Design and Fabrication of a Building Mounted Vertical Axis Wind Turbine

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A Final Year Project Report

Presented to

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In Partial Fulfillment
of the Requirements for the Degree of
Bachelors of Mechanical Engineering

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ABSTRACT

This report describes the theoretical solution of our final year project, in basic fulfillment of our Bachelor's Degree at SMME, NUST, H-12, Islamabad, which is harvesting energy from the wind through VAWT in urban areas where wind speed is low.

Energy demands are increasing day by day in Pakistan and there is conspicuous need of renewable sources. This report represents the thorough estimation of energy that can be extracted through wind in densely populated areas. The detail of turbine design and modelling is provided with improvements.

ACKNOWLEDGMENTS

We would like to acknowledge the support; both monetary and moral, of our parents, and our mentor, Dr. Zaib Ali, who have been there for us throughout this project. We would also like to acknowledge the help of Dr. Adeel Javed and Dr. Jawad Aslam for helping us out in the simulation on Qblade and providing us with valuable feedback during this project.

ORIGINALITY REPORT

We hereby confirm that the work included in this report is our own except for the works cited.

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ABBREVIATIONS

AEDB	Alternative Energy Development Board
BEM	Blade Element and Momentum Theory
CFD	Computational Fluid Dynamics
DMST	Double Multiple Stream Tube
HAWT	Horizontal Axis Wind Turbine
LLT	Lifting Line Theory
NACA	National Advisory Committee for Aeronautics
SMME	School of Mechanical and Manufacturing Engineering
TSR	Tip Speed Ratio
USPCAS-E	U.S. Pakistan Centre for Advanced Studies in Energy
VAWT	Vertical Axis Wind Turbine

NOMENCLATURE

P	Power
A	Angle of Attack
C_l	Coefficient of Lift
C_d	Coefficient of Drag
C_P	Coefficient of Performance
Σ	Solidity
P	Density of Air (kg/m^3)
L	Blade Length
Ω	Rotational Speed (rad/s)
A	Swept Area
Λ	Tip Speed Ratio
V	Velocity (m/s)
C	Chord Length
N	Number of Blades

CHAPTER 1: INTRODUCTION

Since early recorded times of history, people have exploited the energy of the wind. Wind energy propelled boats along the Nile River as early as 5000 B.C. By 200 B.C., simple windmills in China were pumping water, while vertical-axis windmills with woven reed sails were grinding grain in Persia and Middle East. In 1940, during Second World War the largest wind turbine fed 1.25-megawatt electrical power to one of the local utility network that was mounted on hill named as Grandpa's Knob. In spite of the availability of cheap oil and low energy prices in Denmark, there was continuous work being done on wind electric turbines. The oil shortage in 1970s in the cold created a bottleneck in energy production; so it created an interest in alternative energy sources, paving the way for the re-entry of the wind turbine to generate electricity.

With growing advancement in the technology and the gradual increase in urbanization, a shift to renewable energy sources is not only recommended for a better and safer environment but also a need of the hour. The fossil fuels are depleting very fast, and the situation demands the utilization of alternate sources of energy In addition, they also in higher amounts of carbon in the environment resulting in This situation in addition to the ever-increasing energy demand, drives the need for a greater research in renewable energy sources all over the world. Our project deals with harnessing the wind energy to generate electricity, the concept which is not very prevalent in Pakistan. The generated electric power is intended to light the light poles on a highway.

1.1-Motivation for Work

The renewable energy sector in Pakistan is highly underdeveloped. Pakistan still produces a major chunk of its electric power from fossil fuels. With growing increase in demand and the short fall affecting the country's economy and standard of living, it has also impeded in the development of industry in the country. So it is necessary to find out and sustainable ways of generating power. The increased research and investment in the green energy will also help in fighting global warming and pollution.

Pakistan being a member of Paris Climate accord, vows to take steps, adopt measures and regularly report its contribution in the control of global warming. Pakistan making almost two-thirds of its power grid from fossil fuels, is contributing to the increase in overall global carbon print. The member countries of the accord are bound to reduce their carbon output to reduce the global warming.

The renewable energy sources leave no carbon print in the atmosphere thus; they do not contribute in any kind of environmental hazards. Converting from the hazardous fossil fuels to the green energy sources that are environment friendly and sustainable at the same time, will act as a stepping-stone to a power-sufficient and developed Pakistan.

Table 1: Comparison of different Energy Sources

	Solar Panel (1 KVA)	Gasoline Generator (1 KVA)	Wind Turbine (1 KVA)
Price	Rs, 65,000	Rs 11,000	Rs. 120,000
Fuel Consumption	Nil	Rs. 114/h	Nil
Life Span	25 years	4-5 years	10-15 years
Maintenance	Nil	Rs. 6.5/h	Rs. 3.5/h
Carbon Monoxide	Nil	6.5 g/Liter	Nil
Un-burnt Hydrocarbon	Nil	0.72 g/Liter	Nil

Nitrogen Oxides	Nil	58 g/Liter	Nil

The table clearly depicts that the renewable energy sources are friendly for the environment by not letting any hazardous gases in the atmosphere. It also shows that renewable energy sources are more sustainable, not only having a greater life but also are much more financially feasible.

Wind energy rose to the attention of the world in 1970s following the oil crisis. The need for finding alternative sources of energy increased as a result of Harrisburg and Chernobyl nuclear reactor accidents in 1980s. The world focus shifted to containing the amount of gases emitted into the atmosphere during 1990s. All of these factors paved way for the development and research of wind energy.

Pakistan, having 1237 MW of cumulative wind power capacity as of 2018, which makes up almost 6% of total power generation, unfortunately has not been able to keep up with the increasing trend of research and development in the wind energy sector, which was one of the reasons why we decided to build a wind turbine as our final year project.

1.2-Problem Statement

Design and Fabrication of building mounted vertical axis wind turbine for urban areas to ensure maximum annual energy yield. Modern world is in the search of cleaner and economical energy resources. Wind power has a lot of potential to make a great impact on energy deficient urban areas. It can reduce our dependency on fossil fuels which have a negative effect on our environment.

In some remote urban areas there is conspicuous shortfall of power which can be met by installing vertical axis wind turbine.

Design should be economical, reliable, durable and efficient.

- Solar cells have power conversion efficiency much lower than the wind turbines. The highest attained efficiency for the multi-junction cells in the laboratory conditions is 46% [4] while the efficiency attained in the actual conditions is much lower. While the commercial wind turbines can have the power conversion efficiency of up to 50%.
- Wind can be harnessed all day and night, while the solar cells cannot generate power at night or in cloudy conditions.

These points affirm that installing a wind turbine will be a very reasonable idea for power generation for these places.

1.3-Objectives of the Project

The objective of the project is to develop a vertical axis wind turbine that can be mounted on a building and will run producing electricity. The project also aims to fabricate a full scale turbine, which can be reduced to a scale model if proper funding cannot be procured.

The objectives of the project can be enumerated as:

1. To select a proper site for designing the turbine based on the parameters like wind velocity and available potential at the site.
2. To design a Darrieus type Vertical Axis Wind Turbine using DMST model.
3. To design and manufacture the foundation to support the turbine.
4. To perform structural analysis of the model including stress analysis.
5. To select and install already available generators in the market for the conversion of mechanical energy to electrical energy to power the road lights.

CHAPTER 2: LITERATURE REVIEW

Turbines convert kinetic energy of fluid into rotational energy through rotor and that energy is transformed into electrical energy by means of a generator.

2.1-Classification of Wind Turbines

Wind turbines are, in general, classified on various basis, e.g. by the axis about which the rotor blades rotate. According to this criteria there are two categories of wind turbines:-

- Horizontal axis wind turbines
- Vertical axis wind turbines

Another criterion that can be used to classify wind turbines is the location of the rotor relative to the tower and nacelle:

- Upwind
- Downwind

Wind turbines are also classified by the mechanism that rotor blades use to achieve the rotation and thus create electricity, following are the types of turbine according to this criterion:

- Lift type
- Drag type

Most commercial turbines today are three bladed, lift type, horizontal axis wind turbines with the upwind rotor [1]. Our wind turbine is a lift type VAWT, so we now shift our focus to VAWTs only. VAWTs are primarily categorized into following categories based on the type of force they will utilize for their working:

- Savonius rotor (Drag type)

- Darrieus turbine (Lift type)
- Giromill (Lift type)

Darrieus rotor uses aerodynamic lift forces to achieve rotation and has the shape of an egg beater, whereas the Giromill (sometimes casually referred to as Darrieus) is also a lift type. VAWT and is a modification of the Darrieus rotor, the only difference between the two is that the Giromill has straight blades.

