of the energy harnessing system[4].

5.1 Power output of the system

In this research work, there are two identical linear generators included in the system, which are used to generateelectricity form a single mechanical system. So the generator efficiency makes a giganticinfluence to the total power output of the system. According to the system capability,it is recommended to increase the number of generators in order to improve the electrical poweroutput where necessarily.

Duly consideration of the testing results of the prototype is being discussed here, it can be calculated the Total system efficiency/Power conversion ratio of the system as follows,

Harness power from Vortex Induced Vibrationsbased Hydro Electricity Generating System (VIVHEGS) is given by equation (5.1);

$$P_{VIVHEGS-harn} = VI \tag{5.1}$$

Where,

$\boldsymbol{V}$ = Induced Voltage @ VIVHEGS
$\boldsymbol{I}$ = Induced Current @ VIVHEGS
Since the VIVHEGS is consisting with two linear generators,

$$P_{VIVHEGS-harn} = P_{VIVHEGS-harn-1} + P_{VIVHEGS-harn-2} \tag{5.2}$$

Where,

$\boldsymbol{P_{VIVHEGS-harn-1}}$ = Harness power from linear generator 1

$\boldsymbol{P_{VIVHEGS-harn-2}}$ = Harness power from linear generator 2

Furthermore, due to the identicalness,

$$P_{VIVHEGS-harn-1} = P_{VIVHEGS-harn-2} \tag{5.3}$$

Then,

$$P_{VIVHEGS-harn} = 2P_{VIVHEGS-harn-1} \tag{5.4}$$

And,

$$P_{VIVHEGS-harn} = 2V_1 I_1 \tag{5.5}$$

Where,

$\boldsymbol{V_1}$ = Induced Voltage @ linear generator 1
$\boldsymbol{I_1}$ = Induced Current @ linear generator 1

According to the experimental data,

Average output voltage of a linear generator ($\boldsymbol{V_1}$) = 1.3V

Stator winding resistance of a linear generator ($\boldsymbol{R_1}$) = 55Ω

Also, the maximum output can be gained when the internal resistance is same as the circuit resistance. Therefore by using equation (5.5),

$$P_{VIVHEGS-harn} = 2 \times 1.3 \times I_1$$

Using,

$$V = IR \tag{5.6}$$

$$I_1 = \frac{V_1}{R_1} \tag{5.7}$$

Then,

$$P_{VIVHEGS-harn} = 2 \times 1.3 \times \frac{V_1}{R_1}$$

$$P_{VIVHEGS-harn} = 2 \times 1.3 \times \frac{1.3}{55}$$

Therefore the harness power from the VIVHEGS is,

$$P_{VIVHEGS-harn} = 0.061 \text{ W}$$

Secondly the Power in the fluid is given by equation (5.8)[7];

$$P_{Fluid} = \frac{1}{2}\rho U^3 \mathcal{D}\mathcal{L} \tag{5.8}$$

Where,

$\boldsymbol{\rho}$ = Flow density (1000kgm$^{-3)}$

$\boldsymbol{U}$ = Flow stream velocity (0.4ms$^{-1)}$

$\boldsymbol{D}$ = Cylinder diameter (5cm)

$\boldsymbol{L}$ = Cylinder length (30cm)

Then,

$$P_{Fluid} = \frac{1}{2} * 1000 * 0.4^3 * 0.05 * 0.3$$

Therefore the Power in the fluid is,

$$P_{Fluid} = 0.480 \text{ W}$$

Finally the Total system efficiency/Power conversion ratio of the system can be defined as equation (5.9);

$$\eta = \frac{Harness\ power\ from\ VIV\ Generating\ System\ (P_{VIVHEGS\ -harn})}{Power\ in\ the\ fluid\ (P_{Fluid})} * 100\%[7] \qquad (5.9)$$

$$\eta = \frac{0.061}{0.480} \times 100\%$$

Therefore, Total system efficiency/Power conversion ratio of the system is,

$$\eta = 12.71\%$$

As per the literature survey, one of feasibility study [7]which was carried out at University of Michigan has predicted that the viable efficiency of a VIV generating system is within the range of 22% -37%. But considering the existing experimental data for research being discussed here, the achieved efficiency of 12.71% is for a 0.4ms^{-1} of water flow speed approximately.Further, the misalignment of the translator of the linear generator due to drag force at the cylinder surface has badly effected to reduce the efficiency of the prototype.

Soas a conclusion,one generator generates0.03W of power output in this prototype design. Therefore, when this concept is improved for a large scale power plant it could be able to achieve considerable power output since this designcomes withmodular, flexible and scalable implementation[7].

