Small Wind Turbine Blade Optimization for smooth Starting Performance in Low Wind Speed Regions

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A thesis submitted in partial fulfillment for the degree of master of Science in Energy technology, in Addis Ababa University, Addis Ababa Institute of Technology (AAiT)

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Energy Center
February 2021

DECLARATION

I, Tewodros Driba, declare that each data presented in this thesis has been obtained from experiment conducted in Addis Abeba Institute of Technology and the preparation and execution of the experiment, data analysis and interpretation are entirely my own work. Any other contribution for the documentation are explicitly referenced. This thesis is submitted in partial fulfillment of the requirement for Masters degree in Energy Center. I assure that this thesis has not been submitted, either in whole or in part, in any previous academic degree, diploma, or certificate application.

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ACKNOWLEDGMENT

Throughout the completion of this research,I face a big challenge but I have received a great deal of support and assistance too.
I would like to thank my advisor, Dr. Ing. Wondwossen Bogale, for his insightful feedback that help me to show a good progress in having a better knowledge on my research. Beside to this, Your kindness and patience was a motivation in addition to the knowledge you own.
I would like to thank Mr. Natnael Bekele for his valuable guidance in each step of the research. Your direction and recommendation make this research successfully completed.
Finally, I could not have completed this research with out the support of my friends and workshop members, who highly participated in manufacturing and testing of my work.

ABSTRACT

Access of electricity in the developing country is a big issue that the government highly concerned. Small wind turbines are one of the alternative the government have in order to address electricity specially in rural areas. Wind turbines are highly dependent on wind speed, hence the areas with low wind speed region can not access the electricity as expected. This is because the turbine works in low wind speed range which gives the annual energy production more less than the desired output.This thesis investigate the way how to get the optimum energy output from small wind turbines by lowering the time at which the wind turbine starts rotating and generating electricity with out decreasing performance of the turbine.

The main objectives of the thesis were starting time and coefficient of performance and the parameters used for the optimization processes were chord value, twist value and type of airfoil. Two non optimized blade with single and mixed airfoil section are designed with usual designing procedure by using horizontal axis wind turbine design code credited to Oboe Daniele and Marinoni Andrea. Three optimized blade which have 0.8466m, 0.5m, and 0.5m radius with the first two blades have SG6043 airfoil section and the third one has SD7062 airfoil section are designed. The optimization is taken by multi objective genetic algorithm and different input criteria like airfoil type, blade number, starting wind speed, resistive torque is taken for a better investigation. Beside to analysis of the optimized and non optimized blade, the effect of weight given to starting, genetic algorithm parameters, limiting the boundary of twist and chord value, airfoil, designing the blade with single and mixed airfoil, blade number, and starting data are well investigated. Non optimized 3-bladed, SD7062 airfoil section blade starts in 16.3sec at $5\frac{m}{s}$ wind speed while the Optimized blade with the same blade specification starts at 8.63 second which means there is 88.8% improvement in starting time but the coefficient of performance only decreases from 0.34 to 0.335, which means its percent reduction is 1.49% . From previously conducted research on starting performance with the same input criteria with this thesis by (1) which gets 87% improvement in starting time and 1.6% reduction in coefficient of performance. This research shows improvement by altering airfoil type, chord and twist value.

The optimum blade which have lowest starting time and better power performance was manufactured from Australian timber by Computer numerical control machine and experimental testing was conducted. In order to get constant wind speed flow, a controlled moving vehicle was used for the experimentation process. The starting time and coefficient of performance of the blade from the software were 8.63sec and 0.335, while the experimental result gives 9sec and 0.3228. This shows there is a 3.61% and 4.2% error while testing in Cp and starting time respectively. Value of errors comes from first the generator, since it needs to be excited it makes some delay on recording some seconds as it starts generating electricity.

Beside to excitation the generator is used and maintained repeatedly, this makes it to do not perform as it is first manufactured. There is also some manufacturing and assembling difficulties while making parts and assembling the wind turbine which add some contribution on the performance of blade under experimental testing. Finally the manufactured wind turbine produce 19.4W electrical power at $5\frac{m}{sec}$ which is the frequent available wind speed in low wind speed region(2).

