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NUMERICAL AND EXPERIMENTAL STUDY WITH OPIMIZATION OF A SMALL – SCALE VERTICAL AXIS WIND TURBINE

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A thesis submitted by Omar Farooq Izzat ARSALAN in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE** is approved by the committee on 10.07.2017 in Department of Mechanical Engineering, Energy Program.

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Omar ARSALAN

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LIST OF SYMBOLS

E_k	Kinetic Energy of Wind [Joule]
V	Velocity [m^2/s]
V_u	Velocity of Wind [m^2/s]
m	Mass [kg]
$\dot{m}$	Mass Flow Rate [kg/s]
P	Power [Watt]
ρ	Density [kg/m^3]
A	Area [m^2]
λ	Tip Speed Ratio
ω	Angural Velocity of Rotor [rad/s]
R	Radius of Rotor [m]
n	Angular Velocity of Rotors [rpm]
F_r	Wind Force [N]
C_D	Drag Coefficient
C_p	Power Coefficient
P	Pressure
η	Efficiency
C_Q	Torque Coefficient
C_T	Thrust Coefficient
β	Overlap Ratio
St	Strouhal Number
f_v	Vortex Shedding frequencies
V_u	Wind velocities
D_t	Diameter of the turbine
F_D	Drag force [N]
C_d	Drag coefficient

LIST OF ABBREVIATIONS

CFD	Computatinal Fluid Dynamics
COG	Center of Gravity
DOF	Degree of Freedom
FEM	Finite Element Methods
HAWT	Horizontal Axis Wind Turbine
LED	Light Emitting Diode
MBD	Multi Body Dynamics
TSR	Tip Speed Ratio
VAWT	Vertical Axis Wind Turbine

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ABSTRACT

NUMERICAL AND EXPERIMENTAL STUDY WITH OPIMIZATION OF A SMALL – SCALE VERTICAL AXIS WIND TURBINE

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Department of Mechanical Engineering

MSc. Thesis

Adviser. Dr. Nader JAVANI

In the current study, a small-scale wind turbine is investigated in order to provide energy requirements such as lighting in urban areas and small scale power needs. Regarding the application, a small- scale wind turbine has been analyzed aerodynamically and in terms of feasibility aspects. The turbine is designed to be a starting-up type which needs no initial excitation even at lower wind speeds. A three blade vertical axes savonius type has been considered in this study. Analytical and numerical analyses in two-dimensions are carried out to determine the optimum design and the most efficient blade geometry. The geometry and position of stators have been modeled to improve the structure of turbine and position of stators which increase the efficiency due to diffuser angle to guide wind through the blades. Numerical studies are conducted in 3 dimensional CFD which shows that the peak efficiency of the turbine has been improved up to 35%. The selected geometry which is determined to be elliptical shaped with circular end profile has higher efficiency than the circular shaped geometry. The optimum geometry has been built to carry out the related measurements. Model assessment has been carried out by comparing the experimental data and measured power with the simulation outputs.

Keywords: Renewable energy, wind energy, vertical axis Wind Turbine, savonius rotor.

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ÖZET

KÜÇÜK ÖLÇEKLİ DİKEY EKSENLİ RÜZGAR TÜRBİNİN OPTİMİZASYONU İLE İLGİLİ SAYISAL VE DENEYSEL ÇALIŞMA

Omar Farooq Izzat ARSALAN

Makine Mühendisliği Bölümü

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Bu çalışmada; şehir aydınlatması gibi kentsel enerji ihtiyaçlarını karşılamak amacıyla küçük ölçekli bir rüzgar türbini geliştirilmiştir. Uygulama göz önünde bulundurularak, küçük ölçekli rüzgar türbini aerodinamik ve fizibilite açısından analiz edilmiştir. Bu amaç doğrultusunda dizayn edilen türbin, düşük rüzgar hızlarında bile başlangıç tahriğine ihtiyaç duymayan "starting-up" tipi rüzgar türbinidir. Bu çalışmada 3 kanatlı dikey eksenli "savonious" tip kullanılmıştır.

Bu amaç doğrultusunda 2 boyutlu "Hesaplanabilir Akışkanlar Dinamiği" analizleri ile karşılaştırmalı çalışmalar yapılmış ve yapılan çalışmalar içerisindeki optimum dizayna sahip en verimli kanat geometrisi bulunmuştur. Statorların pozisyonu ve geometrisi, verimi artıran türbin yapısını ve stator pozisyonunu geliştirmek amacıyla modellenmiştir. Son olarak 3 boyutlu HAD çalışmaları yapılarak gerçek durumlara yönelik sayısal veriler alınmıştır. Seçilen dairesel sonlu profile sahip eliptik şekilli geometri, dairesel şekilli geometriye

nazaran daha verimlidir. Optimum geometri, ilgili hesaplamaları uygulamak amacıyla seçilmiştir. Model değerlendirmesi, deneysel veriler ve simülasyon çıktılarıyla hesaplanan güce göre yapılmıştır. Ayrıca, türbinin zirve verimi %35 oranında artırılmıştır. Model değerlendirmesi, deneysel verileri ve ölçülen gücü simülasyon çıktılarıyla karşılaştırarak gerçekleştirilmiştir.

Anahtar Kelimeler: yenilenebilen enerji, rüzgar enerjisi, dikey eksenel rüzgar türbini, savonius rötörü.

CHAPTER 1

INTRODUCTION

1.1 Literature Review

Vertical axes wind turbines (VAWTs) divide in to two common types, the Darrieus rotor and Savonius rotor. The Darrieus type is a VAWT which rotates around a central axis due to the lift force produced by the rotating airfoils, whereas a Savonius type rotates due to the drag force created by its blades. To increase the efficiency of the wind turbine the geometry of the rotor blades plays a very important role, according to literature there are many studies have done to design and analysis of Savonius VAWT blade.

The following studies are some of the literature reviews on designing and analyzing of Savonius VAWT blades, they conducted many experiments and analysis carried out for different overlap ratio, blades with end plate or without end plate, for different wind velocities, different tip speed ratio, different rotor geometries, with and without stators.

Buckets and rotor shapes influence an infinite number of buckets and rotor shapes combinations. The performance curves of the turbine will suffer interference for each type of bucket and rotor. Among the most studied profile options it's been founded that buckets with profile shape like a "hooks" are more efficient than the classic semicircular profiles. This bucket design studied by Kamoji et al. [1] who obtained a value of 0.21 for the averaged power coefficient of a turbine with that kind of bucket against the value of 0.19 averaged power coefficient of a rotor with buckets of semicircular profile. Rotors with buckets shaped like a "hooks" have slightly higher moments due to air flow to be directed more to the tip of the buckets. Another studies have done on twisted bucket rotors as a result it produced more moment than a device with semicircular profile buckets, due to the same increase on the moment occurred on a rotor with buckets shaped like "hooks".

Saha et al. [2] obtained values of 0.31 for averaged power coefficients for rotors with twisted buckets, and 0.29 for rotors with semicircular profile buckets.

R. D. Maldonado, et al [3]; has done detailed investigation on Savonius wind rotor in order to obtain the optimal characteristics. They designed Savonius wind rotor with different geometry and gap distance between the blades. Simulations results showed that the geometry and gap distance of the blades increases the Cp about 20%. Through gap distance between the blades, An air deflector was located front the Savonius rotor to increase and guide the flow of air to the blades. The deflector increased the velocity of the Savonius rotor up to 32%.

A. A. Kadam, et al [4]; has studied various performance parameters to increase savonius efficiency. Experimental results showed that two blades rotor is more stable in operation than three or more rotor blades. rotor blades with end plates gave higher efficiency than those of without it. CFD analysis was carried out to study the flow behavior of a rotating two bucket Savonius rotor. Data were taken from the experiments conducted earlier on the rotor in a subsonic wind tunnel for five different overlap conditions. Results showed at 16.2% overlap condition power extraction is maximum from the wind.

Mohammed Hadi Al [5]; has carried out experimental comparison and investigation of performance between two and three blades Savonius rotor. two models of two and three semi-cylindrical blades were designed and fabricated from Aluminum sheet, Subsonic wind tunnel is used to investigate these two models under low wind speed condition, which shows that maximum performance at (TSR = 1) and a high starting torque at low wind speed, and also gives reason for two bladed rotors is more efficient than the three blades.

K.K. Sharma, et al [6]; has studied the performance of three-bucket Savonius rotor by Computational Fluid Dynamics software. Moreover, the flow behavior around the rotor was also analyzed with the help of pressure, velocity and vorticity contours, for different overlap ratios.

Sukanta Roy, et al [7]; has studied the effect of overlap ratios in unsteady two-dimensional computational study on static torque characteristics of a vertical axis wind turbine (VAWT) with Finite Volume based computational Fluid Dynamics. The analysis was carried out for a two-bladed conventional VAWT having different overlap ratios. Analysis which done by the computational study showed that an overlap ratio of 0.20

destructs the effects of negative static torque coefficient, gives a low static torque variation at different angular positions of the turbine and also gives a higher mean static torque coefficient as compared to the other overlap ratios.

B. Wahyudi, et al [8]; has studied the performance of hydrokinetic turbines of Savonius using all three types of Tandem Blade Savonius rotor. The simulation work shows the way of the flow characteristic and pressure distribution pattern in and around of the blade swept area. The results show that the convergence Type has a higher gap pressure between upstream and downstream or they have best performance than other types.

Sumpun Chaitep, et al [9]; has studied the effect of the operating conditions. tip speed ratio, reverse up rotation, power and torque coefficients of Curved Blades Vertical Axis Wind Turbine. All tests done in wind tunnel with different velocities.

N.H. Mahmoud, et al [10].has done an experimental analysis by using, wind tunnel experimental setup, the results showed that -Two bladed Savonius rotors are more efficient than the three and four bladed Savonius rotors. The rotor with end plates gives higher efficiency than the without end plates. Blades having overlap ratios are better than the blades with without overlap ratios. By increasing Aspect Ratio Coefficient of performance (Cp) will also increase.

Widodo, W.S, et al [11] has designed and analyzed of the Savonius rotor blade to generate 5 kW power Output. They designed blades and done structural analysis and (CFD) analysis. The two flow types were analyzed in this study external flow and internal flow analysis. Both analyses were static analysis.

K.K. Matrawy, et al [12]; has studied the main performance parameters of a small scale vertical axis wind turbine (VAWT). They design two models (Two and Four cambered blades) and tested in an open wind tunnel. The final experimental results showed that the blade angle of 45° increase the performance of (VAWT) comparing the other ones for both two and four bladed rotors. Using of flap blade which shows increase power coefficient by 2.4% compared with the same model without flap blade.

Anum [13] has studied and proved that improvement of Savonius rotor performance is depending on partial differential equation. Investigations were conducted to show the effect of geometrical configuration on the rotor performance. all the analysis was carried out with the CFD. The results obtained shows that partial differential equation was important in the increasing in the performance of the savonius rotor.

Patel C.R, et al [14]; hasstudied the aerodynamic performance of Savonius wind turbine. By using a Wind tunnel to find the aerodynamic characteristics like, drag coefficient, torque coefficient, and power coefficient of three bladed Savonius wind turbine rotor models, with and without overlap ratio, at various Reynolds numbers. Numerical investigation was also carried out using (CFD) to find the effect of overlap ratios. Results showed at higher Reynolds number, turbine Model without overlap ratio gives better aerodynamic coefficients and at lower Reynolds number Model with moderate overlap ratio gives better results.

K.K. Sharma, et al [15]; has investigated the performance of a two-stage two-bladed configuration of the Savonius rotor. Experimental part has done in a subsonic wind tunnel. The parameters studied are overlap, tip speed ratio, power coefficient (Cp) and torque coefficient (Ct). Optimized Overlap ratio was used to generate maximum performance of the rotor. The results showed that a maximum Cp of 0.517 was obtained at 9.37% overlap condition. Similarly power and torque coefficients decrease with the increase of overlap from 9.37% to 19.87%.

Burcin Deda Allan, et al [16] ; has introduced a new curtaining arrangement to improve the efficiency and performance of Savonius wind rotors. The curtain placed in front of the rotor to avoid negative torque opposite the rotor rotation. The rotor with different curtain arrangements were tested out of a wind tunnel and its performance was compared with that of the conventional rotor. The maximum power coefficient of the Savonius wind rotor is increased to about 38.5% with the optimum curtain arrangement. The experimental results showed that adding suitable curtain arrangement improves the performance of Savonius wind rotors.

Dhrubajyoti Rajbongshi, et al [17]; has ivestigated about the effect of semicircular deflector. They designed three bladed Savonius rotor and its base is fixed on square plate of cast iron. Around the savonius rotor eight semi-circular (non movable) deflectors had been kept and are fixed on the square cast iron plate. The model is tested by and the square plate has been rotated by 30°, 45°, 60°, 75° and 90°. Results show that at 15% valve opening at 60° of rotation of cast iron plate has maximum rotation speed.

Animesh Ghosh, et al [18]; has studied about design and performance of Savonius, H-Darrieus and combined Savonius -Darrieus turbines. The experiments were conducted for Savonius rotor for different overlap ratios from 16.2% to 35%. Results showed that the maximum Coefficient of performance (Cp) is 0.38 at which overlap is 20%, for a Tip Speed Ratio 0.625. Wind tunnel experiments Results showed that both the turbines produced a similar value of maximum aerodynamic torque and two bladed H-Darrieus turbine shows higher coefficient of performance than the three bladed turbines.

K.K. Sharma, et al [19] ;has investigated about the Combination of Savonius and Darrieus type of Vertical Axis Wind Turbine (VAWT) rotors, which came out with many advantages over their individual designs. They measured the performance of a three-bladed combined Darrieus-Savonius rotor, with Darrieus mounted on top of Savonius rotor, for different overlap variations. It's been founded that Cp increases with the increase of overlap. However, there is an optimum value of overlap for which, Cp is maximum, beyond this Cp starts decreasing. The present Darrieus-Savonius rotor can be suitably placed in the built environment where it can harness more power from wind low wind amount and, at the same time, would self- start in low wind condition prevalent in such environment.

So according to all these previous studies this study is about to investigate the effects of deferent rotor geometries and stators positions to find the most efficient geometry for savonius wind turbine.

1.2 Objective of the Thesis

This study aims to design a wind turbine that can be placed in the living quarters in order to meet the demand in the neighborhoods. Further design criteria and limitations are made in accordance with this aim.