However the power output is mainly depend on the harnessing efficiency of the system and the flow speed in the water stream. Therefore it is necessary to pay attention for those things when implementing large scale VIV based hydro energy power stations.

CHAPTER 6

LIMITATIONS AND FUTURE WORKS

The prototype is implemented in a small canal which having a comparably lowwater flow speed in a paddy filed, where the power output from the vortices are very low. Theprototype need to be tested in a water stream where the speed is high and thegenerator output need to be observed and by taking the decisions on observations,improvements on mechanical design and generators should be done with a suitable power electronic converter.

Also, as per the water resource conditions to achieve a significant level of output powerwhere electricity can be generated at the upper layer of the water stream is utilized wherethe speed is high. By using a water stream having relatively higher speed, experimentson prototype needed to be done further at different levels of the water stream wherethe speed is at a considerable value to make power output.

6.1 Mechanical system

According to the experiences which are gathered during the experiments with themechanical system, it was realized that the design I is some kind of complex and highexpensive design. That mentioned complexity and expensiveness have become due tothe friction and stability of the system. But when implementing this VIV concept in a power plant, that design I is suitable rather than design II due to its capability forlarge scale structure in design I.

Therefore as a future improvement, the design I can be developed by mitigating aboveoccurred problems such as friction between the sliders and guiders which made fromwheels. And in that design, the drag force on the cylinder is cancelled by the sliderguiders. So the sliders and the slider guides should be totally frictionless for optimumoutput. Further those two springs are used to continue the cylinder vibrations whichoccurred due to VIV.

Therefore for a vortex hydro energy power plant, the design I is more suitable andit should be developed for a usable condition to get optimum output as a futureimprovement of the mechanical system. The following Figure 6.1 shows the structure ofthe total system of design I.

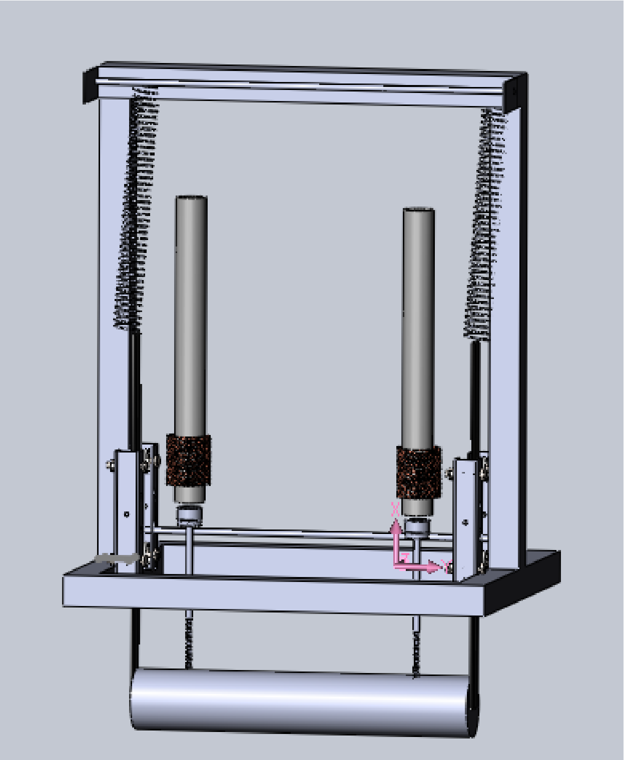

Figure 6.1: Total System of Design 1

In addition to improving this mechanical design, a frequency optimization can be done to get a maximum output from theenergy harness system. During the experiments it was observed that the vortex shedding frequency is varying and so the natural frequency of cylinder mechanism shows a little deviation from that vortex frequency. Therefore as an improvement, a mechanism can be introduced to minimize that frequency deviation according to the changing vortex shedding frequency.

6.2 Linear Generator

Generator need to be constructed using an iron core where the output will be higherthan an air core where magnetic field will rise up. Difference of magnetic field between air core and iron core shown in below figure 6.2.