Keywords: Optimization, Starting time, Coefficient of performance

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Nomenclature

$\acute{\sigma}$	Solidity
$\acute{a}$	Angular induction factor
α	Angular acceleration
η	Efficiency of the generator
λ	Tip speed ratio
ω	Angular velocity
ρ	Density
θ	Twist angle
A	Area
A	Area
a	Axial induction factor
B	Number of blade
c	Chord length
C_D	Drag coefficient
C_l	Lift coefficient
C_p	coefficient of performance
E	Electrical power
F_x	Axial force
I	Moment of inertia
J	Inertia of the blade
KE	Kinetic energy
L	Angular momentum

m	mass
P_2	downstream pressure
P_{mech}	Mechanical power
P_t	power extracted by the wind turbine
$P1$	upstream pressure
Q	Aerodynamic torque
T	Torque
U_1	Upstream wind speed
U_2	Downstream wind speed
V_{blade}	Blade velocity
$V_{relative}$	Relative wind velocity
V_{wind}	Actual wind velocity
BEM	Blade element momentum theory
PMG	permanent magnet generator
RANS	Reynolds-averaged Navier–Stokes
SWRDC	Small wind turbine design code

Chapter 1

INTRODUCTION

This chapter describes the background and significance of optimizing small wind turbine for a good starting and power performance. Besides, it discuss the scope, statement of the problem, objective, methodology, and limitation of the research

1.1 Background of the Study

Energy is one of the world big concerning issue that controls the economy, environment, and even politics of a country. The GDP of one country is mainly dependent on the amount of power produced by the nation and also total energy consumption of the countries. It is clear that the great demand of power indicates the country are in process of development. Beside the demand the other concerning issue related to energy is how much it is secured. Many countries tried to address electrification for their citizens in different way. But most of them were dependent only in hydro power and fossil fuel base power generation. The main reason for this was technology and resource limitation. In recent years, different technologies are showing up with a great expanding rate. Now a day's countries are trying to conduct mega projects for power generation with these technologies.

Among different upcoming technologies extracting an energy from the wind is the one used to generate electricity. Even if using wind energy is a developed working principle for pumping water and grinding grains, the application shifts into power generation in recent year. The blade that is design in aerodynamic principle can extract energy from the blowing wind. Since the blade is connected with a rotating shaft it makes the circular shaft to rotate. At the end the generator that is connected with the rotating shaft generates electricity which is very dependent on how fast the blade is rotated.

In Africa, among the countries that are in the underway of developing wind projects, Ethiopia is the promising country following Egypt,Morocco, and Tunisia that have a total capacity of 550MW,291MW, and 114MW respectively by the end of 2011(8). Generation of electricity based on diversified energy source is the aim of government of Ethiopia by second period of the growth and transformation plan(9). Currently wind projects are a promising complement of hydro energy which it took around 96% of power generation of the country.Eight wind farms were planned and four of them are under construction to achieve the planned 17000MW from renewable energy sources by the end of GTP-2 period. And also the Ethiopia electric power corporation showing willingness to act as a purchaser for the individual power producers rather than owning and operating all power production projects(10).

Different researches are conducted on wind energy starts from wind resource assessment to a very detail performance analysis of the turbine. Structural analysis, power conversion efficiency, controlling system, integrating system, techno- economic analysis and many other areas are studied both in macro scale and small-scale wind energy application by many researchers. For the area that have low wind speed and there is difficulty for power transmission, using small scale wind turbine is a very advisable technology for power generation. Different countries like Australia, Denmark and many other countries applied small scale wind turbine for either grid connected or off-grid residential areas that have low wind speed. Besides the applicability of small-scale wind turbines, researches have been conducted on starting performance, economic feasibility, structural strength, and aerodynamic performance of blade.

1.2 Significance of the study

Since 80% of the Ethiopian population lives in rural area, addressing electricity is a very difficult and expensive task. Therefore, electrifying these remote areas with small scale wind turbine is the best option in terms of access and cost relative to connecting to the grid system. This can change the life style of the population; reduce the cost they spend for getting power-based services. It is very difficult to address continuous power for all the country population especially for those who lives in the rural and remote area. In addition to that the country's power generating capacity is not enough to address all the population of Ethiopia. During the GTP 1 period, 8:875 million biomass stoves were distributed (against the target of 9:415 million), a total of 11; 618 bio gas plants have been constructed (against target of 26; 000 bio gas plants) and 2:032million solar technologies have been distributed against target of 3:16 million(11). But here the share of small wind energy system in the supporting of addressing the energy need for the population is enough to say 0%(11). Moreover, In the low wind regions, the capacity of the wind speed is not enough to produce a usable power for the reason that power is highly dependent on the speed. Therefore, it is very important to have a diversion small power generation projects in the country for rural areas and also the areas there is unsecured power distribution. To achieve these, installing small scale wind turbines that have a good starting performance can be additional power source