1.3 Hypothesis

In the scope of this study, six subsidiary design criteria are specified and through the design process they are clarified with more details. At the first stage, it is expected from the turbine to recover energy in the amount that a LED lighting unit requires. After a detailed investigation for lighting requirements with the consideration of the turbine’s comparatively small size; the power of the turbine is desired to be around 35W. Secondly, turbine is designed in the principle that it has the capability of starting-up by itself without an initial excitation even at lower wind speeds. Third design criteria of the study are related with the safety and noise characteristics of the turbine. Since the project is oriented at the living quarters, the turbine should be durable in the emergency cases and it should not create annoying noises during its regular operation. As a fourth design criteria, the turbine should have a modular structure for the ease of assembly and disassembly. Apart from these criteria, the turbine should have an aesthetic aspect and not spoil the existing view in the neighborhoods. In the general manner, the turbine is expected to have a low manufacturing and maintenance costs with the minimum effort to increase its sustainability and expected to be further improvable with ongoing studies.

CHAPTER 2

GENERAL INFORMATIONS

2.1 Renewable and Non-Renewable Energy Sources

The era beginning with the Industrial Revolution forced the human race to produce and consume more. Since then the necessity of energy has been rapidly increased. At first, fossil fuels became in demand to meet the requirements. After 19th century, petroleum sources became a convenient energy source for industries. Today besides petroleum and fossil fuels; natural gas and nuclear energy are widely used.

With increasing population and energy consumption, today it is more important than ever to use renewable energy sources and make them feasible. Restricted natural sources and environmental pollution due to use of them led the humankind to develop a renewable energy perspective. Today; hydropower, geothermal, solar and wind energy sources are to be focused and developed more renewable energy aspect allowed new technologies and industries to show up and further improve them. Since then; wind energy, with its high potential and feasibility, has become very popular. Wind turbines are being used throughout the world to generate electricity from off shore wind farms to residential smaller scale wind turbines [20].

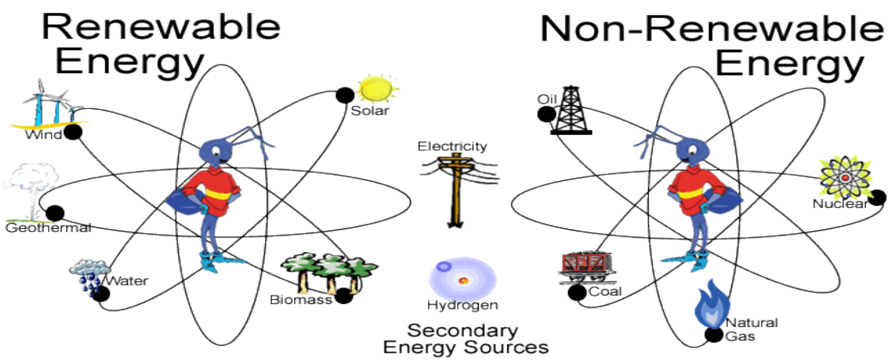

Figure 1.1 Renewable & Non-Renewable Energy Sources [1]

Wind turbines, like aircraft propeller blades, turn in the moving air and power an electric generator that supplies an electric current. Simply stated, a wind turbine is the opposite of a fan. Instead of using electricity to make wind, like a fan, wind turbines use wind to make electricity. The wind turns the blades, which spin a shaft, which connects to a generator and makes electricity [21].

2.2 A Brief History of Wind Turbines

People began using wind energy to propel boats along the Nile River as early as 5,000 BC. By 200 BC, simple wind-powered water pumps were used in China, and windmills with woven-reed blades were grinding grain in Persia and the Middle East.

New ways of using wind energy eventually spread around the world. By the 11th century, people in the Middle East were using windpumps and windmills extensively for food production. Merchants and the crusaders brought wind technology to Europe. The Dutch developed large wind pumps to drain lakes and marshes in the Rhine River Delta. Immigrants from Europe eventually took wind energy technology to the Western Hemisphere. American colonists used windmills to grind grain, to pump water, and to cut wood at sawmills. Homesteaders and ranchers installed thousands of wind pumps as they settled the western United States. In the late 1800s and early 1900s, small wind-electric generators (turbines) were also widely used.

When power lines were built to transmit electricity to rural areas in the 1930s, the wind pumps and small turbines were used less frequently. However, wind pumps are still in use on some ranches to supply water for livestock. Small wind turbines are becoming common again, and they are mainly used for supplying electricity in remote and rural areas [22].

2.3 Types of Wind Turbines

Depending on their shaft position, two main types of wind turbines are existed: Horizontal Axis Wind Turbine (HAWT) and Vertical Axis Wind Turbine (VAWT). Presently, due to their early development and capability of high power production; horizontal axis wind turbines are extensively used.

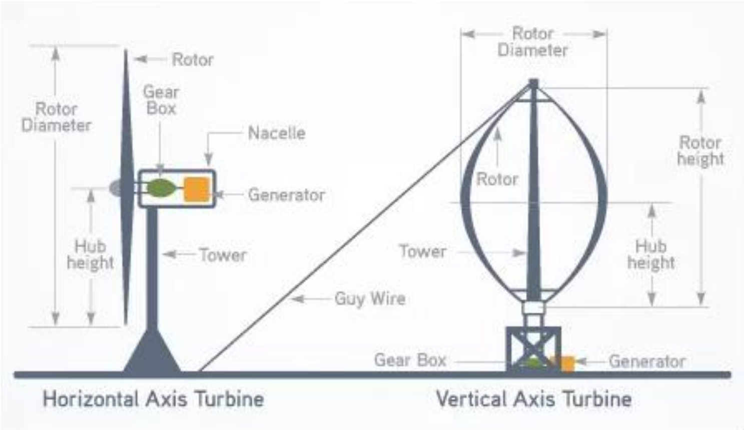

Figure 2.1 Two Main Types of Wind Turbines [23]

2.3.1 Horizontal Axis Wind Turbines

Wind energy converters with their axis of rotation in a horizontal position are realized almost exclusively on the basis of propeller orturbine like concepts.This design, which comprises European windmills asmuch as the American wind turbine ormodern wind turbines represents the dominating design principle of wind energy technology. Rotor speed and power output can be controlled by pitching the rotor blades around their longitudinal axis. Blade pitching can be used as a highly effective protection against overspeed and extreme wind speeds, especially for large wind turbines.

The rotor blade shape can be aerodynamically optimized and achieves its highest efficiency when the aerodynamic lift is exploited to maximum with lower drag force. These are the main advantages of this design. Figure 3.5 shows the schematic concept of a horizontal axis wind turbine. Thistype of turbines can be classified by two main concepts first of them is blade number and the other one is by determining the rotor position to wind as upwind or downwind. Nowadays largest capacity, in a horizontal axis wind turbine is three bladedupwind type, is 5 MWwith a 126.3 m rotor diameter and 120mheight tower installed in Hamburg/Germany [24].

2.3.2 Vertical Axis Wind Turbines

Wind turbines with a vertical axis of rotation represent the oldest design.

Initially vertical axis rotors could only be built as pure drag rotors. Later researchers have succeeded in developing vertical axis designs which could alsoeffectively utilize the aerodynamic lift. The specific advantages of vertical axisturbine conceptsare, their basically simple design includingthe possibility ofaccommodating mechanical and

electrical components, gear box and generator on the ground and the absence of a yaw system. This causes somedisadvantages like low tip speedratio, its inability to selfstart and not being able to control power output orspeed by pitching the rotor blades.
The Savonius rotor, the Darrieus rotor and H rotor concepts are the main types of vertical axis machines. The Savonius rotor can be found as ventilators or cupanemometers. The constructionissimple andinexpensive.The lift solidity
produces high starting torque so Savonius rotors are used for water pumping. Due to its low tip speed ratio and its comparatively low power coefficient it isn’t suited for electricity generation. In the Darrieus rotor, the rotation of blades follows a spinning rope pattern, with a vertical axis of rotation which utilizes aerodynamic lift force. A variation of the Darrieus rotor is the so called H rotor. Instead of curved rotor blades, straight blades connected to the rotor shaft by struts are used. It is also known as Musgrove rotor concep [24].

2.4 Components of a Wind Turbine

Wind Turbine converts the straight linear air flow to rotation motion via its components which are rotor blades, transmission system, generator, brake system, yaw system, blade pitch mechanism and tower.

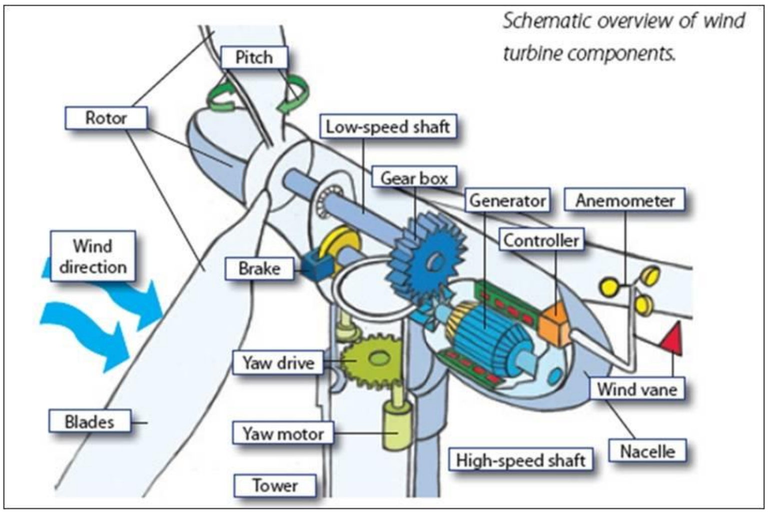

Figure 2.2 Components of a Conventional Wind Turbine [25]

All of these components might be in a wind turbine or may not be depending upon its type. To illustrate, while a horizontal axis wind turbine (HAWT) needs a transmission system, vertical axis wind turbine (VAWT) does not need. All of the components will be explained below regardless of its type. [25].

2.4.1 Rotor Blades

Rotor blades vary depending on its type. Basically wind turbine is subdivided in two types which are VAWT and HAWT. However, VAWT is also subdivided in two groups which are Darrieus wind turbine and Savonius wind turbine.

A Darrieus style of wind turbines uses lift mechanism to rotate the shaft. The design of blades is in shape of airfoil which results lift mechanism. Today, most of the Darrieus style of vertical axis wind turbine is designed in helical shape to obtain less vibration, noise levels and to gain more energy by enhancing the efficiency. A representative figure for lift mechanism of blades of Darrieus style of wind turbine is shown below.

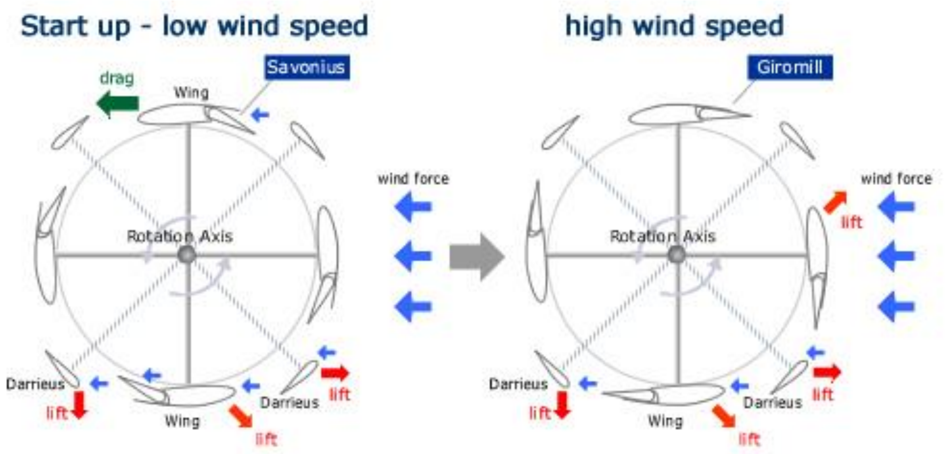

Figure 2.3 Lift Mechanism of Darrieus Style Wind Turbine blade

A Savonius style of wind turbine uses drag force to rotate the shaft. Although the blade shape can be a simply cup design, it can be more complex structure by parametric blade design to increase efficiency by increasing drag force. The idea of the design of blades is based on obtaining different drag forces at front and back faces which creates a moment on shaft. A simple Savonius style of wind turbine blades are shown in figure below [26].

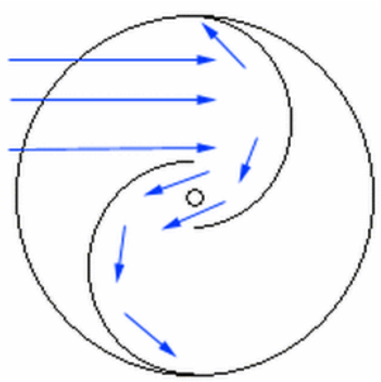

Figure 2.4 A Simple Savonius Style of Wind Turbine Blades [26]

HAWT type of wind turbine uses blades which rotation direction is vertical to shaft rotation direction. HAWT type of wind turbine is also based on airfoil structure which results lift mechanism by pressure difference between upper and lower surfaces. Number of blades of HAWT type of wind turbine can vary; nonetheless, two or three blades are most efficient. A figure for HAWT blades is shown below [27].

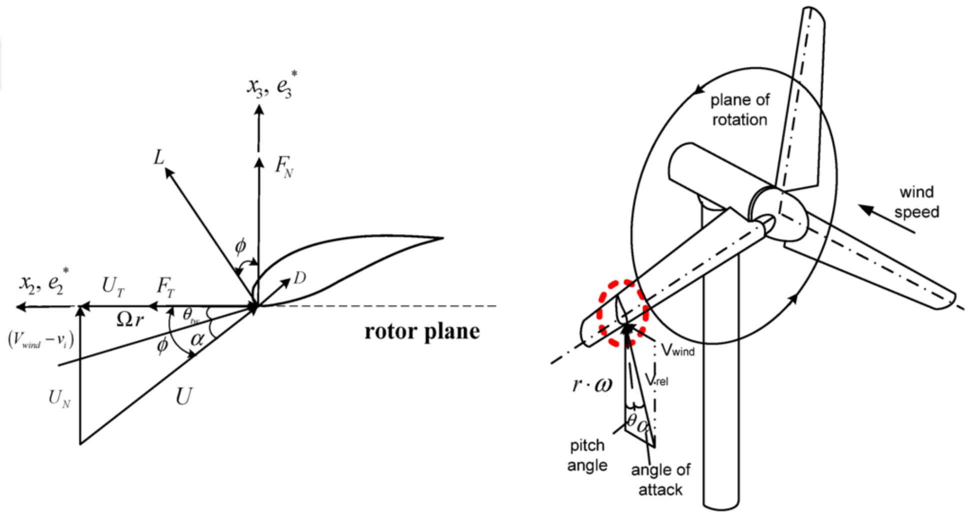

Figure 2.5 A Figure for HAWT Blades [27]

2.4.2 Transmission System

Transmission system is used to change the rotational speed of the shaft for the generator via gearbox mechanism since electrical generator speed is higher compared to rotor speed. Gearbox increases the rotational speed of rotor to higher speed. Each tooth in gearbox is too much loaded because the power is power is located on each tooth of the gear which is used for transmission [27].