Our application requires us to convert the energy present in the air into electrical energy, a decision was made that for this application, Giromill would be the most suitable rotor, and the reasons for this decisions will be elaborated in the following chapters. For now, we will focus mainly on Giromill or straight bladed VAWT

2.2-Components of a Wind Turbine

A wind turbine (Giromill in particular) primarily is a combination of the following main components:

A. Rotor
B. Nacelle
C. Foundation and Tower

2.2.1-Rotor

Rotor consists of the frame that rotates as a result of wind, with rotor blades that are attached to the shaft with the help of connecting links, since we are talking about a lift type VAWT, the blades used are NACA airfoils. The rotor is mounted on a hub that is in tum fixed to the shaft for power transmission to the generator in order to convert the energy into electrical power.

2.2.2-Nacelle

A housing that collectively holds generator, power control mechanism (can either be mechanical or control systems). For VAWTs the nacelle can be on the ground, making VAWTs relatively easier to maintain as compared to HAWTs in which the nacelle has to be at the top of the tower

2.2.3-Foundation and Tower

Foundation is used to support the tower and the whole structure of the wind turbine in order to ensure structural integrity of the turbine as a whole. Tower is usually a hollow tube through which the shaft passes.

2.3-Efficiency of a Wind Turbine: Important Parameters

This section highlights the important parameters that affect the performance of turbines:

2.3.1-Performance Coefficient

The efficiency of a wind turbine is determined by various parameters. We start by stating the available potential in wind, which is given by [2]:

$$P_{wind} = \frac{1}{2}\rho A V^3$$

Where P is power, p is density of the air, A is the swept area of the rotor and V is the incident freestream velocity. From this available power, a wind turbine can extract the following amount [2]:

$$P_{Turbine} = \frac{1}{2}C_p \rho A V^3$$

Where, C_p is the performance coefficient of the rotor. The maximum value of performance coefficient is given by Betz limit as 0.593 [2]. Commercial three bladed HAWTs have achieved a Cp of up to 0.45 whereas VAWTs reach up to 0.35 [2] as shown in Figure 1.

2.3.2-Tip Speed Ratio

Tip speed ratio (TSR) is defined as the ratio of the speed of the tip to incident freestream velocity, given as

$$\lambda = \frac{\omega R}{v}$$

λ is the TSR, ω is the radial velocity in rad/s and R is the rotor radius.

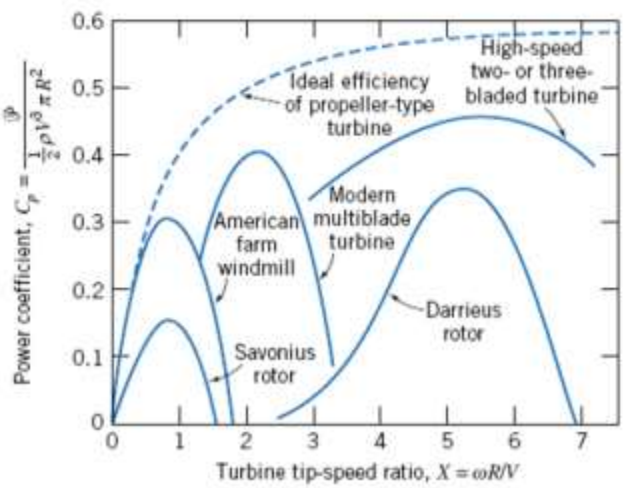


Figure 1: Performance coefficients of various turbines [2]

As can be seen from this figure, Cp varies with TSR.

2.3.3-Swept Area

Swept area is the area swept by the rotor blades and it directly affects the amount of power that can be extracted from the wind, increasing swept area increases power but it also increases cost, so a balance between the two is made where the amount of power can justify the cost incurred.

2.3.4-Airfoil

Since, we are talking about lift type turbines, the turbine blades are airfoils, mostly NACA airfoils. For the Omni directionality of VAWTs, the airfoils used are mostly symmetrical airfoils NACA00xx [3]. Aerodynamic analysis of these airfoil blades at specified. Reynolds numbers is necessary for performance prediction and design optimization methods. The choice of a correct airfoil for a particular application is very crucial to the performance of a wind turbine. At optimum angle of attack (a), an airfoil generates maximum lift and minimum drag as shown:

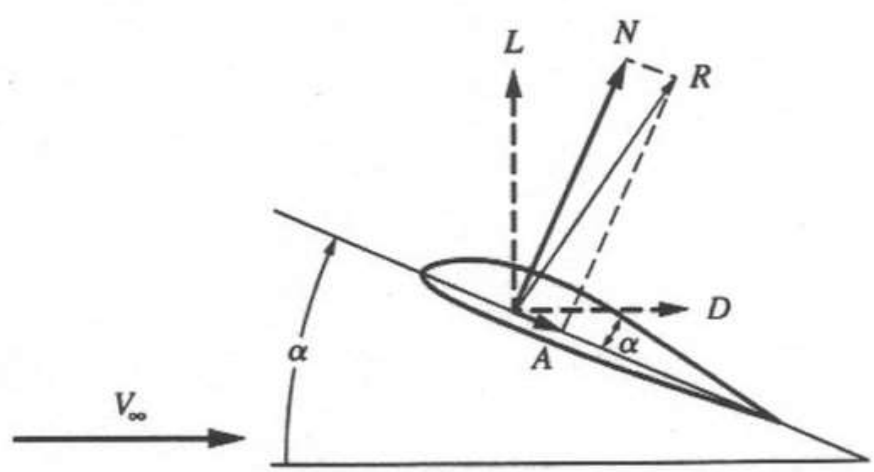


Figure 2: Lift and Drag Forces on Airfoil [2]

2.3.5-Solidity

Rotor solidity is defined as the developed surface area of all blades divided by the rotor swept area, this is a key variable and greatly affects the performance and the cost of the turbine (4]. Solidity is given as:

$$\sigma = \frac{Ncl}{A}$$

Where, σ is the solidity, N is the number of blades, c is the chord length of the airfoil, I is the length of the blade and A is the swept area.

2.4-Turbine modeling theories

There are two widely accepted theories to model wind turbines:

2.4.1-Double Multiple Stream Tube

The Double Multiple Stream tube (DMST) models helps us to calculate the differences between the downwind and upwind stream of a flow that passes through them by separating each stream tube for an upwind and downwind. Turbines interact with each stream separately. The turbine actually behaves like an actuator disk, and the stream expands at first half and then develops again and interact with the downwind pass. Downwind blades considerably receives less amount of energy compared to upwind.

Paraschivoiu’s method gives the most reliable insight into the flow variation across the turbine. In DMST model each stream-tube interacts with blades separately, at first with upstream blade and then downwind. During all these interactions turbine is pictured as a pair of actuator discs and flow exert force on them.

DMST solves equations simultaneously, one equation from momentum theory and the other one from aerodynamics coefficients i.e. drag and lift. These equation are solved for both and upstream and downwind stream.

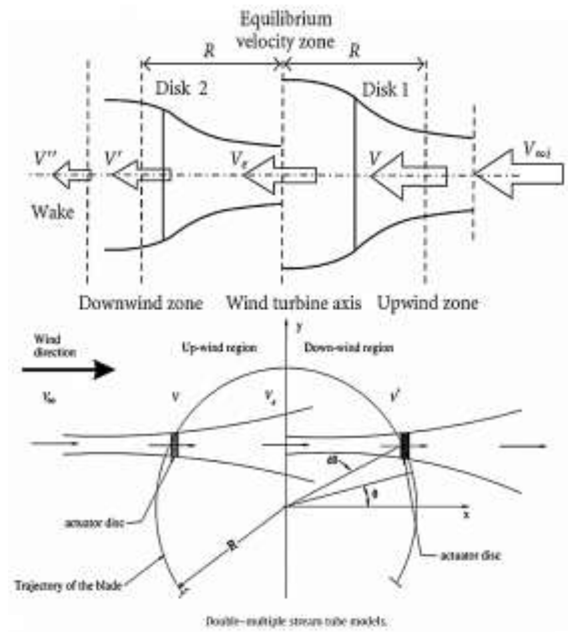


Figure 3: VAWT Rotor Geometry Definition [15]

2.4.1.1-Flow Velocities

There are five different velocities to be considered:

- Undisturbed Inflow velocity ($V\infty$) of the stream.
- Velocity after the energy extraction from the first blade which is Upwind induced velocity (V).
- Velocity between the upwind and downwind i.e. Equilibrium velocity (V_E).
- Velocity after the energy extraction from the downwind blade is Downwind induced velocity (V').