1.3 Scope of the study

In this research how electricity can be generated in low wind speed area is studied and an optimized blade profile is designed by considering the starting time and the coefficient of performance of the turbine at low speed. the optimization is taken by small wind rotor design code (SWRDC) which is the main tool used by previous research conducted on the starting performance of small wind turbine. The result of the optimized and non optimized blade is compared and validated with previous research output. After the design procedure, the blade is manufactured and assembled with generator and some other parts. However, the wind speed data is not collected instead it is taken from the ranges of wind speed that is specified by standard. The design of tower is not included in this project but a supporting device is manufactured to function the tower purpose and integration the output power to some electrical and controlling device are not included here. However, the electrical equipment needed related to small scale power generation is described.

Generally, the research is concerned mainly in the area of the time at which the blade can starts and the difference made form the optimization of blade design for better starting time.

1.4 Statement of the problem

The main issue raised in the application of small wind turbine is its capability of producing usable power in low wind speed region. Most of the commercial wind turbines can not be used in this region for the reason that they are designed to give a maximum power production in a good wind speed areas without considering the applicability in low wind speed regions and also their power production range is not fit with low wind speed region(12).

Moreover, the commercial small wind turbine blades are manufactured with single airfoil, no pitch adjustment, and aims only to give pick power production, hence the range at which the turbine works shifts to high value of wind speed and this makes the turbine to do not operate in low wind speed region.

Additionally, researches showed "the best power producing blades had relatively poor starting performance"(13) and this could affect directly the energy that we can get from the system. Therefore, in order to get maximum energy production, the starting performance of the turbine should be optimized(13)(5)(7)(1). Although researches were conducted on the optimization of small wind turbine for starting and coefficient performance, no effort is shown to validate the software value with the experiment until this paper.

1.5 Limitation of the research

Among the designed blade for experimental testing the one with lowest blade radius and small chord length and twist angle range is manufactured for the reason that a machine which have specification fit to the best designed blade is not available.

1.6 Objectives of the research

1.6.1 Main objective

To develop small scale wind turbine optimized for coefficient of performance and starting performance at the time in low wind speed region

1.6.2 Specific objectives

- Designing a blade with blade element momentum theory
- Designing an optimized blade considering high power extraction and a better starting performance by using blade element momentum theory and model it by solid work and Artcam
- Manufacturing the optimized small wind turbine blades
- Selecting a compatible small generator and some electrical equipment
- Conducting an assembly process of the blade with the generator and other components
- Conduct experimental testing on the performance of the manufactured blade
- Validating the experimental result with the values that are achieved by other researches which have nearly the same design parameter with this research.

1.7 Research Methodology

To conduct this research basically four steps is followed, the design stage, the optimization stage, manufacturing stage and experimental testing state. In the design stage first, a reasonable assumption of different input parameters is taken and the data is analyzed by a mathematical model (i.e. blade element momentum theory) and in the second stage some of the parameters are optimized by an evolutionary optimization technique for a better power performance and to achieve optimum starting time. After the design stage is completed the blade will be manufactured. In this stage, beside to the manufacturing of the blade yaw modeling and assembly of the blade with the generator and also other interconnecting process is taken. Finally, the assembled small-scale wind turbine is tested and the data taken from the experiment is compared with the design output of the non optimized blade and the optimized blade is validated with the experiment result.