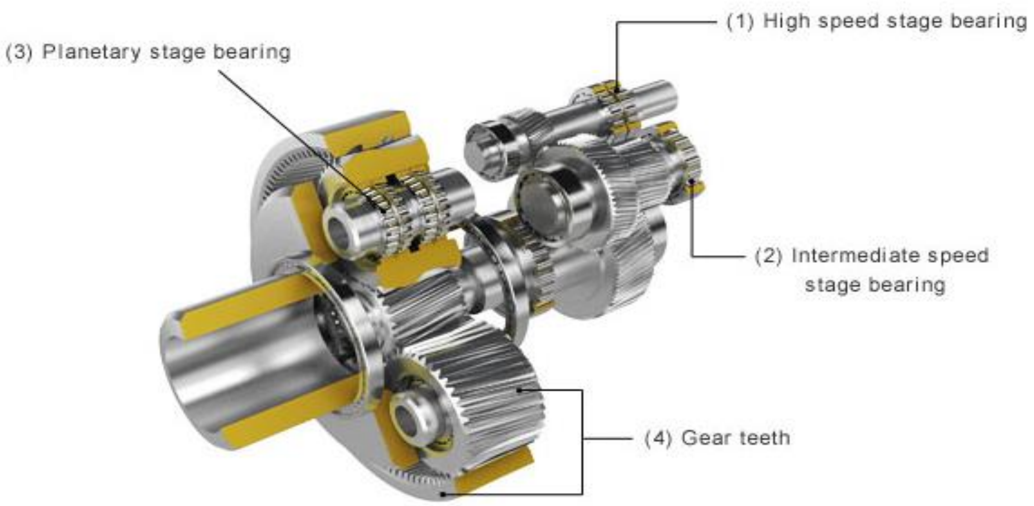

Figure 2.6 A Figure for Transmission System [27]

2.4.3 Generator

Generator is used to convert energy from mechanical to electrical. There are two types of generator which are synchronous generator and induction generator used in wind turbines. Induction generator has a non-rotating part named stator. Stator connected to load. Working mechanism is rotating at constant speed via magnetic field which is provided by three phase winding on a multiplex iron core. Difference of synchronous generators compared to induction generators is magnetic field creation form. Synchronous generator uses direct current to create magnetic field.

Figure 2.7 Wind turbine Generator. [27]

2.4.4 Brake System

Brake system is used to prevent damages on wind turbine when speed of wind exceeds the certain level. Being not able to stop the turbine may lead to irremediable results at wind turbine. There are two types of braking system which are Aerodynamic Braking System and Mechanical Braking System.

Aerodynamic Braking System is based on rotation of the turbine blades 90 degrees by using spring. Aerodynamic system is safe enough to stop the rotor without create a stress or wear at the turbine system. Mechanical Breaking System is used to repose the rotor. It is kind of back-up system for hydraulic system [27].

2.4.5 Yaw System

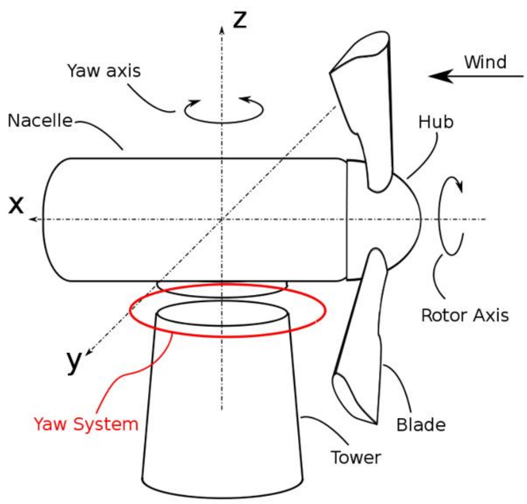

Figure 2.8 A Figure for Yaw System [28].

Yaw mechanism is the system responsible for giving direction to the turbine and so the blades towards the wind. For wind turbines operating in the dominant wind direction it is crucial in order to produce maximum amount of the electrical energy. Thus, yaw mechanisms are components of horizontal axis wind turbines. A yaw error implies that a lower share of the energy in the wind will be running through the rotor area because the generated energy is going to be proportional to the cosine of the yaw error.

2.4.6 Blade Pitch Mechanism

Blade Pitch Mechanism is used to change position of blades with respect to wind speed to obtain better power curve. This position changes is achieved by rotation of blades around its longitudinal axis. Blade pitch mechanism is designed and controlled electronically [27-28].

2.4.7 Tower

Tower is a component which carries the generator, transmission system and rotor. The height of the tower is important since the speed of wind increases with respect to distance from ground. Besides, the turbulence decreases with higher height of tower since there will be elimination of turbulence factors such as trees and buildings.

CHAPTER 3

SYSTEM DESCRIPTION

3.1 Governing Equations of Wind Energy

3.1.1 Amount of Energy That Can Be Obtained From Wind

Wind turbines basically absorb the kinetic energy of moving wind in an amount and convert it first mechanical and then further electrical energy. Hence, the amount of energy that can be obtained from a wind turbine is limited with the kinetic energy of the incoming wind and how much of it could be used. The kinetic energy of an incoming wind is as following:

$$\boldsymbol{E_k = \frac{m{V_u}^2}{2}} \tag{3.1}$$

With some basic manipulations, the amount of energy that can be obtained from wind in motion in unit time can be expressed as following:

$$\boldsymbol{P = \frac{\rho A{V_u}^3}{2}} \tag{3.2}$$

As it can be seen from the equation above, when fluid density is accepted as constant, the power of an incoming wind has two main parameters: Cross-sectional area of the turbine and speed of the incoming wind.

Cross-sectional area is an important design parameter in wind turbines. When average velocity and wind characteristics of a region are known, it simply determines the amount of the available power. For vertical axis turbines it is equal to rotor diameter time height and rotor diameter for horizontal axis turbines. Hence, it can be said that this way cross-sectional area determines the dimensions of the wind turbine.

Velocity of incoming wind has further influence on the available power. Thus, before the design process has started, the wind characteristics of the interest are should be investigated carefully.

3.1.2 Wing Tip Speed Ratio

Tip speed ratio (λ) is described as ratio of speed of blade tip to the incoming wind speed.

$$\boldsymbol{\lambda = \frac{\omega R}{V_u}} \tag{3.3}$$

Tip speed ratio (TSR) has a vital importance in the design of wind turbine generators. If the rotor of the wind turbine turns too slowly, most of the wind will pass undisturbed through the gap between the rotor blades. Alternatively if the rotor turns too quickly, the blurring blades will appear like a solid wall to the wind. Therefore, wind turbines are designed with optimal tip speed ratios to extract as much power out of the wind as possible [29].

3.1.3 Power Coefficient and Betz Limit

The coefficient of power of a wind turbine is a measurement of how efficiently the wind turbine converts the energy in the wind into electricity [30]. Amount of energy that can be obtained from wind in motion was shown in previous section. It is major subject to determine and improve the availability of that energy by the wind turbine. By neglecting the frictional and mechanical losses, the maximum energy that can be obtained from a wind turbine is examined by Frederick W. Lanchester (1915) and Albert Betz (1919) which can be found in Reference [30].

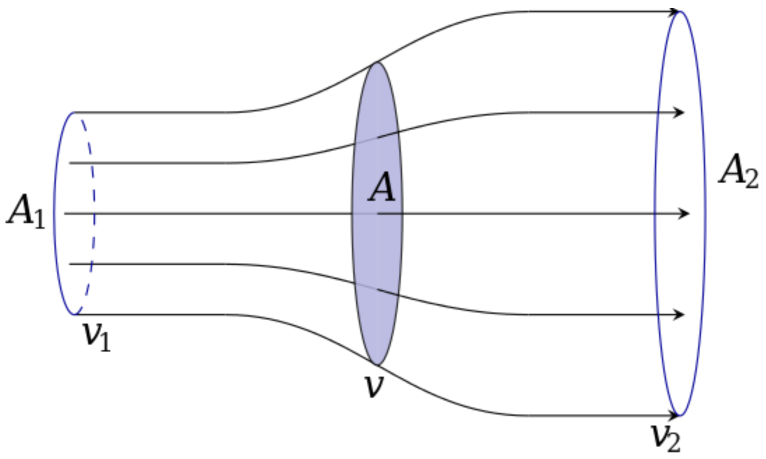

Figure 3.1 Schematic of fluid flow through a disk-shaped actuator for a constant density [30]

In figure 3.1, it is shown that an incoming wind with a velocity of V_1 leaves the turbine with a velocity V_2. It is also seen that cross-sectional area of the incoming wind is inversely proportional to speed of the wind. When considering the kinetic energy difference, it can be said that the amount of energy absorbed by the turbine is as following:

$$\boldsymbol{P_a = \frac{\rho A}{2}(V_1{}^3 - V_2{}^3)} \quad (3.4)$$

Continuity and mass flow rate formulations can be written as:

$$\boldsymbol{\dot{m} = \rho \dot{V}} \quad (3.5)$$

$$\boldsymbol{\rho V_1 A_1 = \rho V_2 A_2} \quad (3.6)$$

Rearranging the equation yields:

$$\boldsymbol{P_a = \frac{\dot{m}}{2}(V_1{}^2 - V_2{}^2)} \quad (3.7)$$

Hence, the amount of the energy absorbed can be increased by decreasing the exit velocity when the mass flow rate ($\dot{m}$) is assumed as constant. When exit velocity is considered as zero, from equation above it is also shown that initial velocity becomes zero too. This discrepancy may be revealed by the conservation of momentum equation.

The wind force on the rotor can be written as:

$$\boldsymbol{F_r = \dot{m}(V_1 - V_2)} \quad (3.8)$$

According to Newton's third law, the rotor should develop a counteracting force against this wind force. The power required to overcome this force is:

$$P' = F_r V' = \dot{m}(V_1 - V_2)V' \quad (3.9)$$

The pressure difference due to velocity drop (P_a) should be equal to the P' which is due to momentum transfer.

$$\dot{m}(V_1 - V_2)V' = \frac{\dot{m}}{2}({V_1}^2 - {V_2}^2) \quad (3.10)$$

Hence, the velocity on the rotor (V') becomes:

$$V' = \frac{V_1 + V_2}{2} \quad (3.11)$$

Rearranging the mass flow rate on the rotor:

$$\dot{m} = \rho A V' = \rho A \frac{V_1 + V_2}{2} \quad (3.12)$$

When mechanical and frictional losses are neglected, the maximum power that can be converted becomes:

$$P = \rho A \frac{({V_1}^2 - {V_2}^2)(V_1 + V_2)}{4} \quad (3.13)$$

As expressed before, the energy carried by a wind in motion with a velocity V_1 in unit time is:

$$P_0 = \frac{\rho A {V_1}^3}{2} \quad (3.14)$$

Ratio of the power that can be converted by wind turbine to the power that wind in motion carries is expressed as power coefficient (C_p) and in the formulation of;

$$C_p = \frac{P}{P_0} = \frac{\rho A \frac{({V_1}^2 - {V_2}^2)(V_1 + V_2)}{4}}{\frac{\rho A {V_1}^3}{2}} \quad (3.15)$$

Rearranging:

$$C_p = \frac{P}{P_0} = \frac{1}{2}\left\{1 - \left[\frac{V_1}{V_2}\right]^2\right\}\left\{1 + \left[\frac{V_1}{V_2}\right]\right\} \quad (3.16)$$

Last equation shows that power coefficient depends only on the entrance and exit velocities of the wind turbine. In order to find the maximum value of the power coefficient derivative of the last equation can be taken.

The results yield:

$$C_p = \frac{16}{27} = 0.5926 \qquad (3.17)$$

This way the maximum value of the power coefficient is found and it is named as Betz Limit. When this limit is reached, the velocity on the rotor becomes:

$$V' = \frac{2}{3} V_1 \qquad (3.18)$$

While designing a wind turbine, equations above and thus Betz Limit are one of the essential parameters and limiting value.

In practice the power coefficient of turbines are lower due to inefficiencies and losses attributed to different configurations. In fact, the type of the turbine is a major parameter that limits the power coefficient.

The map of wind turbines, gives an overview of power coefficient (C_p) as a function of tip speed ratio (λ). The numbers are estimated efficiencies only. From theory (Betz, Glauert), there are clear efficiency limits, but no theoretical maximum TSR. In contrast, the semi-empirical curves for each type of wind turbine have a clearly defined maximum efficiency value [31].

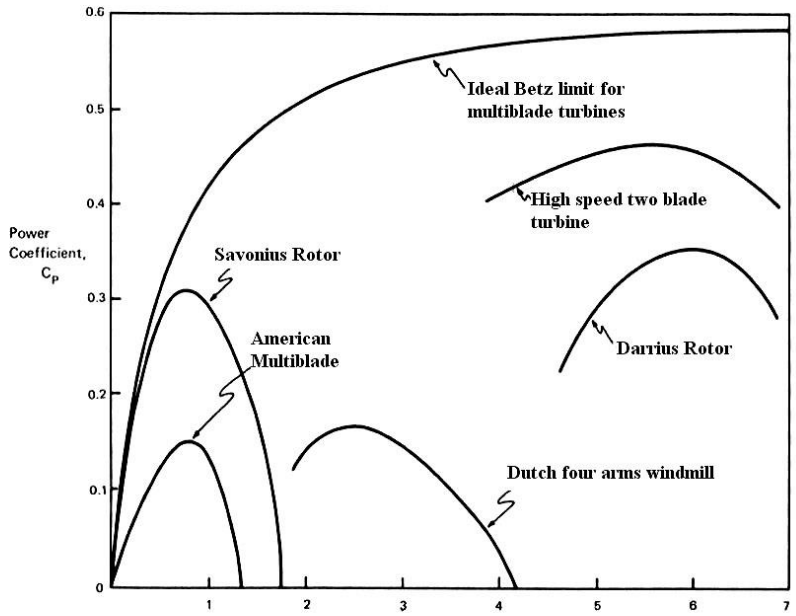

Figure 3.2 Map of wind turbines [32]

The discrepancy is caused by drag and tip losses but the stall also reduces the C_p at low values of the tip speed ratio. Even with no losses included in the analysis the Betz limit is not reached because the blade design is not perfect [32].

It can be clearly seen that every design has its own theoretical limits. From this point of view it can be said that savonius type wind turbines are expected to have a C_p value around 0.3.

3.1.4 Mechanical Efficiency

In the previous chapter, limits of energy conversion was expressed in detail. In practise, this conversion leads to many losses. The wind turbine involves gearbox, generator, alternator, convertor, control equipments and cables which obviously cause some energy losses. The mechanical efficiency of a wind turbine is actually sum of all these electronic, mechanical and control equipments' efficiencies.

In general, mechanical efficiency can be examined in three basic sub-topics.