- Velocity of a whole double disk i.e. Wake velocity (V’’).

We did our DMST analysis on Giromill type Vertical axis wind turbine with NACA 0015 having fixed pitch.

Interference factor for the upwind and downwind can be identified as:

$$u = \frac{V}{V_\infty}$$

$$u' = \frac{V'}{V_E}$$

If the interference factor equals one then it means no energy has been extracted, and if it equals to 0 then flow velocity is zero.

2.4.1.2-Iteration

The iterations of DMST depends on interference factor. It is user defined and thus can be constant or variable for all azimuthal angles. All simulation is executed on various Tip Speed Ratios, for that purpose it is done by changing the wind speed. For each tip speed ratio iteration is carried out for all azimuthal positions and height until the interference factor converge at the user defined value.

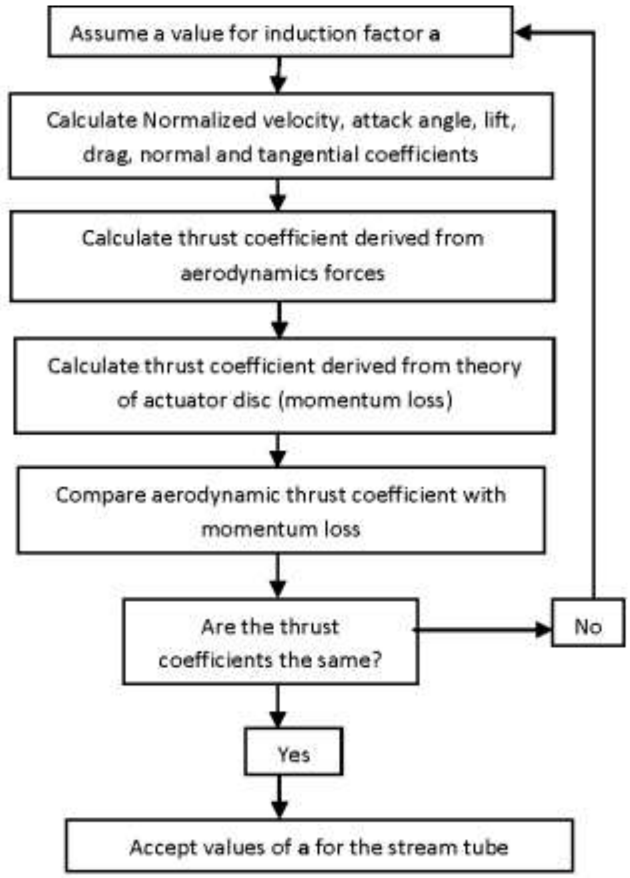


Figure 4: DMST Algorithm [15]

2.4.2-Non Linear Lifting Line Theory (LLT)

The lifting line theory comes from the background of vortex methods. This vortex method is the combination of Blade Element Theory and Computational Fluid Dynamics. Computational work and physical modelling of vortex lies in between BEM and CFD. Flow field here is considered inviscid, non-rotational and incompressible. Horseshoe vortices are located in the middle of blade and they are modeled with the rotor through vortex lattice method.

Vortex components are presented as either straight line or curved fragments to display both the rotor blades and the wake. The upper and lower surfaces of the blades are modelled through panel method with a mesh of vortex rings. The lifting line method models the blades with a single line of vortices which is located at ¼ of the blade.

Vortex methods can be classified into two types on the basis of wake modelling i.e. prescribed wake methods and free wake methods. In prescribed wake methods the wake elements are projected on a prescribed path. On the other hand, free wake methods update the position of the wake end nodes which depends on the local velocity. Free wake method is a combination of inflow velocity and induced velocity from all wake elements in the domain.

When compared the free wake convection method has a much higher accuracy than prescribed wake method. This is due to the fact as the wake shape is forming based on the underlying physical principles. However it all comes at the cost of Computational effort. We have the same code in Q-Blade as "nonlinear lifting line theory" which is free vortex wake algorithm. It is stated as nonlinear since all the results come from nonlinear drag and lift polar.

Vortex method has quite an advantage over BEM due to solid modelling of macroscopic fluid flow, where boundary layer flow play a vital role. In many studies vortex method is considered better than BEM and it can replaced in the near future for more accurate turbine results.

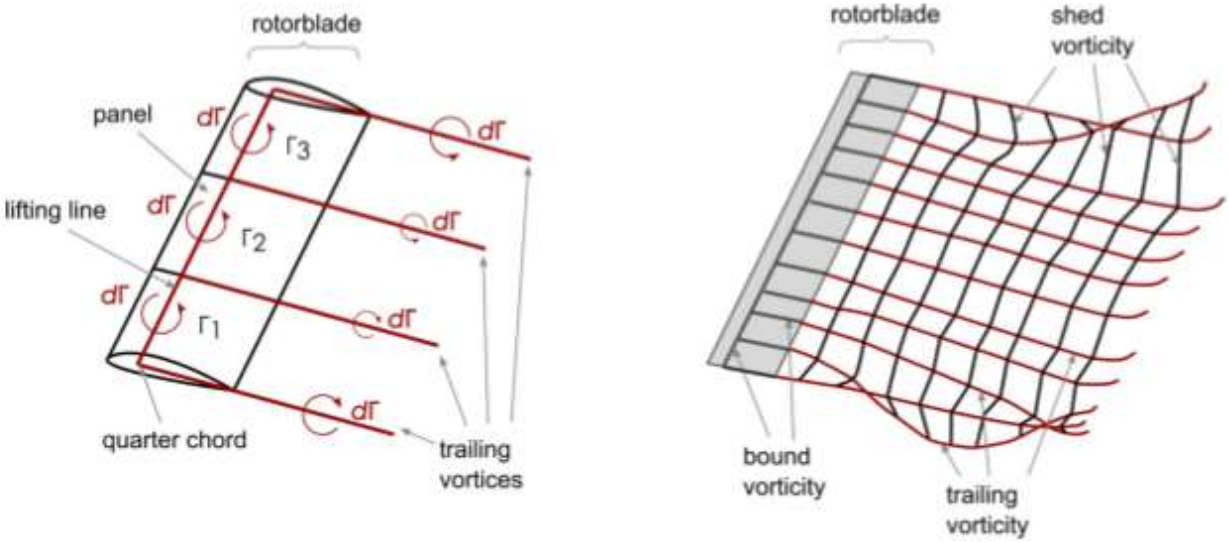


Figure 5: Illustration of Blade and Wake Modeling [16]

Apart from this, a detailed study of literature was also done prior to the design and fabrication of model. A summary of the literature that was reviewed is presented in this section and is later applied in the next chapter:

- Tore Wizelius [2] described the types, basic working, relevant parameters and components involved in all wind turbines
- Parascivoiu [3] explains the performance of Darrieus type VAWT. All the parameters involved in the performance of a Darrieus rotor are presented in detail along with their effects on the overall performance of the turbine. Especially, the Double Multiple Stream.
- Tube model later used to predict and optimize the performance of our turbine, is mostly adapted from the chapter 6 of this book. A scaled prototype for the desired application was manufactured [5]. The senior design project was mainly concerned

with the bearing design and airfoil selection optimization for the said application. It was concluded that NACA 0018 was the optimum airfoil for this application.

- Another prototype designed for conditions similar to roadside was manufactured [6].Another methodology used for the design of the small scale VAWT is described. The airfoil used was NACA 0021.
- Effects of Aspect ratio (H/R) of the rotor on the performance of Rotor are discussed [7]. It is concluded that lower aspect ratio for an identical rated power, yields more power as compared to the rotor with higher aspect ratio. But, the resulting gain in performance coefficient is very small
- The effects of various design parameters; chord, number of blades, Re number etc. on the performance of the rotor are discussed [8]. The prominent result for this kind of application is that the efficiency gain for 4 blades compared to 3 blades is not as big as shifting from 2 to 3 blades. So, three blades offers a marginally good efficiency at a reasonable cost for our application.
- Numerical approach is used to predict the performance of VAWTs [9] based on Double Actuator Disk theory and Momentum models and is compared with results obtained from Computational Fluid Dynamics, the results are fairly close and thus both techniques for performance prediction are equally reliable.
- Various possible configurations are reviewed [10]: Savonius, Darrieus, Giromill, Straight bladed, Egg beater shape. It is concluded that a straight bladed Darrieus rotor or a Giromill would be the most suitable option for this application.
- Economic aspects of small scale site specific wind turbines are reviewed [11]. The results from this paper also favors a three bladed rotor.
- The effects of pitch angle of airfoil on the performance of the rotor is explained [12] Having a variable pitch would be highly beneficial in terms of total power produced by the turbine, as in commercial HAWTs. But the design configuration of VAWTs makes it relatively tedious to vary the pitch.