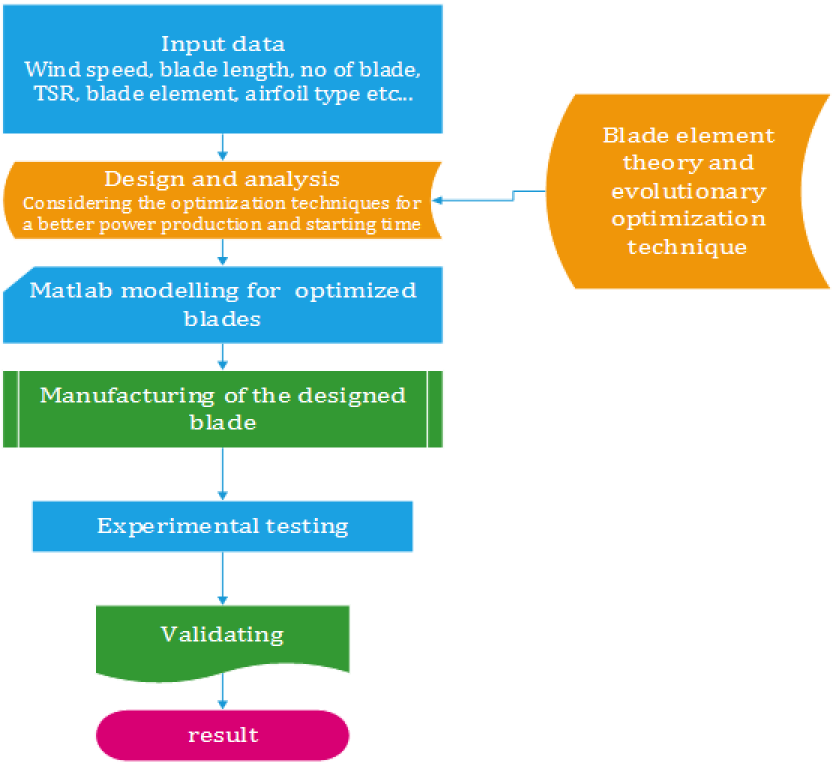


Figure 1.1: Method followed to accomplish the research

1.8 Research outline

Generally, this paper has three main section with each have numerous subsection and allocated in seven chapters. In the first section, wind energy system is briefly discussed and significance of the research with shortcoming which affect the result is mentioned. Besides to this the way how this research accomplished is discussed. The second which is the main part of the paper begins by review of researches regarding about designing, classification, and concerning issue of small scale wind turbine. It also deals about the criteria fulfilled in order to design a blade which is how airfoil selected, choosing number of blade and blade size. Blade which have single airfoil shape and mixed airfoil shape is designed discretely. These blades are designed based on the blade element momentum theory, hence they are not optimized.

In the next chapter of the main part, previously stated specification for the designing of non optimized blades are used here for designing the optimized blade. Genetic algorithm which govern the optimization process is discussed and some modeling is undertaken in this section. The tool used for the optimization process is briefly discussed and finally the optimized blade is taken from the result of optimization process.

The last part in the main body section is concerned about the manufacturing and experimental testing process. Here the selection of blade material and how the designed blade manufactured with assembly process is mentioned. The procedure followed in order to carry out experimental testing is also briefly discussed.

The whole process conducted in the body section is ended by listing the output from the design process and experimental testing in the result and discussion chapter. Effects of some parameters used in the designing process is briefly discussed and comparative analysis is taken between the optimized and non optimized blade and also with mixed airfoil shaped blade.

In the last chapter, conclusion is made from what the result and discussion section gives and finally recommend the list to be considered in the future research conducted on starting performance and power coefficient.

Chapter 2

LITERATURE REVIEW

In this section, how the energy of wind is converted to mechanical energy and the detail principles behind wind energy system is described. secondly, the theory of aerodynamics of wind turbine is well discussed. The chapter also brifely discuss the classification of wind turbine with different perspective and issues which concern wind turbine. previously conducted researches on starting performance are well discussed at the end of the chapter.

2.1 Wind energy system

Wind is the movement of air through the atmosphere. Its generation, movement and speed are depending on number of factors. The first factor to be considered for the generation of wind is the uneven distribution of heating of the earth surface (14), (15). As long as the sun radiates the earth surface receives its energy (i.e temperature) but the energy received is different from region to region. This means temperature gradient will be formed from the equator to the poles and pressure gradient from the poles to the equator. Thus, from the equator low density hot air rises up to the high atmosphere and moves towards the poles and from the poles, higher density cold air flows from the poles towards the equator along the earth's surface (14). The reason for uneven solar heating is because the earth is a sphere revolving around the sun. Thus the equator receives the greatest amount of energy per unit area, with energy dropping off towards the poles. The inclination off the earth(about 23.5 with respect to ecliptic plane) can be the reason for uneven solar heating.

The other reason is the earth is covered by different materials that has different reflective and absorbing rates to solar radiation. This leads to high temperature on some areas like deserts which is covered by sand and rock and low temperature on the areas covered by vegetables, waters and ice. In addition to the above reasons the earths topographic surface affects the uneven solar heating. The direction and speed of the wind is affected by the earths self-rotating behavior. The Coriolis force, which is generated from the earth's self-rotation, deflects the direction of atmospheric movements. In the north atmosphere wind is deflected to the right and in the south atmosphere to the left. Additional to the Coriolis force the geography of the earth surface highly affect the speed of the wind. Frictional drag and obstructions near the earth's surface generally retard with wind speed and induce a phenomenon known as wind shear.