- Gearbox Efficiency
- Generator Efficiency
- Electrical Efficiency

Hence, overall efficiency becomes:

$$\boldsymbol{\eta_{overall} = \eta_{g-box}\eta_{gen}\eta_e} \tag{3.19}$$

Finally, the energy that can be produced by the turbine in an unit time in a practical application becomes:

$$\boldsymbol{P = \frac{1}{2}\eta_o \rho A V_u{}^3} \tag{3.20}$$

The drag force can be expressed as:

$$\mathbf{F_d = C_d\ 1/2\ \rho\ v^2\ A} \tag{3.21}$$

3.1.5 Capacity Factor

Due to the natural characteristics of the wind, a wind turbine may not generate power at any instance. For that reason, capacity factor is defined as the ratio of the turbine's power generated to the power estimated for a period of time. Hence, the capacity factor is strongly dependent on wind characteristics e.g. wind speed. For large scale turbine capacity factor is around 0.25-0.4. Moreover, it is one of the essential factors while an investment in wind turbine in an area is planning.

3.2 Wind Turbine Performance

Performance of a wind turbine is characterized by three main concepts which are varying with the wind speed: Power, torque and thrust. These three concepts contributes the overall turbine design in different ways. Power of a turbine indicates the amount of energy captured by the rotor, torque of a turbine is main property determining the alternator and gearbox design and total thrust provides necessary information related to tower design. As a scientific approach, performance indicators are usually represented with non-dimensional parameters. This way any design processes can be carried out regardless of operation conditions and dimensions.

3.2.1 C_p – λ Curve and Determination of Blade Number

It is a common phenomenon to represent the power performance on the $C_p - \lambda$ curve which is a dimensionless curve. In the selection process, experimental curves are guidelines for designers. Thank to researchers and scientists, today there are many studies carried out comparing the blade number for their performance on savonius type wind turbine. In the following figures, experimental $C_p - \lambda$ curves are shown with many number of blades for HAWT and Savonius VAWT types.

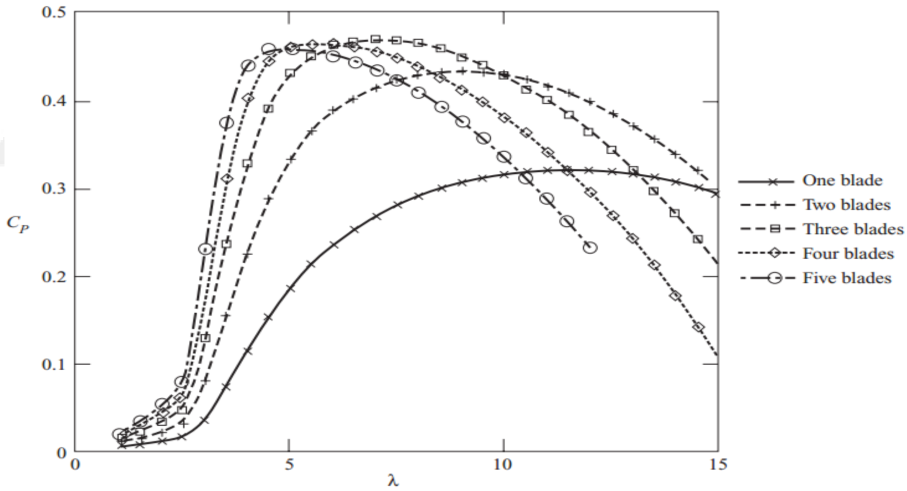

Figure 3.3 $C_p - \lambda$ Curve of HAWT for different number of blades[32].

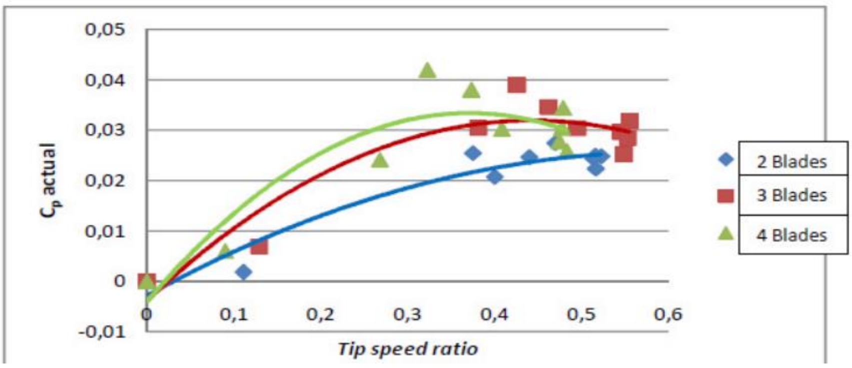

Figure 3.4 $C_p - \lambda$ Curve of Savonius VAWT for different number of blades [33].

Results obtained from the figures and relevant studies are following:

- Four blades wind turbine has good performance at lower tip speed ratio, but three blades wind turbine has the best performance at higher tip speed ratio.
- When considering the spread of the maximum values, 3 blades configuration offers a good solidity compared to other configurations.
- High solidity produces a narrow performance curve with a sharp peak making the turbine very sensitive to tip speed ratio changes and, if the solidity is too high, has a relatively low maximum C_p. The reduction in maximum C_p is caused by stall losses.

When self self-starting and directional independence of turbine came into the front it is not practical to study with two blade savonuis. Hence, decision is made to design the turbine with three blades.

3.2.2 $C_Q - \lambda$ Curve and Alternator Selection

The torque coefficient is derived from the power coefficient simply by dividing by the tip speed ratio and so it does not give any additional information about the turbine's performance. The principal use of the $C_Q - \lambda$ curve is for torque assessment purposes when the rotor is connected to a gear box and/or generator.

This is an important concept for the alternator design because the curves show the optimum torque intervals for various number of blades. In the "Alternator Selection" part more details are given about this topic.

3.2.3 $C_T - \lambda$ Curve and Tower Design

Thrust force is directly applied to the turbine and eventually to the tower. The force exerted is met by the occurred balancing forces at the tower. Broadly speaking, the thrust on the rotor increases with increasing solidity [32].

The forces and moments are important for the tower design. Since tower design is not included in this study, this part is just mentioned.

CHAPTER 4

System description and model development

The rotor geometry of the turbine is determined in the base of creating the most efficient geometry since there is not any methodology of determining the geometry. For that purpose; types of vertical axis wind turbines are compared in the respect of suitability of the aims and limitations of the project.

When the aims and limitations of this project is considered, wind turbines with a vertical axis are to be studied. Today, there exist many types of VAWT but savonius wind rotor has many advantages over others in that its construction is simpler and cheaper. It is independent of the wind direction and has a good starting torque at lower wind speeds. Hence, it is concluded that savonuis type VAWT is going to be examined pursuant to all these factors. Compared to the darrieus turbines, the low efficiency of savonuis is aimed to be improved at this part of the project.

As mentioned before, this part of the project aims to increase the efficiency of the savonius type wind turbine. For that purpose; previous studies are carefully investigated and final design is aimed to be created by a three stage study. The work plan of this study is demonstrated in the figure below.

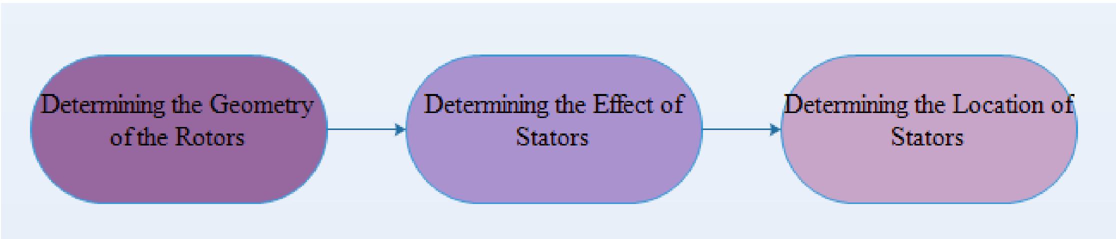

Figure 4.1 Work Plan of Turbine Design

4.1 Determinantın of Rotor Geometry

As it can be seen in the figure above, first step is determining the geometry of the rotors. For that purpose, Computational Fluid Dynamics (CFD) analyses are used to examine the efficiency of the every single geometry. In order to find the most efficient geometry, parametric geometries are created and much iteration is executed.

It should also be pointed out that in order to provide ease and increase the total number of computed models; 2D rotational CFD methodology is used. When considering the capacity of the computers available, it is a less time consuming method compared to 3D computations.For that purpose, each geometry is modelled in the CATIA V5R20 software and extracted from the defined fluid flow region. Models are consisted of two major volumes:

Rotating Frame Boundary conditions

Non-Rotating Frame Boundary conditions

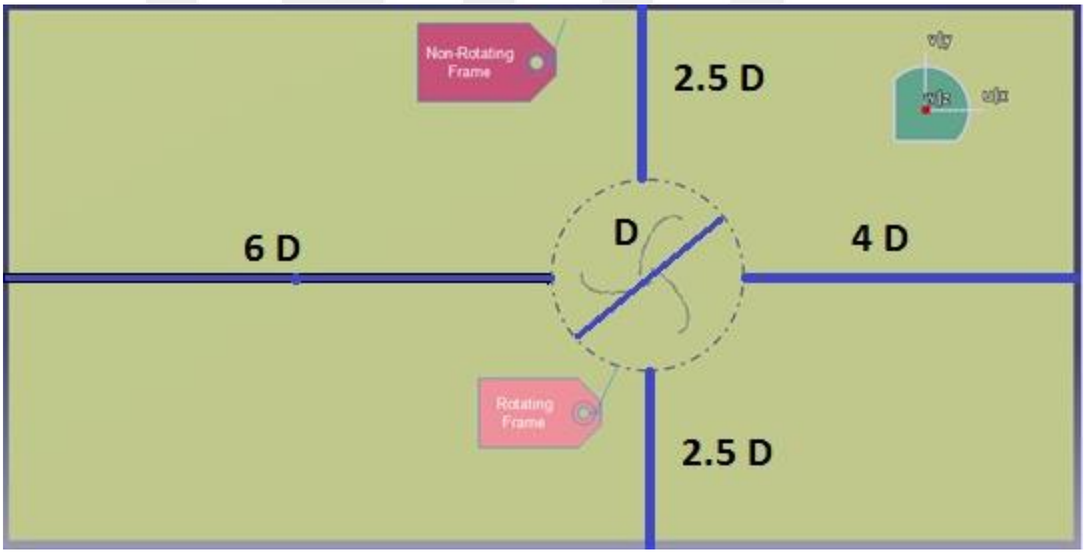

Figure 4.2 Boundary condition (Preparation of Model for CFD Analysis)

After the model is prepared, next step is to mesh the geometry. In order to sustain reliability for comparison of blade geometries all the CFD processes are made in the same or similar fashion.

(Spalart-Allmaras) (SA) turbulence model used in this study

Spalart-Allmaras is a low-cost RANS model solving a transport equation for a modified eddy viscosity. İts Mainly intended for aerodynamic/turbomachinery applications with mild separation, such as supersonic/transonic flows over airfoils, boundary-layer flows, etc. Embodies a relatively new class of one-equation models where it is not necessary to calculate a length scale related to the local shear layer thickness. İt is Designed specifically for aerospace applications involving wall-bounded flows. It has been shown to give good results for boundary layers subjected to adverse pressure gradients.

The one-equation model is given by the following equation: The turbulent eddy viscosity is computed as: 1e-5

$$\frac{\partial \hat{\nu}}{\partial t}+u_j\frac{\partial \hat{\nu}}{\partial x_j}=c_{b1}(1-f_{t2})\hat{S}\hat{\nu}-\left[c_{w1}f_w-\frac{c_{b1}}{\kappa^2}f_{t2}\right]\left(\frac{\hat{\nu}}{d}\right)^2+\frac{1}{\sigma}\left[\frac{\partial}{\partial x_j}\left((\nu+\hat{\nu})\frac{\partial \hat{\nu}}{\partial x_j}\right)+c_{b2}\frac{\partial \hat{\nu}}{\partial x_i}\frac{\partial \hat{\nu}}{\partial x_i}\right] \tag{4.1}$$

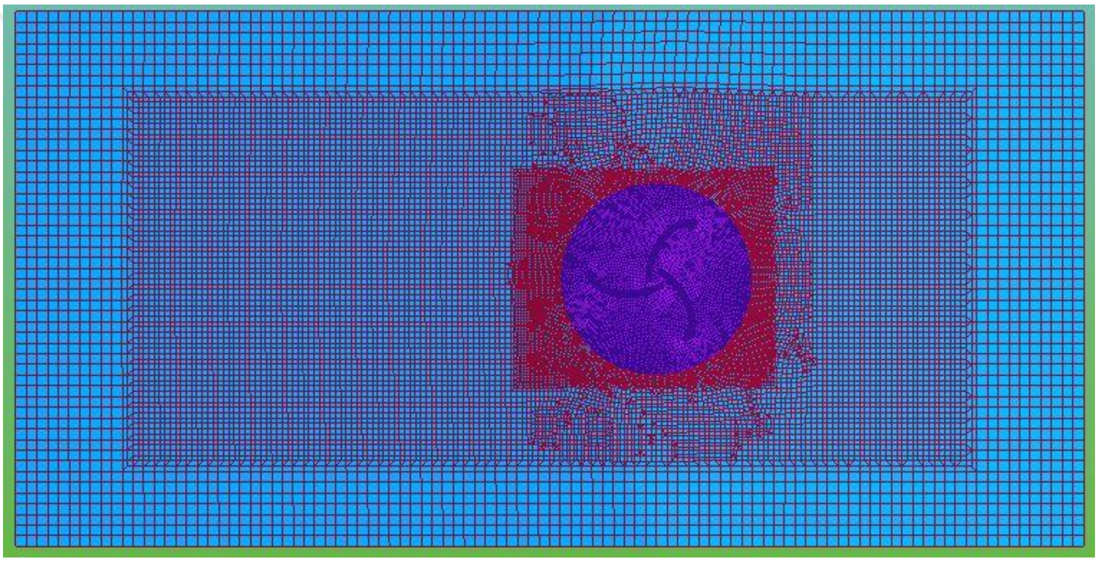

Figure 4.3 2D Rotational CFD Model

All of the CFD studies are executed in standard dimensions and mesh structure. In the table below, mesh structure and Boundary Layer properties for 2D Rotational CFD studies are given.