- The difficulties involved in the self-starting of VAWT are discussed |13]. It is concluded that a Savonius-Darrieus Hybrid may be used for the turbine to have the self-starting capability.
- The effects of unsteady winds on the performance of the VAWT are discussed [14]. For the roadside application, unsteady wind gusts affect the performance of wind turbines.

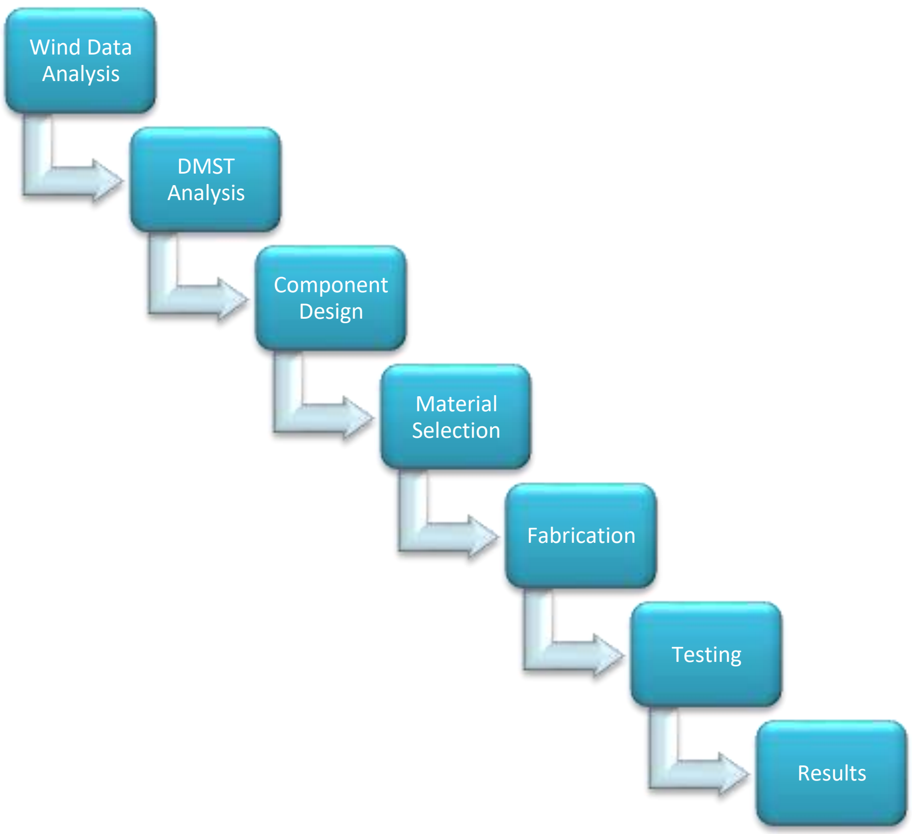
All literature review helped in understanding the working of VAWT and suggested measures to improve the efficiency and self-starting capability of turbine.

CHAPTER 3: METHODOLOGY

This chapter focuses on the methodology and the thought process employed to go about this project.

3.1-Project Plan

We are conducting our project based on the strategy shown below:



3.2-Wind Data Estimation

The first step needed before starting the design was to get the wind data so we can get potential energy estimate at the site. Wind distribution of data has been obtained from Centre for Advanced Studies- Energy CAS-EN. The data was provided in the form of excel sheets that contained the hourly data of wind and gust speeds for about 3 years. After doing the statistical analysis on data, we got an average wind speed of 6.5 m/s.

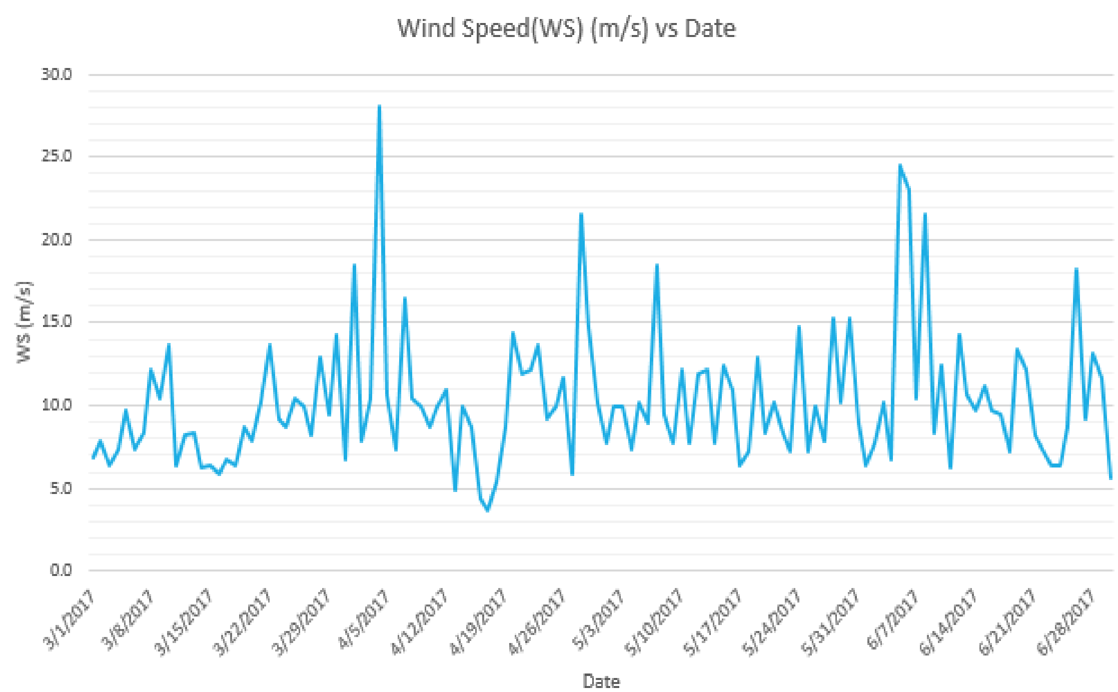


Figure 6: Average Wind Speed Estimation

3.3-Design Parameters

Following Choices were made to focus our analysis on significant family of turbines.

- H—type Darrieus Straight bladed (most used)
- Number of blades equal to 3 (Good efficiency, flat torque profile)
- Two struts for supporting the blades

The future performance maps must be related to this classification.

Main design parameters

- The height/diameter ratio (φ=H/D)
- The chord/diameter ratio (ϑ = c/D)
- The swept area of the rotor (A)
- Dimensions of struts
- Type of Airfoil

3.4-Turbine Parameters Calculation

We chose straight bladed H-type profile over conventional designs for various reasons:

- Easily Manufacturability
- Cheaper
- Lesser Swept area for same height

Each decision on design was made keeping in view the cost at hand. It would be difficult to manufacture chambered profile and curved blades. They are usually made through 3D printing which makes it expensive for us.

3.4.1-Rotor Dimensions

Swept area was calculated to be:

$$A = L \times D$$

Radius, height and chord width was altered in a way that swept area remains the same and we get maximum power out of it. In addition, after conducting many iterations on the QBlade software we selected the length to be 1.6 m and diameter to be 2.4 m. Thus,

$$A = 3.84$$

3.4.2-Number of blades

Increasing the number of blades increases the power rating of turbine, but that is not the only effect. If we increase the solidity, our cost goes very high as well. Moreover, we decided to choose 3 number of blades so that we can achieve maximum power as well as maintaining cost under budget as well.

3.4.3-Airfoil

To reduce the weight of the turbine in order to achieve maximum power output, we needed a high performance and lightweight profile. After going through many simulations on the QBlade, we found NACA 0015 airfoil to meet our requirements. The decision of aerodynamic profile was also based on literature review.

3.4.4-Solidity Selection

This is all an iterative procedure. Normal solidity values range from 0.2 to 0.6. If we have a large value our peak performance is high but average power is not satisfying and vice versa. So, we chose an optimum value that gives us a good average value at the cost of peak value.

3.5-Performance Prediction through DMST

Q-Blade was used to predict the performance and design optimization of turbine. Q-Blade gives us the DMST results which are validated by nonlinear lifting line theory.