The energy from wind have been assisting human kind in different uses for a long time. Earliest records shows that wind power has been used to move ships, grind grain, and pump water. There is also an evidence that wind energy was propelled boats along the Nile River as early as 5000 BC(16). Within several centuries before Christ, simple windmills were used in China to pump water(15). Around 300 BC, ancient Sinhalese had taken advantage of the strong monsoon winds to provide furnaces with sufficient air for raising the temperatures inside furnaces in excess of 1100°C in iron smelting processes. This technique was capable of producing high-carbon steel (17). In ninth century a Persian geographer recorded that, in Sistan (eastern Persia) vertical axis wind mill were built practically for grain grinding and water pumping and in 1180s horizontal axis wind mills were invented in northern Europe (15) Few decades before wind is used to generate electricity unlike the windmills which was used for directly to do works like grinding and pumping. with wind turbine generators, the mechanical energy created by the wind is converted into electricity (14).

It has been estimated that the total solar power received by the earth is approximately $1.810^{11} MW$. Of this solar input, only 2% (i.e. $3.6 * 10^9$ MW) is converted into wind energy that is about 50 to 100 times more than the energy converted into biomass by all plants on Earth[renewable] and about 35% of wind energy is dissipated within $1000m$ of the earth's surface (18). Therefore, the available wind power that can be converted into other forms of energy is approximately $1.26 * 10^9$ MW. Because this value represents 20 times the rate of the present global energy consumption, wind energy in principle could meet entire energy needs of the world (14).

Relatively from traditional energy source, the benefits and advantages of wind energy sources is high. wind power is a clean and environmentally friendly energy source compared to fossil fuels that emits harmful gases nuclear power that generate radioactive wastes. In most of the earth regions, wind sources is available and plentiful as an inexhaustible and free energy source. In addition, the demand of fossil fuel would be reduced, if there is more extensive use of wind power.

raising total capacity by almost 9% over 2016, Renewable power generating capacity show its largest annual increase ever in 2017, with an estimated 178GW installed worldwide. Solar PV led the way, accounting for nearly 55% of newly installed renewable power capacity. Wind and hydro-power accounted for most of the remaining renewable capacity additions, contributing more than 29% and nearly 11%, respectively. Wind power is providing a significant share of electricity in a growing number of countries. In 2017 wind power capacity in operation was enough to account for an estimate of 5.6% of the world electricity generation. In addition to generation, developers and manufacturers are working together to include battery storage in the wind turbine system for both on shore and of shore turbines (19). The upcoming new innovative technologies are wind to heat energy storage system, integrating wind energy with pumped storage system, building a turbine that will produce hydrogen directly.

Besides the improvement of large-scale wind turbines, researches are taking place on small scale wind turbine for remote areas. Small-scale turbines continued to be used for a variety of applications (both on- and off-grid), including defense, rural electrification, water pumping and desalination, battery charging, telecommunications, and increasingly to displace diesel in remote locations. Approximately 1 million small-scale turbines, or over 1GW, were operating worldwide by year's end of 2015. As the summary released by WWEA in 2016 The world market for small wind turbines reaches 830MW at a growth rate of 10.9%, after 10.4% in the previous year. Currently 50% of the market share on small scale wind turbine is on the hand of four countries (china, Canada, Germany, and USA). But as WWEA 2017 report mention developing countries continue to pay a minor role in manufacturing of small-scale turbines(20).

2.2 Working principle of wind energy system

Windmill have been assisting mankind for converting energy contained in the wind to different purposes starting before two thousand years (16). Now a days wind turbines are capable of converting a large amount of energy which exists in the wind into electricity. The main reason for this is the structural design and aerodynamic analysis of the wind blade. If the wind can rotate a blade electricity will be generated by the generator attached to the rotating wind blade. However, the question here is how the blowing wind can rotate the blades?