Table 4.1 Mesh Structure Properties

Mesh Structure Properties	**Corresponding value [Meter]**
Mesh Geometry	Quads+ Trics
Total Elements	20,000
Mesh Thickness	0.04

Table 4.2 BL Properties

BL Properties	Corresponding Value [Meter]
Number of Layers	12
First Layer Thickness	0.0007
BL Growth Rate	1.2
Element Size	0.012
Element Type	Quads Only
BL Reduction	Disabled
Mesh Thickness	0.04

Table 4.3 Dimensions for the CFD Model

Parameter	Dimensions [m]
Rotor Diameter	1.245
Rotor Height	0.04
Overlap Ratio	0.16
Blade Thickness	0.006

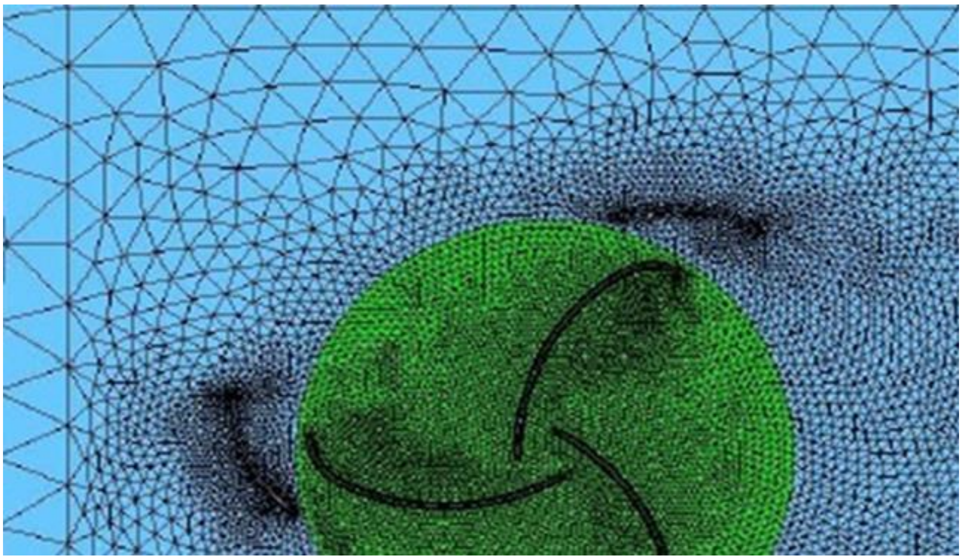

Figure 4.4 Computational mesh domain and enlarged view around squid surface

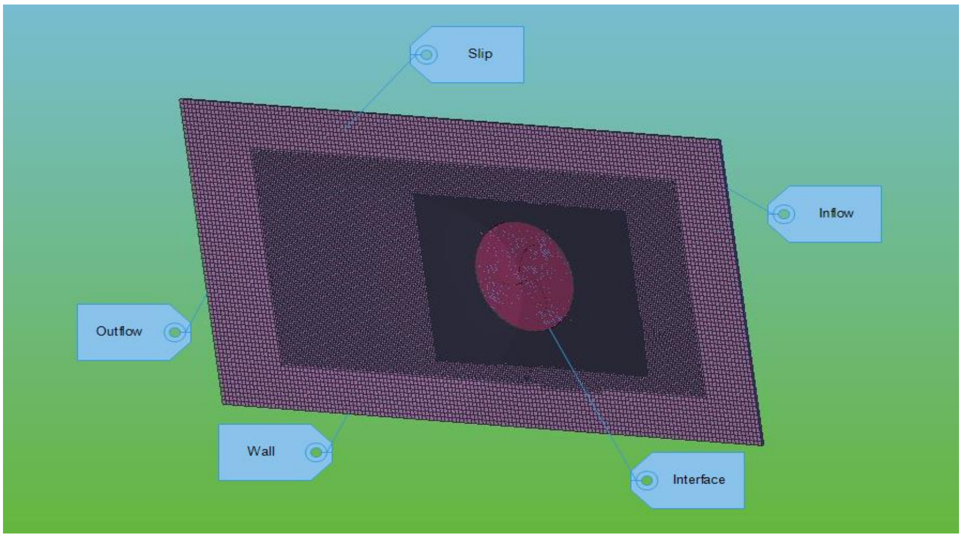

Figure 4.5 Boundary Conditions Defined in CFD Studies

Also, it is known that savonius wind turbines with having an overlap ratio (β) of 0.21 has the best efficiency [30]. In all the models, this overlap ratio is preserved. The definition of overlap ratio is given as following:

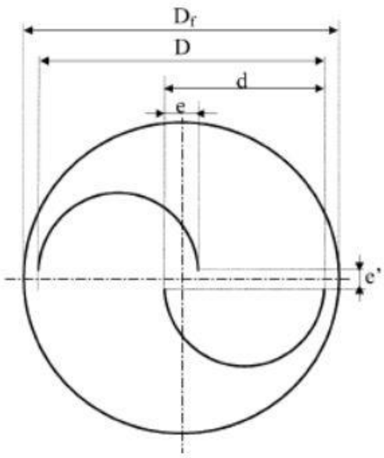

Figure 4.6 Overlap Ratio for Savonius VAWT [30]

$$\boldsymbol{\beta} = \frac{\boldsymbol{e}}{\boldsymbol{d}} \qquad (4.2)$$

In urban areas, average wind speed can be taken as 6 m/s.[17] From previous studies it is known that optimum tip speed ratio of savonius wind turbine is around 0.8 [32].

The blade geometry has a special importance since it is the main part that limits the efficiency. The geometry which is going to be examined should be carefully investigated before starting the CFD studies. For that purpose it can be said that blade design can be created in the standard circular or some arbitrary shaped geometric bases. In this part of the study it is aimed to improve the efficiency of standard circular shaped blades with suggested 2 design alternatives.

4.1.1 Design Alternative #1

A very initiatory idea was constituted in the basis of creating the blade through three circle intersection points. For that purpose, a circle with a diameter ϕ_1 and symmetrical secondary circles with diameter ϕ_2 are created as in the figure.

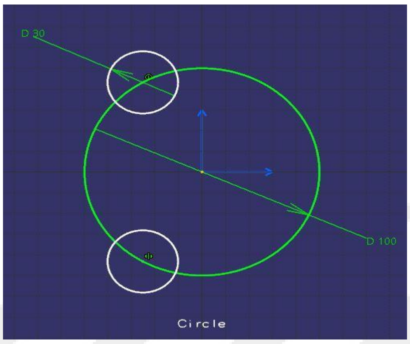

Figure 4.7 A Circle with Diameter ϕ_1 and tow Symmetric Circles with Diameter ϕ_2

Further, a circle with diameter ϕ_3 is created tangent to three other circles. Blade end is determined by two inclined lines from the origin. First line determines the location of the smallest circle location and second determines blade tip. These two parameter is represented by the angle between them (α_1) since there is only one line that passes through the small circle center with three circle combination.

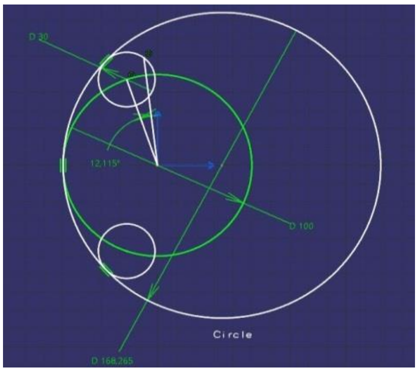

Figure 4.8 Final Parametrization of Blade Geometry Design #1

Consequently 4 parameters are created (ϕ_1 , ϕ_2 , ϕ_3 and α_1). The modified 3-blade geometry is to be in the following manner.

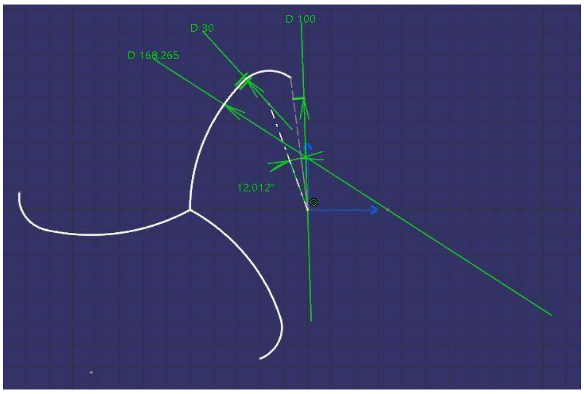

Figure 4.9 Final Three Blade System Design for Alternative #1

The parametrization step is completed. Arbitrary values are set for each parameter and shown in the table below. The effect of each parameter for the efficiency of turbine is uniquely calculated. This inference is obtained by changing one parameter while other parameters remain constant.

Table 4.4 List of Parameters Set for Design Alternative #1

Model Number	**Small Diameter X [MM]**	**Large Diameter Y [MM]**	**Tangent Circle Diameter U [MM]**	**Angle V [Digree]**
1	80	700	1300	5
2	100	700	1300	5
3	120	700	1300	5
4	140	700	1300	5
5	250	700	1300	5
6	140	700	900	4
7	140	700	1000	5
8	140	800	1000	4
9	140	600	900	4

With this test methodology, 5 different ϕ_1 values, 3 different ϕ_2 values, 3 different ϕ_3 values and 2 different α_1 values are examined. Consequently, the most efficient geometry is determined as shown on the table below:

Table 4.5 List of CFD results for Design Alternative #1

Model No	**angular velocity [R/S]**	**blade diameter [M]**	**Initial Time Increment**	**efficiency**	**Power [W]**
7	7.61	1.26	0.006874961	0.3132	66.05
9	7.85	1.2605	0.006874961	0.30-0.32	65-67
6	7.61	1.26	0.006874961	0.3128	65.96
8	7.59	1.265	0.006899505	0.3104	65.73
2	7.61	1.263	0.006883142	0.29	57.82
4	8	1.2	0.006544985	0.29	57.58
3	7.61	1.26	0.006544985	0.28	59.82
1	7.85	1.223	0.00667043	0.26	53.63
5	7.61	1.26	0.006544985	0.23	48.35

After all the selection and elimination processes are made with CFD analyses, it is concluded that most efficient geometry is the one notated with X4Y1U2V1. It can be said that it corresponds to the (model 7) for alternative design #1. Subsequent efficient geometries are model 6 and 8.

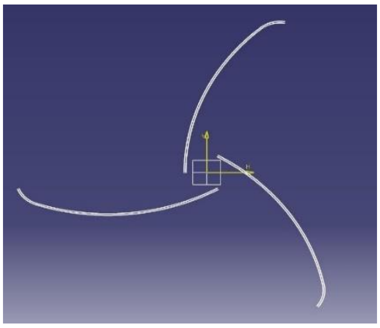

Figure 4.10 Model 7 Blade Geometry for Design #1

4.1.2 Design Alternative #2 (elliptical)

A secondary idea was constituted in the basis of creating the blade through an ellipse and circle intersection points. For that purpose an ellipse with major radius r_1 and a minor radius r_2 is created.

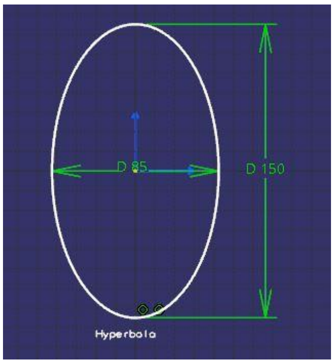

Figure 4.11 An Ellipse with major radius X and a minor radius Y

After, a tangent circle with radius r_3, an angle between centers of ellipse and circle ϑ_1 and ending point with inclination ϑ_2 from the center is created.

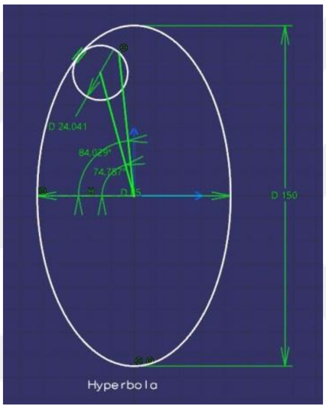

Figure 4.12 Final Parametrization of Blade Geometry Design #2

Consequently, 5 total parameters are occurred to determine the geometry (r_1, r_2, r_3, ϑ_1 and ϑ_2). The modified 3-blade geometry is to be in the following manner.

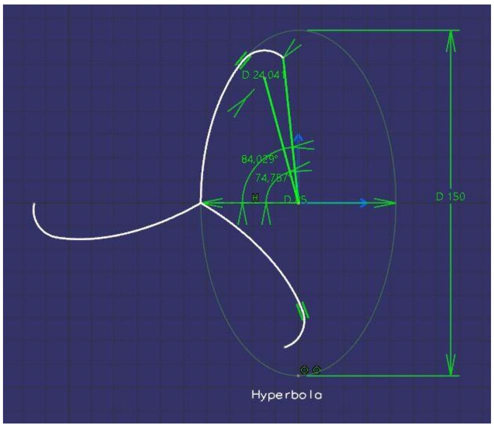

Fig 4.13 Final Three Blade System Design for Alternative #2

The parametrization step is completed. After, some arbitrary values are set into the 5 parameters. The effect of each parameter into the efficiency of turbine is uniquely calculated by changing their value while other remains constant.

With this methodology, 15 blade geometries are created and comparisons of their efficiencies are done by 2D rotational CFD. List of values set and notations for models are given as following.

For simplicity, the parameters Major Radius (r_1), Minor Radius (r_2), First Angle (ϑ_1), Second Angle (ϑ_2) and Circle Diameter (r_3) are represented by the letters X, Y, U, V and Z respectively. With 15 total different geometries;

7 Different Major Radius

9 Different Minor Radius

2 Different First and Second Angle

Table 4. 6 List of Parameters Set for Design Alternative #2

Model Number	**Major Radius X [mm]**	**Minor Radius Y [mm]**	**First Angle U [digree]**	**Second Angle V [digree]**	**Circle Diameter [mm]**
1	580	500	65	80	150
2	580	450	65	80	150
3	600	400	65	80	150
4	625	400	65	80	150
5	600	475	65	80	150
6	640	400	65	80	150
7	600	500	65	80	150
8	590	510	65	80	150
9	580	530	65	75	150
10	580	550	60	75	150
11	625	460	65	80	150
12	630	450	65	80	150
13	630	440	65	80	150
14	650	530	60	75	150
15	630	440	65	80	150

Table 4.7 List CFD results for Design Alternative #2

model number	**angular velocity [R/S]**	**blade diameter [M]**	**Initial time increment**	**efficiency**	**Power [Wat]**
1	7.685976615	1.248	0.006812391	0.3232	67.51
10	7.682704312	1.244	0.006815293	0.3223	67.09
8	7.61931369	1.26	0.006871994	0.3204	67.56
11	7.646404756	1.255	0.006847647	0.319	67.1
14	7.735335496	1.241	0.006768921	0.317	65.83
4	7.729232117	1.242	0.006774266	0.316	65.77
13	7.64623423	1.255	0.006847799	0.317	66.58
7	7.640246271	1.256	0.006853166	0.311	65.54
2	7.987273611	1.202	0.006555413	0.3107	62.52
5	7.734787044	1.242	0.006769401	0.318	65.26
12	7.702886817	1.264	0.006797436	0.3108	65.75
9	7.700946575	1.247	0.006799148	0.29	60.51
3	8.119491855	1.182	0.006448664	0.236	46.78
6	7.733353956	1.242	0.006770656	0.22	22.57
15	7.702886817	1.244	0.006795347	0.20	20.04

Values are examined and most efficient combination is determined. The selection and elimination processes are shown in table below.