We analyzed the performance of Q-blade at various solidities ranging from 0.2 to 0.6 and at TSR between 0.5 and 8. Analysis were conducted at five different solidities with respective chord lengths. At the end an optimum chord length was chosen.

The graphs predicting the performance are given below:

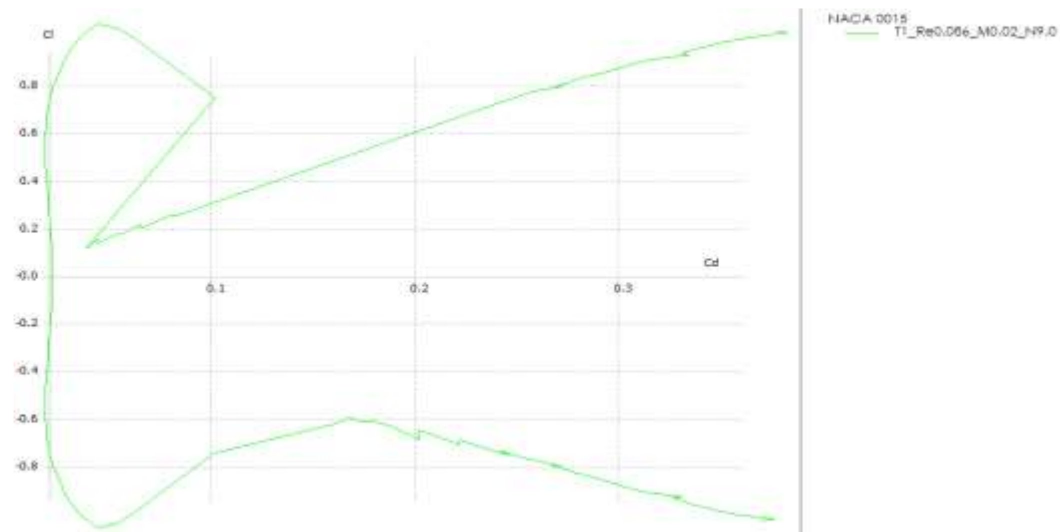


Figure 7: C_l vs C_d from Qblade

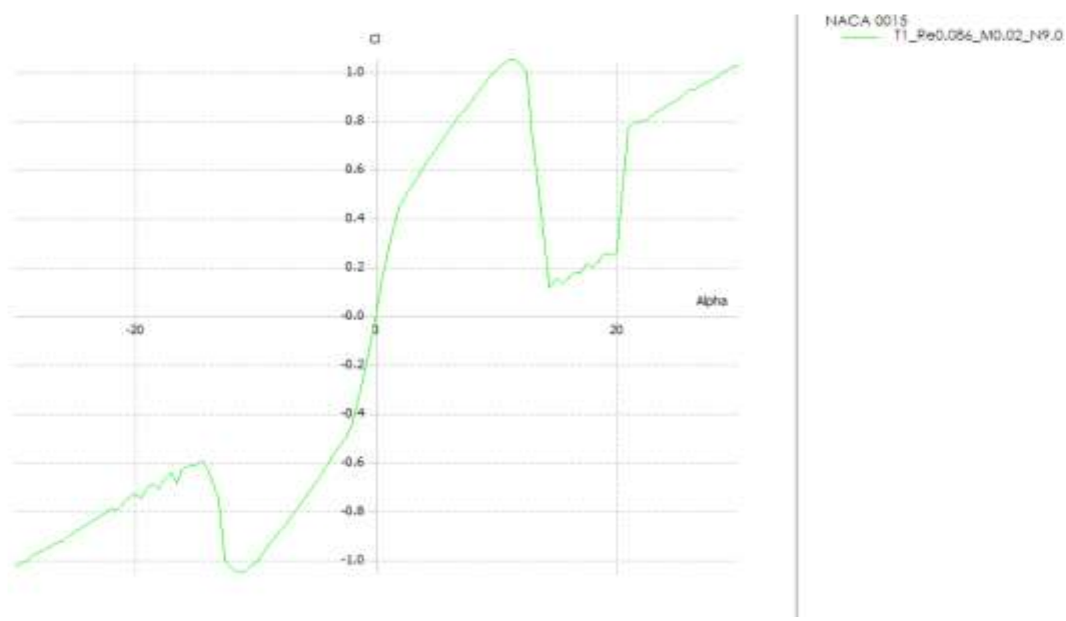


Figure 8: C_l vs Alpha from QBlade

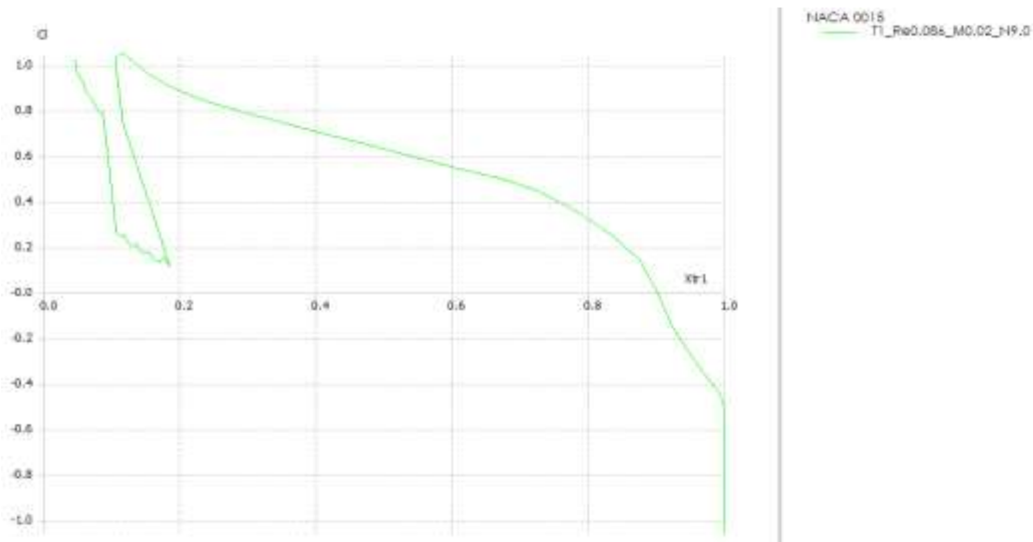


Figure 9: C_l vs XTR1 from Qblade

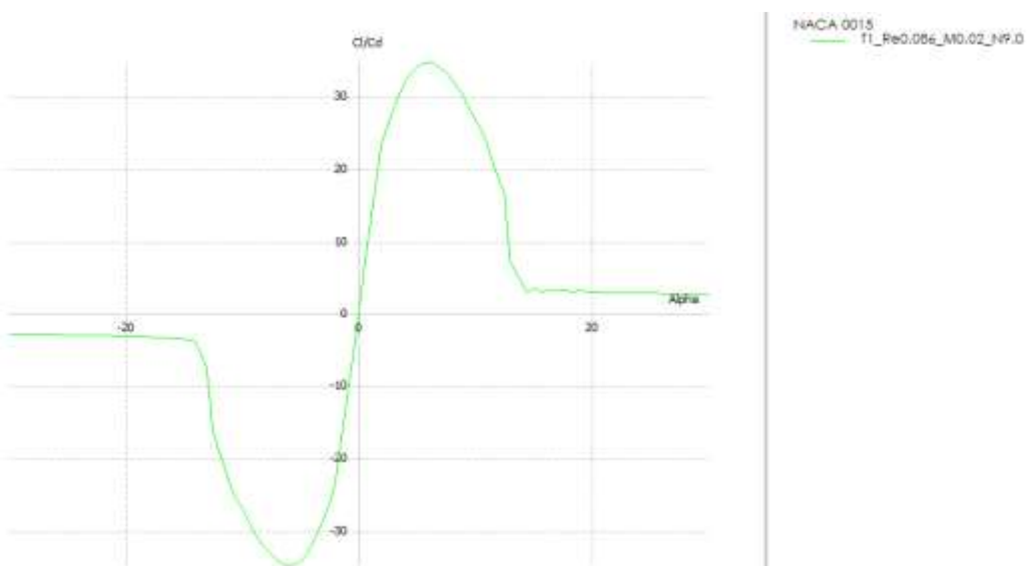


Figure 10: C_l/C_d vs Alpha from QBlade

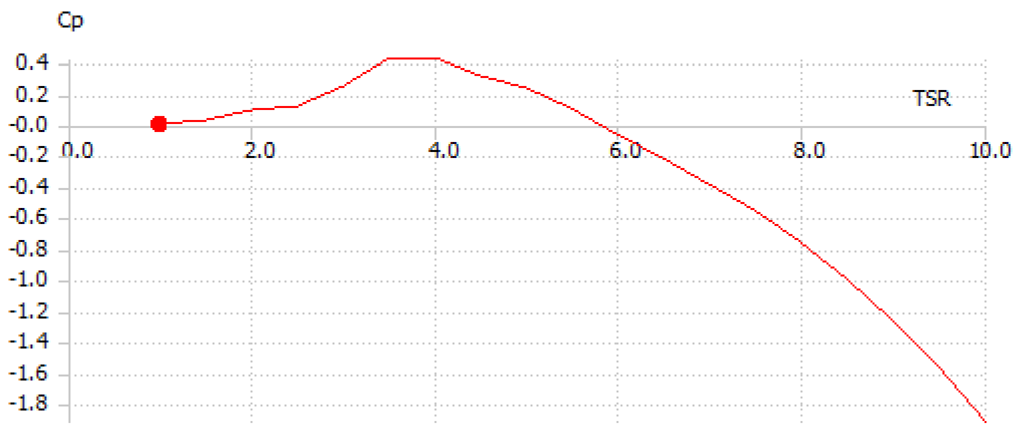


Figure 11: C_p vs TSR from QBlade

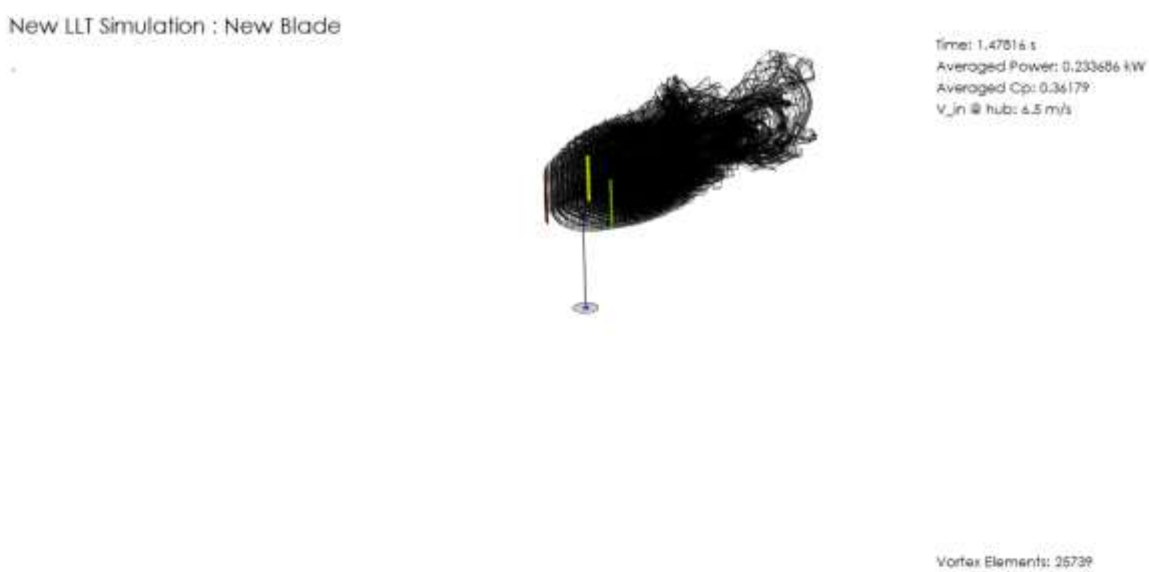


Figure 12: LLT Simulation

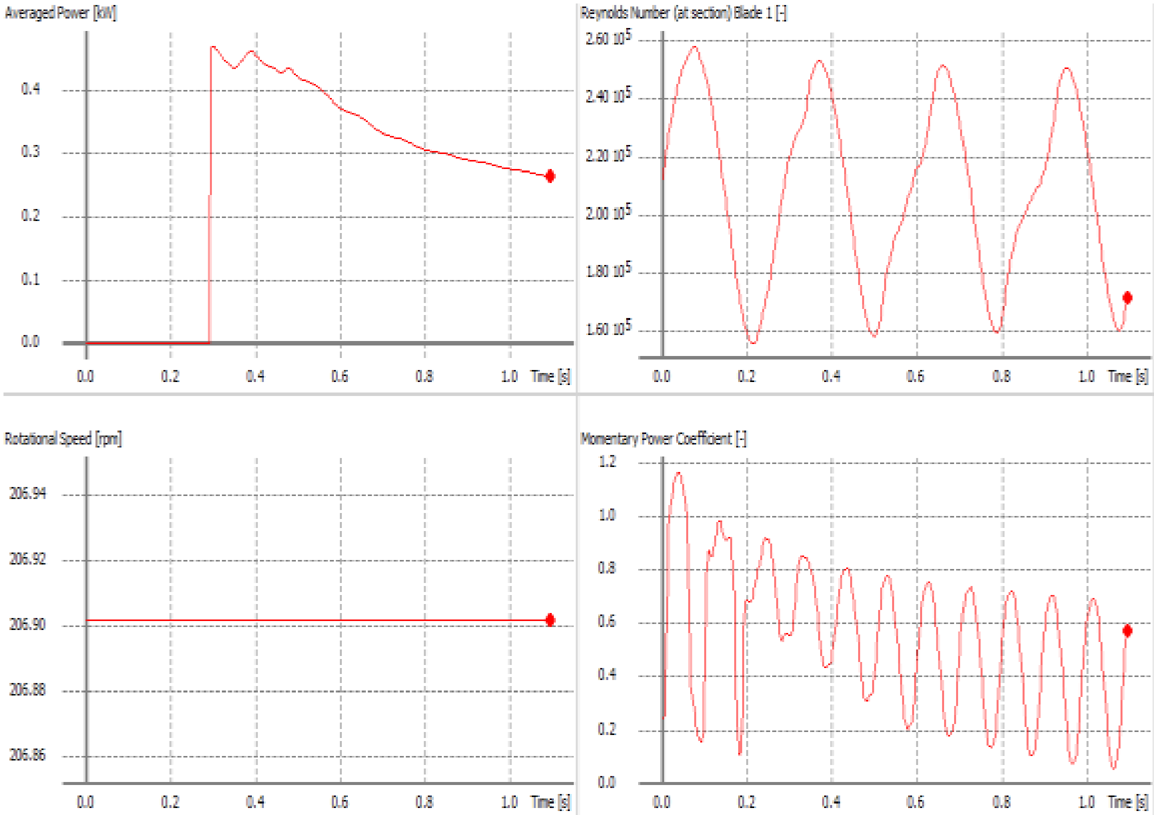


Figure 13: LLT Simulation Results

3.6-Ansys Results

The design was simulated on ANSYS Fluent for turbulence modeling and stress analysis to get desired results.

3.6.1 Grid independence and validation

Following table specifies the grid speculations:

Table 2: Grid Specifications

Parameter	**Specification**
Mesh Type	Coarse
Number of Mesh Elements	70,164
Smoothing	Medium
Curvature Angle	25 degree
Controls	Dynamic Mesh

Firstly, the mesh was designed using fine pitch mesh, which gave mesh elements up to 1 million, to speed up the process the mesh elements had to be limited close to 65 thousand elements. For this purpose, coarse mesh instead of fine was used which slightly affected the parameters but reduced the mesh elements up to 75 thousand. In order to further reduce the element size, a curvature angle of 25 degree was given to the mesh and stationary wall boundary condition was imposed, which resulted in 70 thousand mesh elements that was early optimum for the calculations and greatly reduced computational effort. The results from both fine and coarse mesh were almost same.