The blade is made of several airfoil section that takes the credit for turning. Because of the shape of the airfoil sections, the air which flows into the blade is split at the airfoils leading edge, passing above and below the airfoils at different speeds so that the air will reach the same endpoint along the trailing edge of the airfoil at the same time. In general, the air flowing over the top of the airfoils speeds up and stretches out because of the curved surface of the upper section of airfoils. This decreases the air pressure above the airfoils. In contrast, the speed and pressure of the air flowing below the airfoils which move straight is about the same. Therefore, the high pressure created below the airfoil pushes it upward towards the air above the airfoil and the airfoil, in the middle, is then lifted by the force of the air perpendicular to the wing. When lift id created in each of the airfoil section the blade starts to rotate.

The blowing wind is the resultant of the actual wind and the relative wind due to the blade motion. The moving wind turbine blade also experiences the wind relatively. For the moving blade the relative velocity is

$$V_{relative} = V_{wind} - V_{blade} \tag{2.1}$$

Therefore, the wind turbine blade is positioned in a tilted manner in order to align with relative velocity. The relative wind speed become more inclined towards the tip as the blade velocity increases to the radius of the blade. Therefore, a continuous twist is needed to the blade from the root to the tip. For maximum power extraction the wind turbine should face the wind direction, even if the wind can change its direction any time. To overcome this, a velocity sensor is feed on the top of nacelle of the wind turbine for measuring the wind speed and direction. As the direction of wind deviates an electronic controller, which is connected to the velocity sensor, sent an appropriate signal to the yawing mechanism to correct the direction. Thus, the wind turbine always aligns with the wind direction. moreover, the rotation of the wind turbine blade cannot be coupled to generator directly because the wind turbine blade typically turns at a low rate of RPM due to the issue of noise and mechanical strength. With this low rotation of the blade it is difficult to produce meaningful electricity frequency from the generator. Therefore, gearbox is used to increase the rotational speed created by the blade before connecting to the generator.

The performance of wind turbine system is other interesting topic. The energy available in the wind is mainly depends on how much wind energy is passed a certain specific place within a certain time, which is the mass flow rate of the wind, m, and how fast this amount of wind is crossing the specified cross section. this energy is called the kinetic energy of the wind.

$$KE = 1/2\dot{m}V^2 = \frac{1}{2}\rho A V^3 \tag{2.2}$$

The power extraction process is analyzed by a simple actuator disc model of wind turbine Assume we are measuring a wind speed upstream and downstream of the wind turbine. It is obvious that the wind speed at the downstream is much lower than the upper one

$$(V_{out} < V_{in}) \tag{2.3}$$

The same amount of energy is converted to mechanical power of the wind turbine.

$$P_{mech} = 1/2\dot{m}V_{in}^2 - 1/2\dot{m}V_{out}^2 \tag{2.4}$$

It is interesting to know that a wind turbine can absorb 100% of the available kinetic energy of the wind only if the downstream wind speed become zero. However, zero wind speed at the downstream is physically impossible condition. It is simply means the whole flow is stuck. This physical reality of the flow determines certain amount of exist wind speed. This implies there is a theoretical maximum limit a wind turbine can achieve. This limit is known as Betzs limit which equals to 59.3%. essentially it means that no wind turbine in the wind can ever cross the limit of 59.3%.

2.3 Aerodynamics of wind turbines

Aerodynamics is a branch of mechanics that deals with the motion of air (and other gases) with the effects of such motion on bodies in the medium. The primary aerodynamic forces that act on wind turbine are lift, drag, and stall. Lift is the aerodynamic force having a direction perpendicular to the direction of motion. Drag is the aerodynamic force exerted on an airfoil, or other aerodynamic body, that tends to reduce its forward momentum. Stall is the loss of lift due to a change in the angle of attack.

2.3.1 Blade Element Momentum (Strip) Theory

Betz and Glauert (Glauert, 1935) was the first to develop the classical analysis of wind turbine in the 1930s. The performance characteristics of an annular section of the rotor is calculated from the combination of Momentum theory and blade element theory. The characteristics for the entire rotor are then obtained by integrating, or summing, the values obtained for each of the annular sections. momentum theory and blade element theory are developed and used to calculate the optimum blade shape for simplified, ideal operating conditions. The results illustrate the derivation of the general blade shape used in wind turbines (3). This analysis uses the following assumptions:

- Homogeneous, in-compressible, steady state fluid flow
- No frictional drag
- An infinite number of blades
- Uniform thrust over the disc or rotor area
- The static pressure far upstream and far downstream of the rotor is equal to the undisturbed ambient static pressure