After all the selection and elimination processes are made with CFD analyses, it is concluded that most efficient geometry is the one notated with X1Y7U2V2. It can be said that it corresponds to the model 10 for alternative design #2. Subsequent efficient geometries are model 1 and 8.

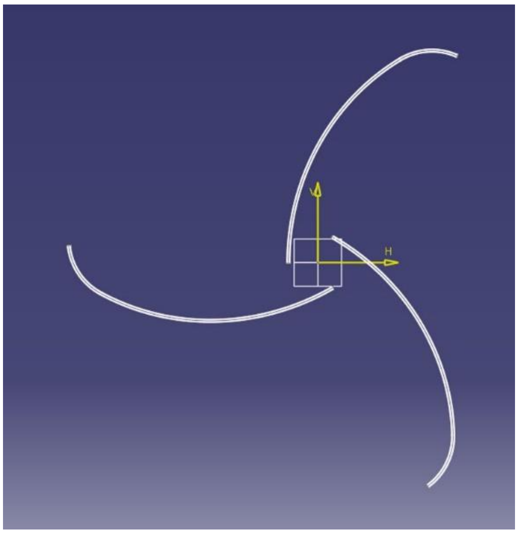

Figure 4.14 Model 10 Blade Geometry for Design #2

Through more than 25 CFD studies, most efficient 6 geometries are selected to be shown in diagrams below. It can be said that among different models and moment-time diagram characteristics which belong to them, the most efficient ones represent moment-time diagram characteristics in similar fashion.

One should consider differences between these similar fashioned Geometries. Hence, the calculations are made for numerical comparison and efficiency ratings are listed. This has led the most efficient geometries to be selected and further examined. Aforementioned diagrams are as following.

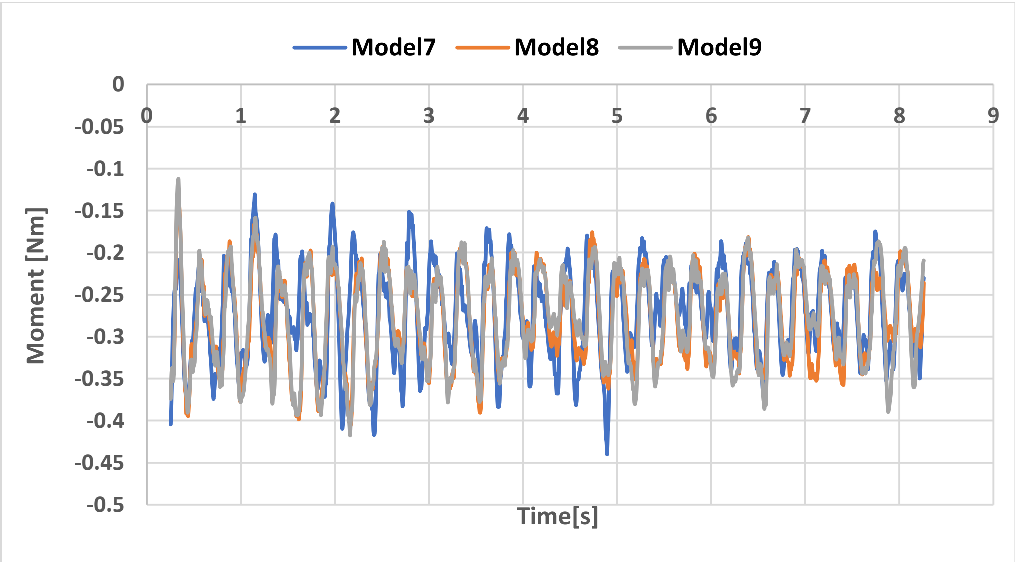

Figure 4.15 Most Efficient Models for Alternative Design #1

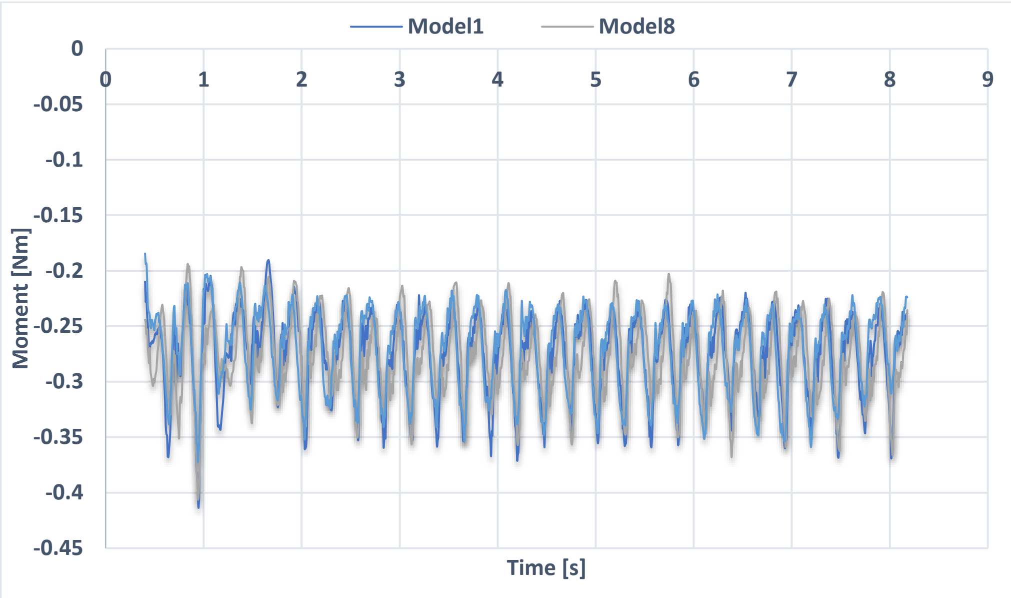

Figure 4.16 Most Efficient Models for Alternative Design #2

Also for clarity, standard circular shaped blade design and overall most efficient geometry (Model #10) are compared. Results have indicated an increase in the average moment and efficiency values. Related diagram is shown below.

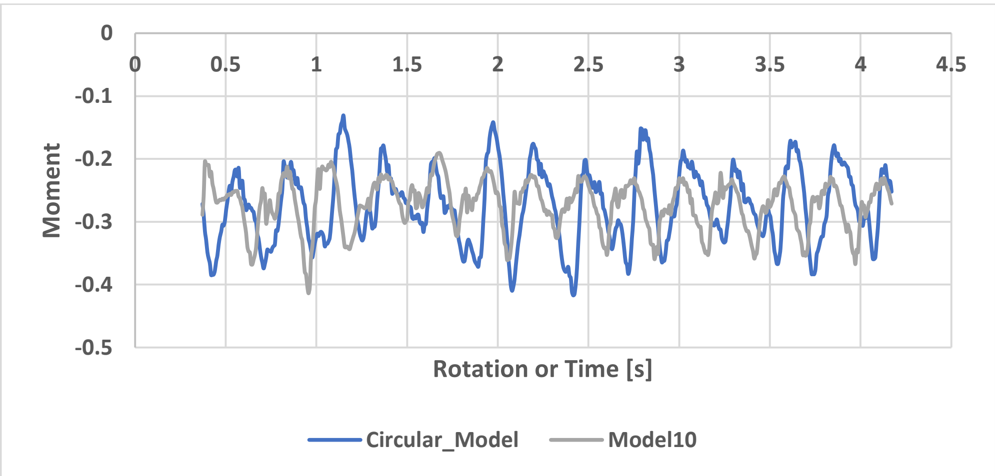

Figure 4.17 Comparison of Model 10 and Standard Circular Shaped Blades

4.2 Determining the Effect of Stators

In this part main objective is to determine whether stators can be added to the system inorder to improve the efficiency or not. From the previous studies it is known that the negative drag blade (passive blade) can be hide behind an obstacle (stator) and it increases the efficiency of the turbine up to %23,8 [33].

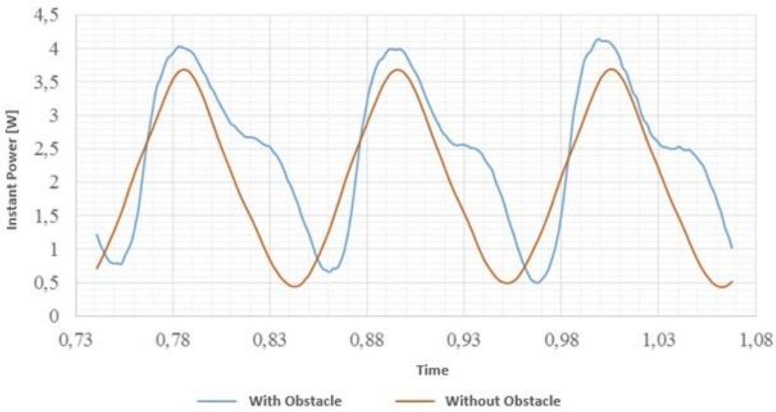

Fıgure 4.18 Comparison of 3-Blade Savonius Wind Turbines with and without Obstacles [33]

4.2.1 Determining the Geometry of Stators

Stator geometry is aimed to be designed in 3 board topics.

- Number of Stator
- Angle of Stator w.r.t Horizontal Axis
- Length of Stator

Rotor geometries are obtained from previous section studies. At this part, the three main topics are investigated separately. The methodology used is the same as previous section in order to sustain reliability.

Firstly, the number of stators should be 3, 6, 9 or 12 since there are three blades and radial symmetry should be preserved. 12 and more stators systems are not investigated since it highly limits the flow. 3 stator system is also not investigated since it is considered to have less influence. Secondary studies are made to determine the angle of stator w.r.t horizontal axis. For that purpose, same rotor geometry is used with stator having an angle of 15,30,…,75 degree w.r.t horizontal axis and CFD analyses are conducted. Finally the best results are given in the tables below.

Table 4.8 CFD result for alternative design #2 with stators

				Efficiency							
				3 stator	6 Stator	9 Stator					
model number	blade radius	angular velocity	efficiency	1	2	3	30deg	45deg	60de	42.5	47.5
1	624.514	7.685976615	0.323	0.301	0.29	0.28	0.301	-	-	-	-
10	621.78	7.682704312	0.323	**0.338**	0.32	**0.335**	0.338	**0.35**	0.3	0.34	0.34
8	629.978	7.61931369	0.32	0.3211	0.304	0.3183	0.3211	-	-	-	-
11	627.746	7.646404756	0.319	0.305	0.2888	0.3023	0.305	-	-	-	-
14	620.529	7.735335496	0.317	0.2898	0.2744	0.2872	0.2898	-	-	-	-
4	621.019	7.729232117	0.316	0.2753	0.2606	0.2729	0.2753	-	-	-	-
13	627.76	7.64623423	0.316	0.2615	0.2476	0.2592	0.2615	-	-	-	-
7	628.252	7.640246271	0.311	0.2485	0.2352	0.2463	0.2485	-	-	-	-
2	600.956	7.987273611	0.31	0.236	0.2235	0.2339	0.236	-	-	-	-
5	620.573	7.734787044	0.31	0.2242	0.2123	0.2222	0.2242	-	-	-	-
12	623.143	7.702886817	0.31	0.213	0.2017	0.2111	0.213	-	-	-	-
9	623.292	7.700946575	0.29	0.2024	0.1916	0.2006	0.2024	-	-	-	-
3	591.17	8.119491855	0.24	0.1923	0.182	0.1905	0.1923	-	-	-	-
6	620.688	7.733353956	0.22	0.1826	0.1729	0.181	0.1826	-	-	-	-
15	621.952	7.717637374	0,20	0.1735	0.1643	0.172	0.1735	-	-	-	-

Table 4.9 the best stator model parameters

Parameter	Best Value	Parameter	Best Value
Number of Stator	9	Number of Stator	3
Stator Angle	45 Degree	Stator Angle	45 Degree
Stator Length	0.4m	Stator Length	0.7m

CHAPTER 5

EXPERMENTAL SETUP AND PROCEDURE

5.1 Structural and Model Analysis of Turbine Using Fem Tools

In this section, the most critical situations related to wind speed and natural frequencies are considered. Rotating parts of the design is considered in structural and modal analysis. Fasteners are not included in the FEM analysis since fasteners strength is calculated manually.

5.1.1 Structural analysis

Firstly, CAD geometry which is drawn in CATİA is imported to HYPERMESH which is used as pre-processor for FEM analysis. CAD geometry covers turbine blades, shafts, blade supports, and connection elements between supports and shaft. Finite element model is created as 2 dimensional (surface) except shaft.

Secondly, model is prepared for structural analysis by HYPERMESH. Model is constraint from bearing position by 6 DOF. Fasteners are represented as rigid elements and parts are connected to each other by rigid elements instead of fasteners like bolt. Static load is calculated for 25 m/s wind speed in a condition that turbine blades are not rotating since most critical conditions occur when turbine blades do not rotate with wind. The reason of choice of 25 m/s wind speed for most critical load is stators are designed as self-closed above the speed of 25 m/s. Therefore, the load is calculated by drag force formula below as 675 N.

$$\boldsymbol{F_D = \frac{1}{2}\rho A C_D {V_u}^2} \quad (5.1)$$

The total wind force is given as nodal force and distributed to total surfaces of one blade by RBE3 elements. Gravity load is also given in a certain direction which corresponds to z-direction in our model. Load-Step is given by SPC and Total Load which covers gravity load and Wind Load. Finite element model is given as following.