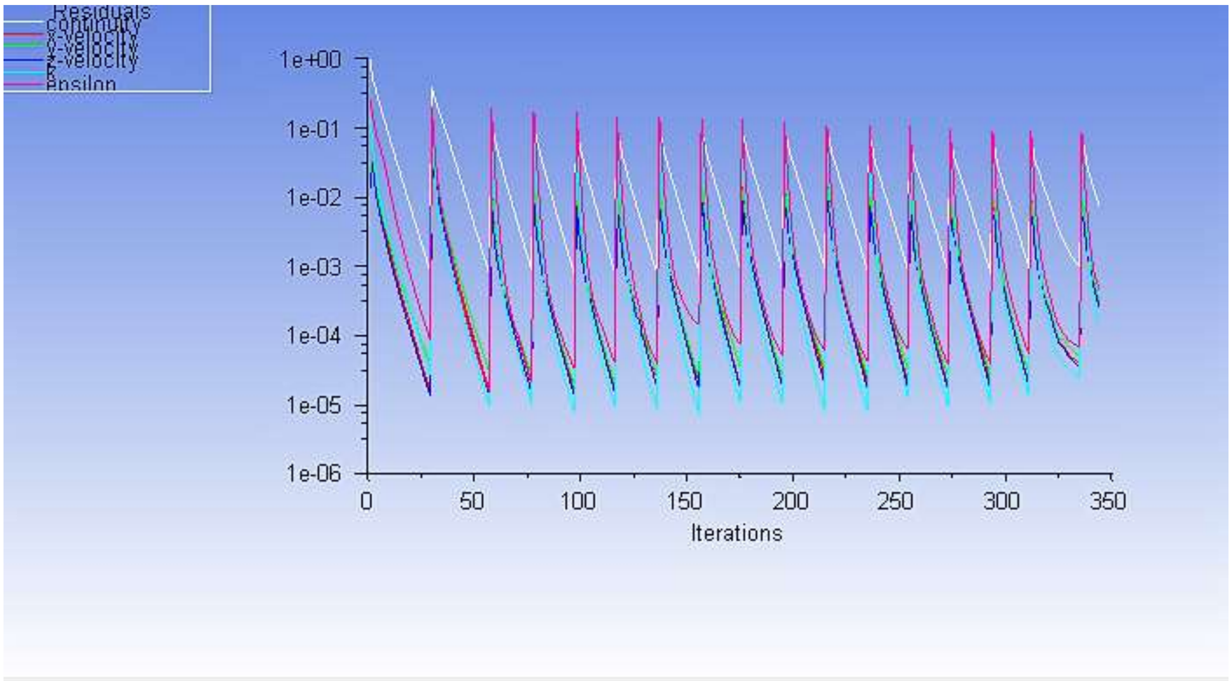


Figure 14: Graphical Interpretations after Ansys Analysis

The above graph depicts the velocity, turbulent kinetic energy and epsilon variations with each time step, there are a total of 20 time steps with each time step having 30 iterations.

3.6.2-Turbulent Kinetic Energy

It is used to analyze the viscous dissipation in flow and its effect on blade structure. It used to analyze the intensity of turbulence in wake region and its effect on structural stability of VAWT.

3.6.3-Wall Shear Stress Model

This model is used to analyze wall shear stress caused by viscous effects and tangential velocity gradient which helps us to choose blade profile and material accordingly.

3.6.4-Strain Rate Model

It gives us the distortion in profile geometry and helps to us analyze the effect of flow on geometry.

3.6.5-Velocity Magnitude Model

Study of velocity distribution on blades validates DMST criteria and maps power requirements according to plotted velocity magnitude.

3.6.6-Total Pressure Model

It gives the total pressure on the blades which is the sum of relative and dynamic pressure and is used for stress analysis of the design to find its strength.

3.7-Drive Mechanism:

3.7.1- Generator Features

500W dynamo 12v 24v

Advantages of using the above-mentioned generator are below

- Low start up speed
- Low cogging torque
- Gearless, direct drive

- Low RPM generator
- For use in all environments
- Excellent heat dissipation
- Designed for 25-year operation life

3.7.2-Generator description

Table 3: Generator Specifications

Model	ARPMG-500
Rated Power	500W
Max Power	536W
Rated Voltage	12 W
Top Rotated Speed	1600 r/m
Top Net Weight (kg)	6.1 kg
Output Current	AC
Start Torque	0.42 Nm
Generator	3 phase permanent magnet synchronous generator
Insulation Class	F

Service Life	More than 30 years
Bearing	HRB
Shaft Material	Stainless Steel
Shell Material	Aluminum Alloy
Permanent Magnet Material	Rare Earth NdFeB
Protection Grade	IP54
Lubrication	Lubrication Grease
Working Temperature	-40^{o}C-80^{o}C

3.7.3-Bearing Selection:

Two spherical ball bearings UC207-20 were considered after meticulously calculations of radial and axial forces due to rotor weight. These bearings exhibit ultra-low friction with dynamic load ratings of 19.75 kN. The bearing is also caged so that any dirt or water is prevented from reducing the life of the bearing.

3.7.4-Belt drive:

Generator and shaft are coupled using belt drive mechanism comprising of a cast iron pulley and a plastic pulley having a gear ration of 1:5 connected through a V-belt. Belt drive provides a noiseless smooth transmission of power.

3.8-Three-Dimensional Model of Turbine:

Figure 15: VAWT Model

Table 4: Components of VAWT

Components	**Figures**
Blades	
Bearings	
Connectors and Nuts	

3.9-Structural Analysis:

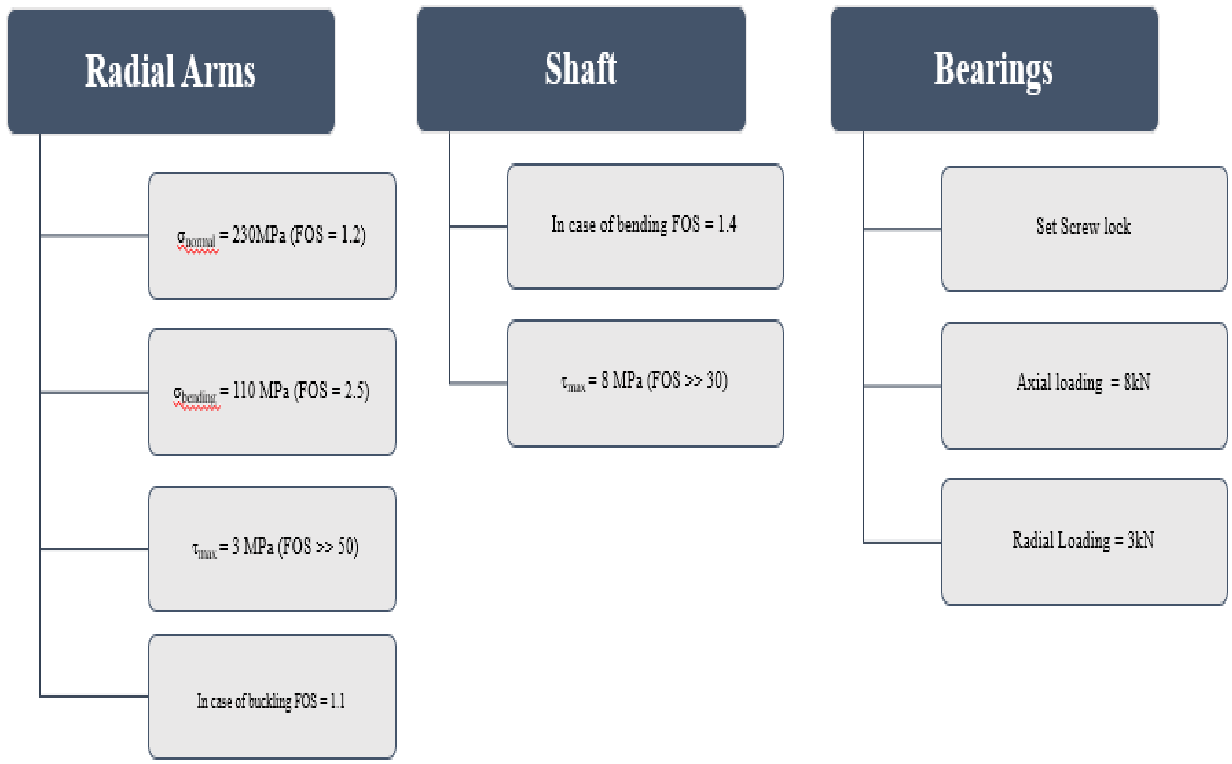


Figure 16: Structural Analysis

CHAPTER 4: RESULTS AND DISCUSSIONS

The turbine was tested in two ways:

1. By simulating the required wind conditions by loading the turbine on a moving pickup van
2. By measurement of torque of the turbine by a weight and spring balance

4.1-Simulation of required wind conditions:

It was necessary to test the turbine in the conditions for which it was designed. The necessary or designed wind speed could not be obtained in Islamabad due to low wind velocity, so an alternate approach had to be adopted. The required flow conditions were produced by placing the turbine on top of load deck of a moving pickup van. The pickup van was accelerated and maintained at a constant velocity of 25 km/hr (7m/s). The rotational speed of the turbine was then measured by a tachometer.