2.3.2 Momentum Theory

this theory uses a momentum balance on a rotating annular stream tube passing through a turbine. By assuming a control volume which its boundaries are the surface of a stream tube having two cross sections up and down stream and representing the turbine by a uniform actuator disc, the force of the wind on the turbine which is called the axial force and the tangential force created by wake rotation can be derived

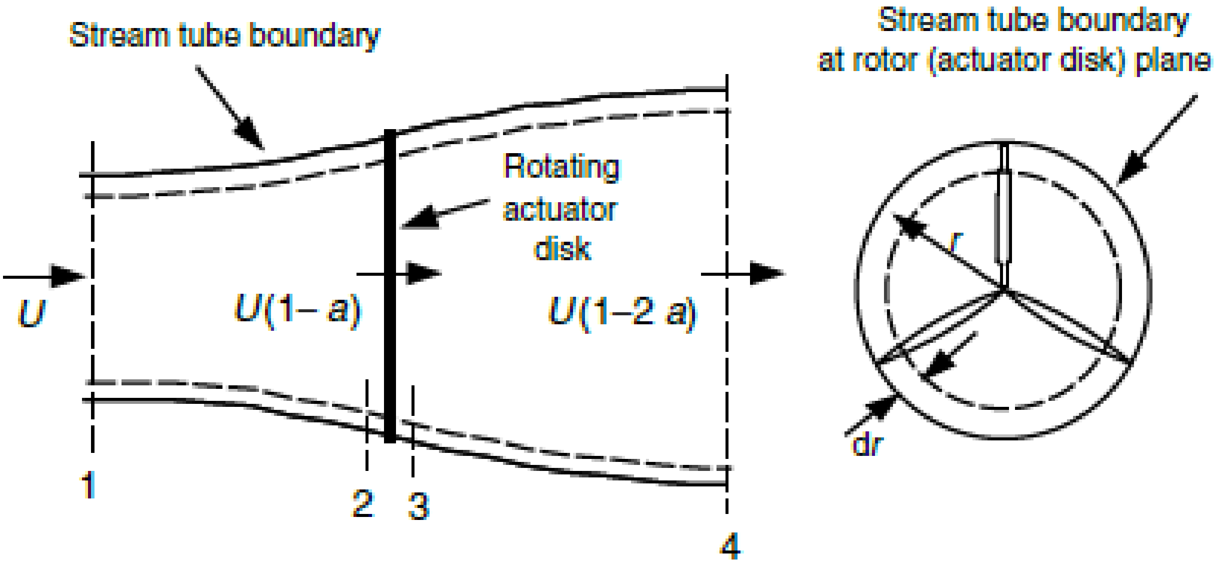


Figure 2.1: Axial stream tube around the wind turbine(3)

Axial Force

From the conservation of linear momentum for an in-compressible, time-invariant flow, the axial force is equal and opposite to the rate of change of momentum of the air stream

$$T = U_1(\rho A U)_1 - U_4(\rho A U)_4 \tag{2.5}$$

for steady state flow

$$(\rho A U)_1 = (\rho A U)_4 = \dot{m}$$

where $\dot{m}$ is the mass flow rate

$$T = \dot{m}(U_1 - U_4) \tag{2.6}$$

Thus, the Bernoulli function can be used in the two control volumes on either side of the actuator disc. In the stream tube upstream of the disc

$$\P 1 + \frac{1}{2}\rho U_1^2 = P_2 + \frac{1}{2}\rho U_2^2 \tag{2.7}$$

in the stream tube downstream of the disc

$$P_3 + \frac{1}{2}\rho U_3^2 = P_4 + \frac{1}{2}\rho U_4^2 \tag{2.8}$$

Where it is assumed that the far upstream and far downstream pressures are equal ($p1 = p4$) and that the velocity across the disc remains the same ($U2 = U3$).

$$P_2 - P_3 = \frac{1}{2}\rho(U_1^2 - U_4^2) \tag{2.9}$$

Recalling force is pressure times area

$$dF_x = (P_2 - P_3)dA \tag{2.10}$$

$$dF_x = \frac{1}{2}\rho(U_1^2 - U_4^2)dA \tag{2.11}$$

If one defines the axial induction factor, a, as the fractional decrease in wind velocity between the free stream and the rotor plane, then

$$a = \frac{U_1 - U_2}{U_1} \tag{2.12}$$

$$U_2 = U_1(1 - a) \tag{2.13}$$

$$U_4 = U_1(1 - 2a) \tag{2.14}$$

The quantity $U_1 a$ is often referred to as the induced velocity at the rotor, in which case the velocity of wind at the rotor is a combination of the free stream velocity and the induced wind velocity. After substituting $U_2 and U_4$, the axial force becomes

$$dF_x = \frac{1}{2}\rho U_1^2[4a(1 - a)]2\pi r dr \tag{2.15}$$

Rotating Annular Stream

In the annular stream, linear momentum is not the only to be generated there is also angular momentum which is generated by the rotating wind turbine. When the wind turbine rotates, the flow behind the rotor rotates in the opposite direction to the rotor, in reaction to the torque exerted by the flow on the rotor. The generation of rotational kinetic energy in the