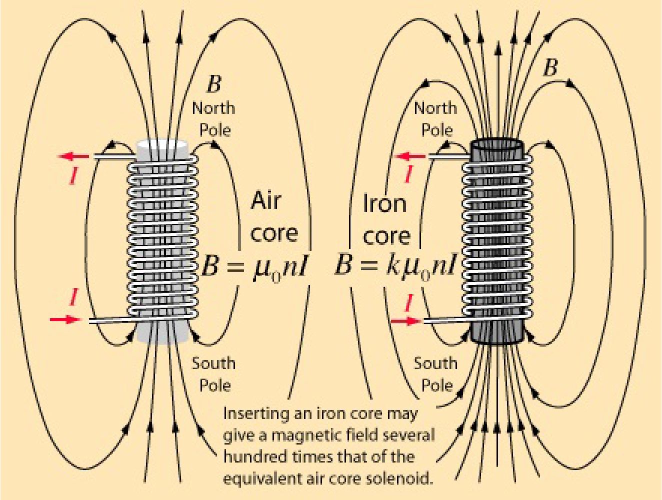

Figure 6.2: Diffrence between air core and iron core [19]

The generator design need to bedone using higher strength permanent magnets andmaking the air gap smaller to anoptimum value where the magnetic flux can be fully utilized in the stator[14]. The designof the generator can be illustrated as in Figure 6.3.

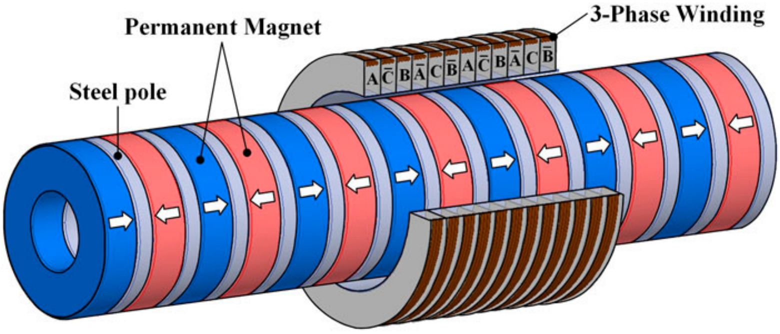

Figure 6.3: Suitable linear generator design [14]

As the generator is design for as a single phase winding and as in a one-phasesystem, the produced power will unavoidably vary over the period and thus will theforces acting on the rotor. The most common system is the three-phase system withthe phases mutually shifted 2pi/3 electrical radians. The benefit of a three-phasesystem is principally to create constant power production and a constant load on therotor, i.e. the force acting on the rotor. So the generator need to be developed to athree phase linear generator to maximize and to achieve a constant load.

6.3 Power Electronic Converter

In the prototype design the output voltage of one linear generator should be able to vary from 0V to2.5V. Therefore it is necessary to use a boost converter to step up that voltage. Hence it is recommended to use a DC-DC boost converter to step up the output voltage[15].

6.3.1 Boost converter

Normally it chooses the boost power stage because the required output is alwayshigher than the input voltage. The fundamental circuit for a boost converter or stepup converter consists of an inductor, diode, capacitor, switch and error amplifier withswitch control circuitry. Figure 6.4 shows a simple circuit of a boost converter.

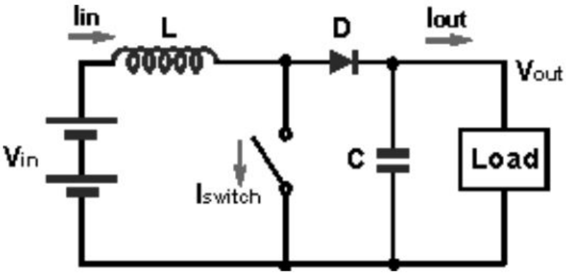

Figure 6.4: Simple Circuit of a Boost Converter [15]

The operation of the boost converter is relatively straightforward. When theswitch is in the ON position, the inductor output is connected to ground and thevoltage across inductor equals to $V_{in.}$ And so the inductor current increases at a ratewhich equals to V_{in}/L.

$$V_L = V_{in} - V_{out} \tag{6.1}$$

$$I_L = \frac{V_{in}}{L} \tag{6.2}$$

When the switch is in the OFF position, the voltage across the inductor changesand current that was owing in the inductor decreases at a rate of;

$$I_L = \frac{V_{out} - V_{in}}{L} \tag{6.3}$$

It should be mentioned that the input current to the boost converter is higherthan the output current. In the theoretical case the converter is a 100% efficient,lossless, boost converter and the output power must equal the input power.

$$V_{in} . I_{in} = V_{out} . I_{out} \tag{6.4}$$

6.3.2 Configuration of the Boost Converter

In order to achieve the results specified for this project and to be able to the resultbe measurable, the output voltage of the converter needs to be higher than the inputvoltage. In order to avoid the effect of ripples, fast switching is required and Schottkydiodes can be used in the designed circuit in this project[15]. The fast switching can be obtainedby using a NPN and PNP coupled oscillator. In order to make the output voltagestable, two smoothing capacitors can be used in parallel at both input and output.