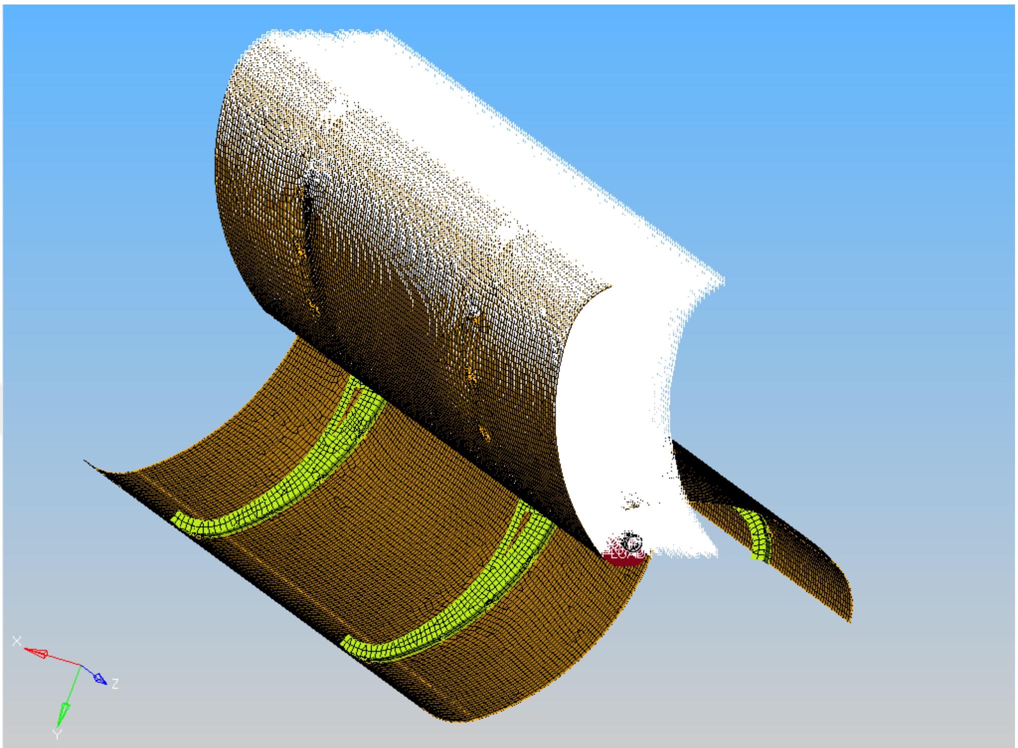

Figure 5.1 Finite Element Model of Wind Turbine for Structural Analysis

Finally, Finite Element Analysis is solved by Optistruct solver. Hyperview is used as post-processor. The stress results of the wind turbine are as following:

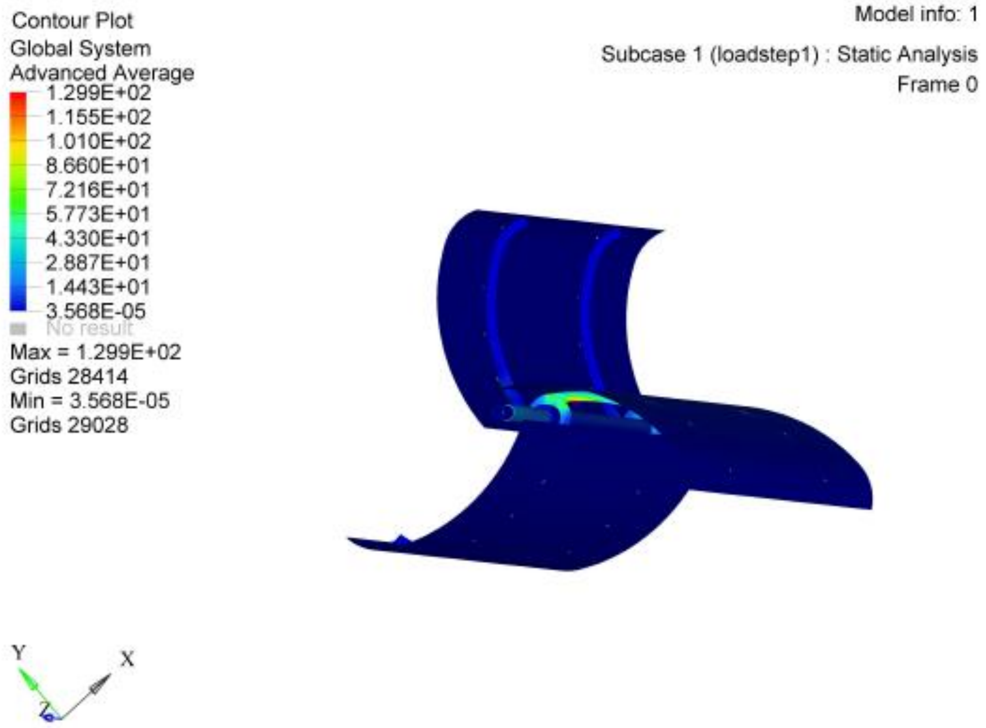

Figure 5.2 Finite Element Stress Results of Wind Turbine for Structural Analysis

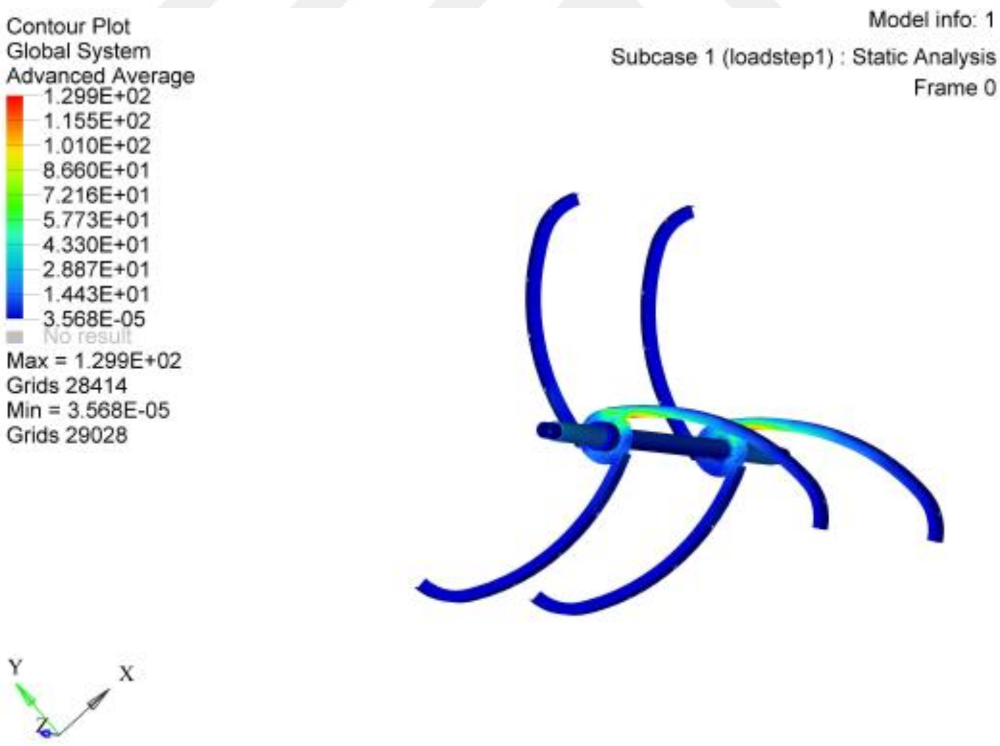

Figure 5.3 Finite Element Stress Results in Details

5.1.2 Improvements

Some improvements are done to increase the strength of the wind turbine. The thickness of the blade sports are increased from 2.0 mm to 4.0 mm and the design of the blade sports are changed in order to reduce to stress. New structural analysis results with improvements are shown in figures below.

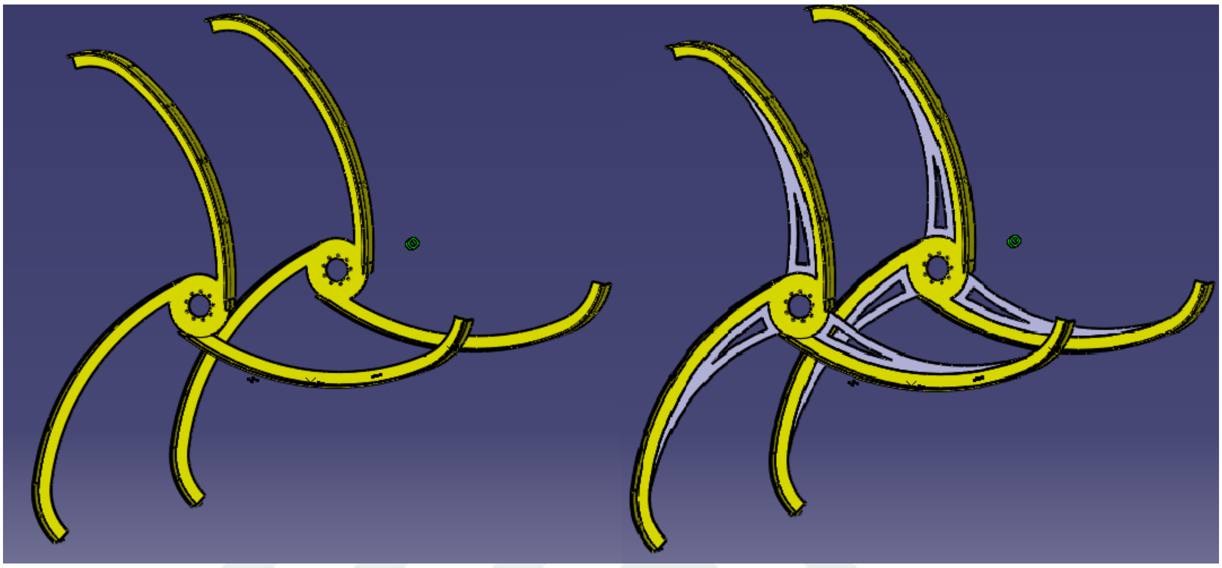

Figure 5.4 Old and new blade supports respectively

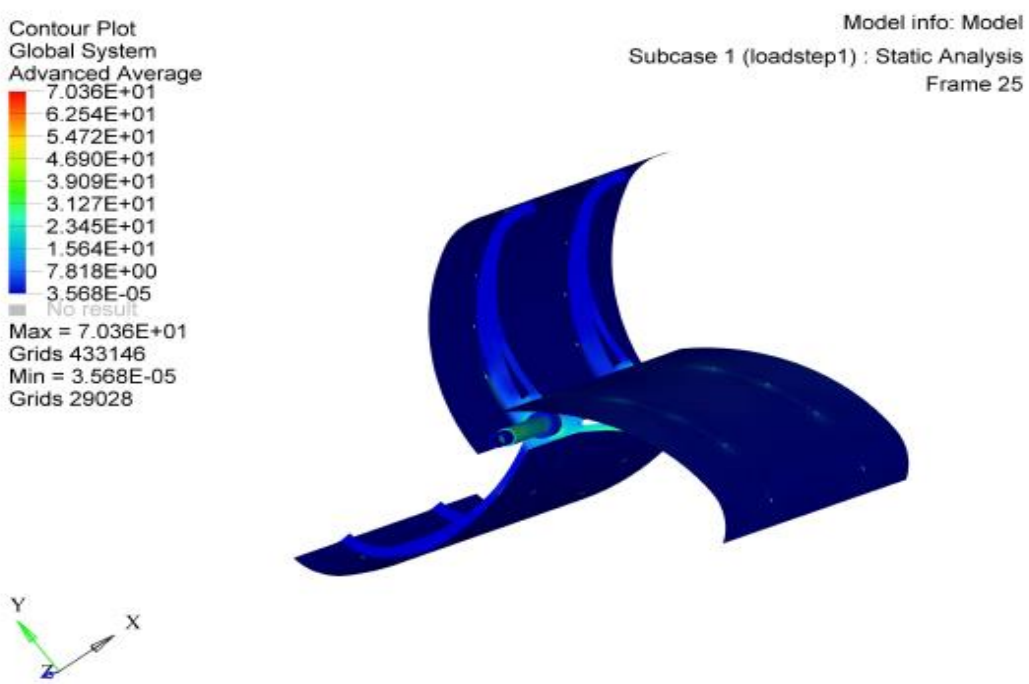

Figure 5.5 New Finite Element Analysis Stress Results

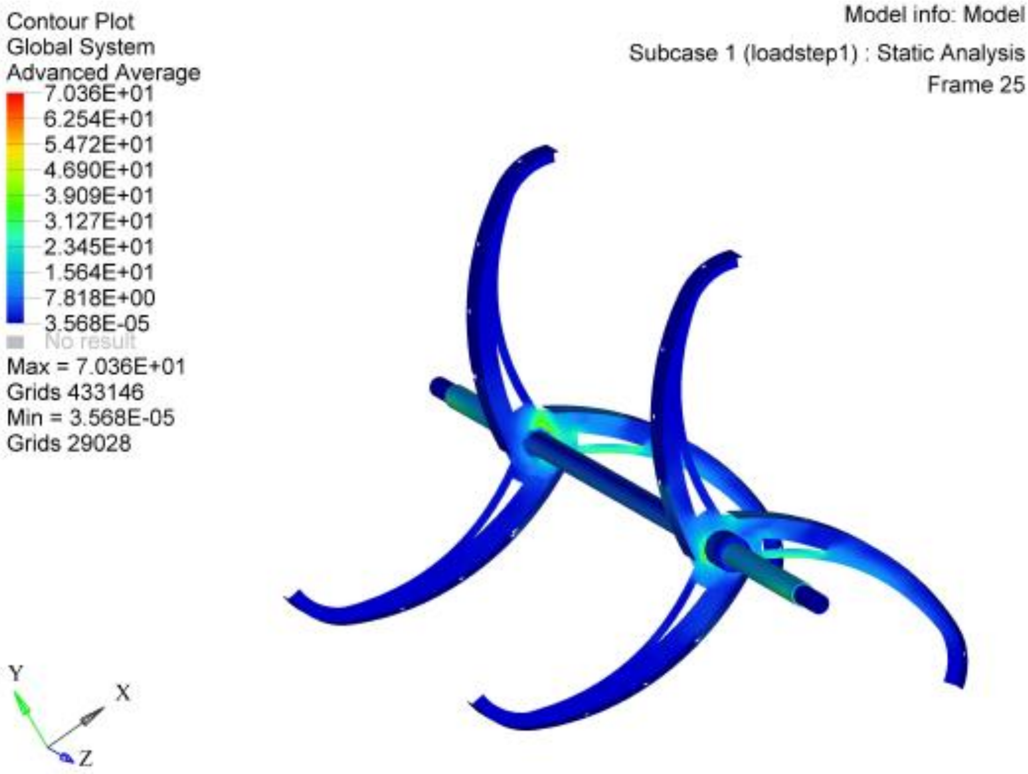

Figure 5.6 New Finite Element Analysis Stress Results in Details

Displacement;

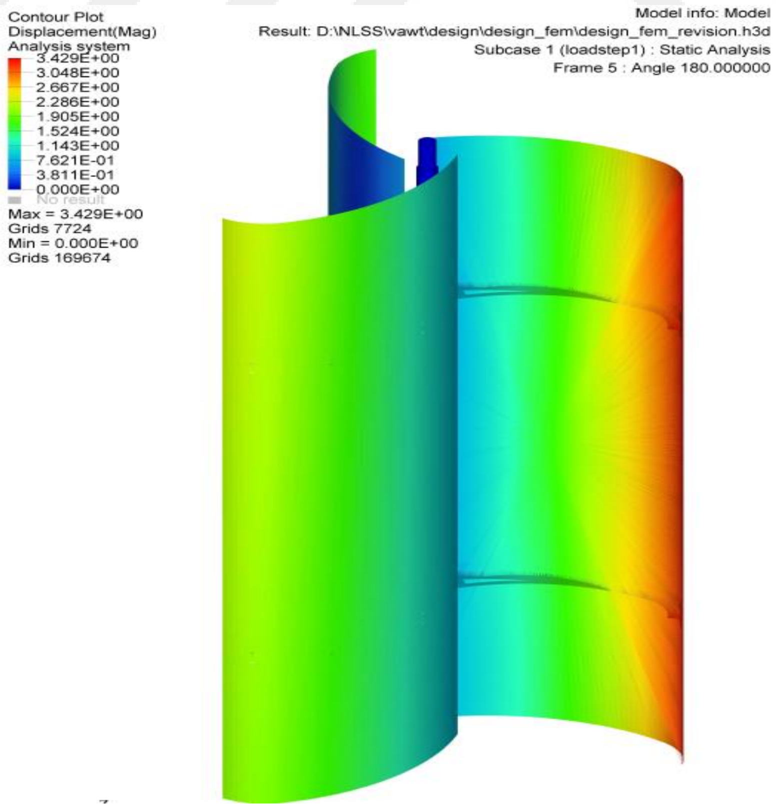

Figure 5.7 Finite Element Displacement Results

5.2 Model Selection and characteristics

Selection of the best model to be manefactured was based on numerical results. The actual manefecturation of selected model was done with help and support of NLSS ENGINEERING GROUP. The selected model is Savonius turbine with elliptical shaped rotor with circular ends and 3 stators with 45 degree angle of attack.