Figure 17: Van Mounted VAWT

4.2-Measurement of torque of turbine:

The turbine was placed on a level surface and was rotated at the previously calculated rotational speed. A weight and spring balance were attached to the rotating shaft of the turbine. By the measurement of weight and spring balance force, the torque was calculated.

Figure 18: Torque Measurement

4.3-Experimentally calculated Turbine Parameters:

Table 5- Turbine Parameters

Optimum TSR	4.07
Achieved TSR	1.2

Optimum RPM	230
Achieved RPM	67
Torque (at TSR=1.2) theoretical	11 Nm
Torque (at TSR=1.2) experimental	8 Nm
Power (at TSR=1.2) theoretical	78 W
Power (at TSR=1.2) experimental	56.12 W
Optimum Value of Torque	80 Nm
Optimum Value of Power	1750 W
C_p (at TSR=1.2) theoretical	0.02
C_p (at TSR=1.2) experimental	0.013
Optimum Value of C_p	0.35

4.4-Discussion

- The power output of the turbine is in line with the theoretically calculated one.

- Experimentally calculated coefficient of performance is in line with theoretically calculated one with design speed.
- The power output of the turbine would increase exponentially with increase in wind speed.
- Experimental TSR is not completely matching with the predicted TSR at the design stage but it can be understood that there are always deviations of the fabrication model from the ideally designed model according to DMST.
- Large variation in angle of attack at low TSR results in dynamic stall.
- Blade should run with 230 RPM in order to get optimum results of power.
- Variable pitch approach should be used in order to widen the band of azimuth angle for higher torque and power.
- Vibrations at low TSR. To overcome it we can:
    - Increase diameter and decrease length of central shaft.
    - Increase thickness of radial arms.
    - Increases toughness of VAWT

CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

5.1-Conclusion

Following conclusions can be made from the project done so far:

A speed of 6.5 m/s ensures the highest power of 300 W at 200 rpm and the speed above 10 m/s can give us the power up to 500W. Both of the results were obtained from DMST and LLT. Among two of them LLT sometimes over predict the performance a bit while DMST gives the reliable results.

Our main aim was to design a turbine that is lightweight, robust and economical. It is best suitable to provide power to urban areas and help them meet their needs.

With more research, efforts and innovation the turbine efficiency and usability can be increased.

As we move towards the fabrication part of the project we will try to achieve as much power as possible through this project.

5.2-Recommendations

Following points can be considered as improvements for future work.

- Variable pitch can be used as it helps in easier starting at low wind speeds and creates more torque.
- Hybrid Savonius-Darrieus type method can be applied for better self-starting of turbine
- Compressed air starting system can be used, it is also cheap and reliable
- Dynamic braking system is also used in high speed wind conditions
- Braking and Control Systems concept is emerging nowadays for shutdown purposes
- Reliability testing of turbine should be done in order to specify it’s working weather conditions

- The advantages of a VAWT with a lower AR are
    - greater coefficient of power
    - thicker blades with greater structural integrity
    - stability due to larger moment of inertia.
- 3-bladed rotor are resistant to stalling conditions

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APPENDIX I: MATLAB CODE

The MARLAB code used for finding the values of solidity, TSR, cord length, thickness, etc. is given below:

```
classdef DMST < VAWT.AeroProfile
   properties (SetAccess = protected)
      solidity  %VAWT solidity.
%TSR - VAWT tip speed ratio.
%
%   Can either be a scalar or a vector.
      TSR
      nblades %VAWT number of blades.
      U  %Free stream velocity
      Density  %Flow density.
      chord  %Blade chord.
      thickness  %Blade thickness.
      diameter  %VAWT diameter.
      height  %VAWT blade height. height = 0 -> 2D case.
      aspratio  %VAWT blade aspect ratio. height / chord.
      omega %VAWT rotation speed.
      speedSound %Speed of sound.
      theta %Azimuthal angle vector. length(theta) = 2*Nth.
      At %Time step between nodes of theta.

      dStall %Structure with the dynamic stall options.
```

```
    wake %Wake interaction option. wake = 0 -> no wake interaction.


    pitch %Constant pitch added to the blade in rad.


%SOLUTION - Structure array with the output variables.
%
%   To know more about its contents, call this structure once the DMST
%   object has been solved. SOLUTION is an array and each position
%   corresponds to the same position of the TSR vector. Hence, to call the
%   solution structure, one must write 'obj.solution(i), where i is the
%   position.
    solution
%DIAGNOSTIC - Structure array with the diagnostic output of the solver.
%
%   To know more about its contents, call this structure once the DMST
%   object has been solved. DIAGNOSTIC is an array and each position
%   corresponds to the same position of the TSR vector. Hence, to call the
%   solution structure, one must write 'obj.diagnostic(i), where i is the
%   position.
%
%   See also FZERO.
    diagnostic



    Nth %Number of discretization points of the azimuthal angle vector.
```

```
        thetaMin %Minimum value of azimuth angle when computing thrust.
    end

    properties (Access = protected)
        NTSR %Length of TSR vector.
        theta1 %Equals to theta(1:end/2)
        theta2 %Equals to theta(1+end/2:end)
    end

    methods
        function vawt = DMST(solidity, TSR, nblades, nacaFile)
%DMST    DMST Constructor
%
%   obj = DMST(solidity, TSR, nblades, nacaFile) sets the object properties
%   that match the four arguments to the given values. Default values are:
%       solidity = 3*85.8/1030
%       TSR = 2.5
%       nblades = 3
%       nacaFile = []
%   The rest of the properties are set to default values that can bee seen
%   when calling the created object.
%
%   See also AEROPROFILE, SET.

            if (nargin < 1) solidity = 3*85.8/1030; end;
            if (nargin < 2) TSR = 2.5; end;
```

```
    if (nargin < 3) nblades = 3; end;
    if (nargin < 4) nacaFile = []; end;

    vawt = vawt@VAWT.AeroProfile(nacaFile);

    vawt.solidity=solidity;
    vawt.TSR=TSR;
    vawt.nblades=nblades;
    vawt.height=1;
    vawt.U=6.5;
    vawt.density=1.225;
    vawt.speedSound = sqrt(1.4*8.314*288/0.029);
    vawt.chord=0.0858;

    vawt.Nth=50;
    vawt.thetaMin=pi/2*0.05;

    vawt.dStall= struct('model','N');
    vawt.wake=0;

    vawt.reset;
end

[CL, CD, alphaRefL, alphaRefD] = getCLCDG( vawt, omega, alpha, W, alphaRate )
[CL, CD, alphaRefL, alphaRefD] = getCLCDS( vawt, omega, alpha, W, alphaRate )
[CL, CD, alphaRefL, alphaRefD] = getCLCDB( vawt, omega, alpha, W, alphaRate )
```

```
    [CL, CD, alphaRefL, alphaRefD] = getCLCDP( vawt, theta, omega, alpha, W, alphaRate )
    [CP, CP1, CP2] = getCP(vawt, TSR, CTb)
    CT = getCT(vawt, CTb)
    CTb = getCTb(vawt, V, Vt, W, theta, Cl, Cd)
    getPlots(vawt, option)
    fig = plotPower(vawt, hAxes)
    fig = plotTorque(vawt, hAxes)
    fig = plotVAWT(vawt, val, titleName, hAxes)
    fig = polarVAWT(vawt, val, titleName, hAxes)
    reset(vawt)
    recalcNth(vawt)
    vawt = set(vawt,optionName,value)
    solve(vawt)
    solveCase(vawt, iTSR)
    postProcess(vawt, iTSR)
    [lambda1,fval,exitflag1,output1] = solveLambda1(vawt, iTSR, ith, alphaRate)
    [lambda2,fval,exitflag2,output2] = solveLambda2(vawt, iTSR, ith, lambda1, alphaRate)
    residual1 = getLambdaEq1(vawt, iTSR, ith, lambda, alphaRate)
    residual2 = getLambdaEq2(vawt, iTSR, ith, lambda, lambda1, alphaRate)
end

methods (Static)
    alpha = getAlpha(theta, beta, pitch)
    beta = getBeta(V, Vt, theta)
    W = getW(V, Vt, theta)
```

```
        [fRate, signfRate] = getRate( f, Ax )

        [fRate, signfRate] = getRateLoop( f, Ax )

    end


end
```

APPENDIX II: TURBINE PARAMETERS

Description	Value
Number of Blades	3
Solidity	0.325
Chord Length	13 cm
Turbine Diameter	2.4 m
Rotor Length	1.6 m
Swept Area	3.84 m^2
Rated Wind Speed	6.5 m/s
Cutoff Wind Speed	15 m/s
Rated Power	300 W