Bibliography

[1] M. M. Bernitsas, «MHL - Facilities:Marine Renewable Energy Laboratory,» College of Engineering, University of Michigan, 2013. [Internett]. Available: http://www.umich.edu/~mrel/. [Funnet 19 05 2019].

[2] Grc.nasa.gov, «Lift of a Rotating Cylinder,» NASA, 2017. [Internett]. Available: http://www.grc.nasa.gov/WWW/k-12/airplane/cyl.html. [Funnet 08 January 2017].

[3] V. Lobo, N. Mainsah, A. Banerjee, and J. W. Kimball, «Design feasibility of a vortex induced vibration based Hydro-Kinetic energy harvesting system,» i *2011 IEEE Green Technologies Conference (IEEE-Green)*, Apr. 2011.

[4] K. M. R. K. M. Rao, «Design optimization of linear generator for a Hydrokinetic energy converter,» *IOSR Journal of Electrical and Electronics Engineering*, vol. 6, nr. 1, pp. 37-40, 2013.

[5] Mathew N.O. Sadhiku., Elements of Electromagnetics, 5 red., Oxford University Press, 2008.

[6] BH. Huynh, T. Tjahjowidodo, ZW. Zhong, Y. Wang, N. Srikanth, «Nonlinearly Enhanced Vortex Induced Vibrations for Energy Harvesting,» i *IEEE International Conference on Advanced Intelligent Mechatronics (AIM)*, Busan, Korea, 2015.

[7] M. M. Bernitsas, K. Raghavan, Y. Ben-Simon, and E. Garcia, «VIVACE (Vortex Induced Vibration Aquatic Clean Energy): A new concept in generation of clean and renewable energy from fluid flow,» *Journal of Offshore Mechanics and Arctic Engineering*, vol. 130, 2008.

[8] N. Ahsan, I. Akhtar, «Computational Analysis of Vortex-Induced Vibration and itsPotential in Energy Harvesting,» i *12th International Bhurban Conference on Applied Sciences & Technology (IBCAST)*, Islamabad, Pakistan, 2015.

[9] J. H. Leinhard, Synopsis of Lift, Drag, and Vortex Frequency data for Rigid, Washington State University, 1966.

[10] «Anon,» Worcester Polytechnic Institute, 2014. [Internett]. Available: https://web.wpi.edu/Pubs/E-project/Available/E-project-042811-120045/unrestricted/MQPFullDraft.pdf. [Funnet 21 September 2017].

[11] K E Hallenius,Elektriska Maskiner, Lund: LiberLromedel, 1980.

[12] Hendrik Aue, Werner Thale, «Capabilities of MFL Inspection in DUPLEX Steel Pipelines,» i *Pipeline Technology Conference*, Lingen, Germany, 2010.

[13] Thomas von B¨uren∗, Gerhard Tr¨oster, «Design and optimization of a linear vibration-driven electromagnetic micro-power generator,» i *Sensors and Actuators A 135*, Zurich, Switzerland, 2007.

[14] Jeong-Man Kim, Min-Mo Koo, Jae-Hoon Jeong, Keyyong Hong,,Il-Hyoung Cho, Jang-Young Choi, «Design and analysis of tubular permanent magnet linear generator for small-scale wave energy converter,» *AIP ADVANCES 7,* nr. 17 January 2017, 2017.

[15] Ned Mohan, Tore M. Undeland, William P. Robbins, Power Electronics: Converters, Applications, and Design, 3 red., Jhon Willey and Sons, 2002.

[16] Johann W. Kolar, Jose Rodriguez, «Review of Three-Phase PWM AC–AC Converter Topologies,» *IEEE TRANSACTIONS ON INDUSTRIAL ELECTRONICS,* Vol. %1 av %2VOL. 58, NO. 11, nr. NOVEMBER 2011, pp. 4988-5006, 2011.

[17] U. o. A. P. Department of Civil Engineering, «Uap-bd.edu,» 2019. [Internett].

Available: http://uap-bd.edu/ce/Handouts/CE-363/Lec.34-35.pdf. [Funnet 18 05 2019].

[18] Williamson, C. H. K. and R. Govardhan, Vortex-induced vibrations, 2004.

[19] «Magnets and Electromagnets,» Georgia State University, 2014. [Internett]. Available: http://hyperphysics.phy-astr.gsu.edu/hbase/magnetic/elemag.html. [Funnet 13 september 2018].