Below are the dimensions of the selected model

- Central vertical shaft length 1.5 meter.
- Rotor length 1.2 meter.
- Rotor diameter 0.75 meter.
- Stators diameter 1 meter.

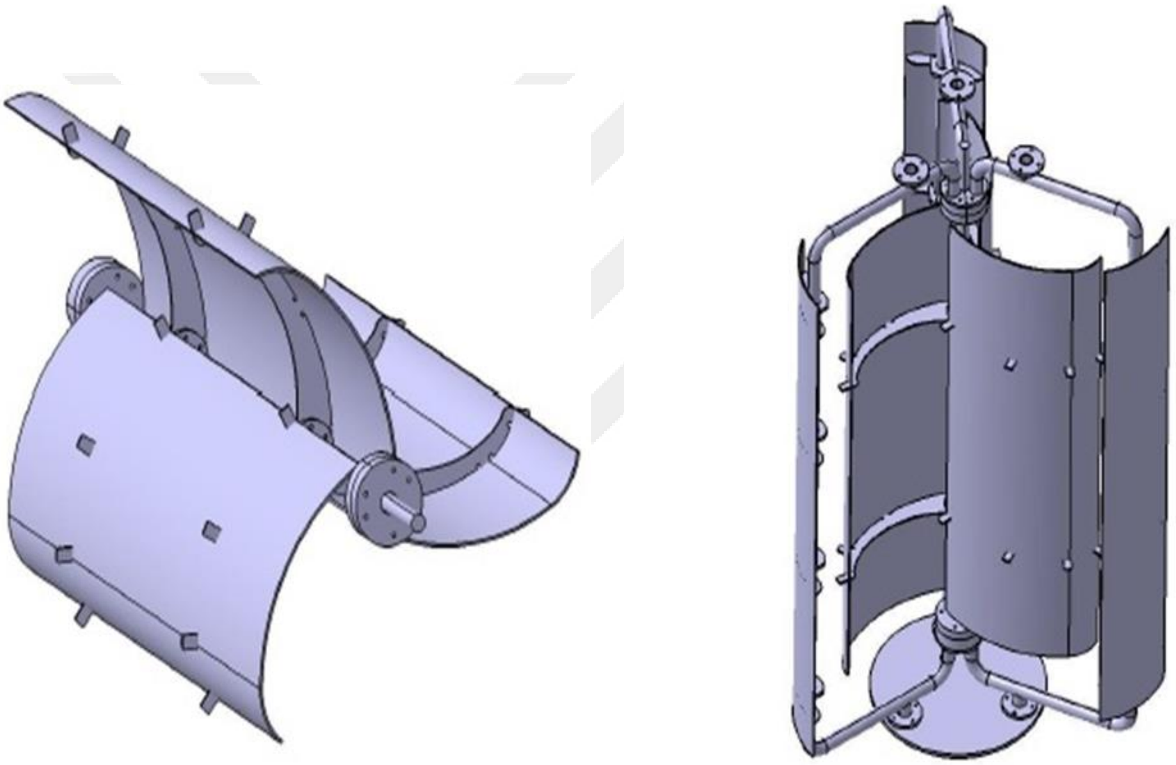

Figure 5.8 the final design structure for Savonius turbine with 3 stators

5.3 Manufacturing Stages

On this stage, as a first step molds and holders of the blades and stators have been manufactured according to selected model dimensions and characteristics.

Figure 5.9 Rotors mold and stator holders

Since aluminum is light and durable, it is been chosen to be used as a rotor and stator material.

Figure 5.10 stator

Figure 5.11 rotor

Figure 5.12 turbine manufacturing

Since wind has irregular behaviors, the produced power is variable and not consistent so the alternator was deployed to transfer the variable produced power to stored power by charging the storing battery.

Figure 5.13 Alternator

A test device include (voltmeter, anemometer and current meter) used to calculate turbine's output power in deferent wind velocities.

Figure 5.14 test equipment

Temporarily installation of the manufactured turbine was accomplished in Istanbul – turkey near (department of the justice - caglayan). The reason of selecting Istanbul as a location of installation was because the turbine has been designed for urban areas and Istanbul is great example of urban areas.

After installation of the turbine all of its' readings was measured in deferent wind behaviors and deferent times along the day period by the measuring equipment we mentioned before.

Figure 5.15 Installation stage

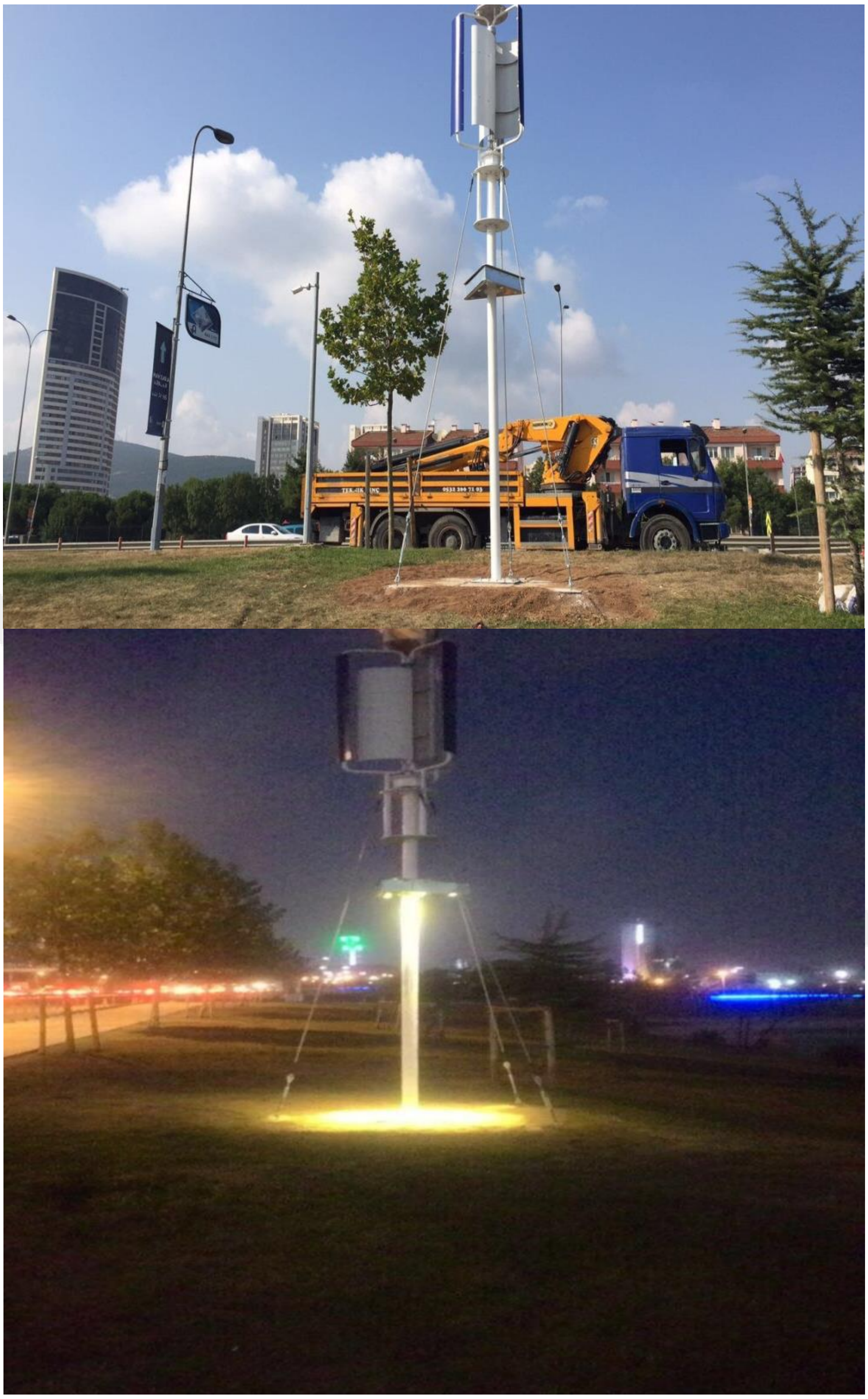

Figure 5.16 the turbine on working position

5.4 Experimental Results

As a final stage in this study, experimental results were collected in different wind velocities. The diagram below illustrate the similarity of numerical and experimental results.

Table 5.1 numerical and experimental results

WIND VELOCITY [M/S]	TEST POWER [W]
12.65	149.8310639
8.65	30.17739316
7.06	27.54148343
10.84	99.54589171
12.41	144.4270708
2.33	0.859270451
2.35	0.703481937
2.92	0.893523422
7.19	20.2762504
11.73	93.3256184
13.42	74.66502118
4.4	6.275698275
5.05	7.4765744
14.96	238.5854371
12.52	108.5217137
4.42	6.059201334
13.08	81.2115276

WIND VELOCITY [M/S]	CFD POWER [W]
4	4.41
6	14.88375
8	35.28
10	68.90625
12	119.07
14	189.07875

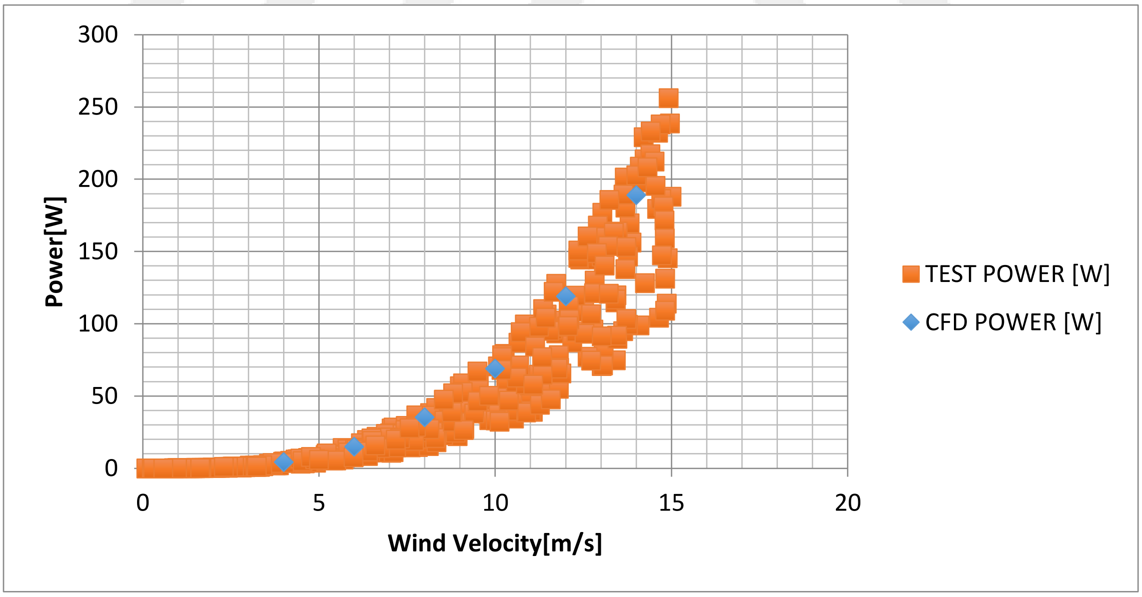

Figure 5.17 numerical and practical test results in deferent wind velocities

CHAPTER 6

RESULTS AND DISCUSSION

On The first stage of this study, after 25 CFD analysis for both circular and eliptical alternative designs with deferent parameters (first design had 9 models with 4 parameters that included small, large, tangential circule diemeter and angle. the second design had 15 models with deferent 7 major radius, 9 diffrent minor radius and 2 deferent angle) it showed that the second design (elliptical rotor with circular edge model 10) is more efficient compared to first (circular rotor with circular edge) and the standard Savonius circular geometry.

On the second stage of this study, the improvments was foucused on on the second model geometry (elliptical rotor with circular edge models). İmprovements included 18 CFD analyses with adding stators to the existing models with different dimentions and angles with reference to the rotorr axis.

It should also be noted that best models has been choosen with cosideration of average moment, power and efficiency values.

As a part of improvements, the results showed that Adding stators on the best geometry model led to increase the peak efficiency of the rotor by 3% from its' previous efficiency which was without stator. Model 10# with 3 or 9 stators, angle of attack about 45 degree with reference to vertical axes was the best design. The 3 stators model is cheaper and it could be structured simply compared with 9 stators model. In addition, it is recommended to use the 9 stator model in a very high wind velocity areas, by designing a movable stators. Which it could close all around the turbine to prevent the wind attack and avoid rotors damaging in cases of very high wind velocities and thunders.

6.1 Conclusion

This study shows that the geometry of the rotor blades plays a very important role to increase the efficiency of the wind turbine, by finding the best geometry.

The results showed that elliptic rotor geometries with circular ends for small-scaled Savonius wind turbines are more efficient than standard circular blade geometry. Also in this study compared the effect of the blade geometry on rotors efficiency and how it gives it a similar moment- time diagram fashion.

The stators could be used to improve Savonius efficiency further and it covers the passive blade, decrease the negative drag force and create a better air flow through the active blade by calculating and finding the optimum parameters (Number of stators, length of stators and angular position of stators).

6.2 Future Work

Further improvements a helical shape for the existing elliptical geometry could be investigated. Since the geometry of stators are plain rectangles, further improvements on the stators could be made by focusing on the geometrical parameters such as airfoils.

A solar panel system can be integrated to the roof of the turbine. Furthermore, it is clear that a tower design can be made for open areas. This project is aimed to meet the electricity demand in the urban areas with off-grid, renewable and cheap wind turbines.

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PUBLICATIONS

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