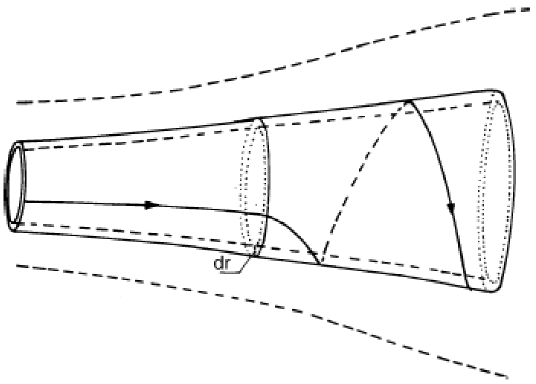


Figure 2.2: Stream tube model of flow behind the rotating wind turbine(3)

wake results in less energy extraction by the rotor than would be expected without wake rotation. The blade wake rotates with an angular velocity,$\omega$and the blades rotate with an angular velocity of Ω . From a basic physics concept

$$momentifinertiaofanannulus, I = mr^2 \tag{2.16}$$

$$angularmomentum, L = I\omega \tag{2.17}$$

$$Torque, T = \frac{dL}{dt} \tag{2.18}$$

$$T = \frac{dI\omega}{dt} = \frac{d(mr^2\omega)}{dt} = \frac{dm}{dt}r^2\omega \tag{2.19}$$

Therefore for small element the corresponding torque will be

$$dT = \dot{m}r^2\omega \tag{2.20}$$

for the rotating annular element

$$d\dot{m} = \rho A U_2 = \rho 2\pi r dr U_2 \tag{2.21}$$

$$dT = 2\rho\pi r dr U_2 \omega r^2 = \rho U_2 \omega r^2 2\pi r dr \tag{2.22}$$

define an angular induction factor $\acute{a}$,

$$\acute{a} = \frac{\omega}{2\Omega} \tag{2.23}$$

recall that $U_2 = U(1-a)$,

$$dT = 4\acute{a}(1-a)\rho U \Omega r^3 \pi dr \tag{2.24}$$

2.3.3 Blade Element Theory

Forces in the wind turbine can also be expressed in different ways to that of the method used in momentum theory. But first it is better to recall about airfoil sections and its parameter to understand and derive the forces. Airfoils are structures with specific geometric shapes that are used to generate mechanical forces due to the relative motion of the airfoil and a surrounding fluid. Wind turbine blades use airfoils to develop mechanical power. The cross-sections of wind turbine blades have the shape of airfoils. The width and length of the blade are functions of the desired aerodynamic performance, the maximum desired rotor power, the assumed airfoil properties, and strength considerations. Therefore, as air flows over the airfoil sections forces will be produce(lift and drag forces). the lift coefficient is defined as

$$C_l = \frac{\frac{L}{l}}{\frac{1}{2}\rho U^2 c} = \frac{\frac{liftforce}{unitlength}}{\frac{dynamicforce}{unitlength}} \tag{2.25}$$

the drag coefficient is defined as

$$C_D = \frac{\frac{D}{l}}{\frac{1}{2}\rho U^2 c} = \frac{\frac{dragforce}{unitlength}}{\frac{dynamicforce}{unitlength}} \tag{2.26}$$

Blade element theory relies on two key assumptions

- There are no aerodynamic interactions between different blade elements
- The forces on the blade elements are solely determined by the lift and drag coefficients

now consider a blade divided up into N elements as shown in Figure below. As they have a different rotational speed (Ωr), a different chord length (c) and a different twist angle (θ) Each of the blade elements will experience a slightly different flow. Blade element theory involves dividing up the blade into a sufficient number (usually between ten and twenty) of elements and calculating the flow at each one. Overall performance characteristics are determined by numerical integration along the blade span.

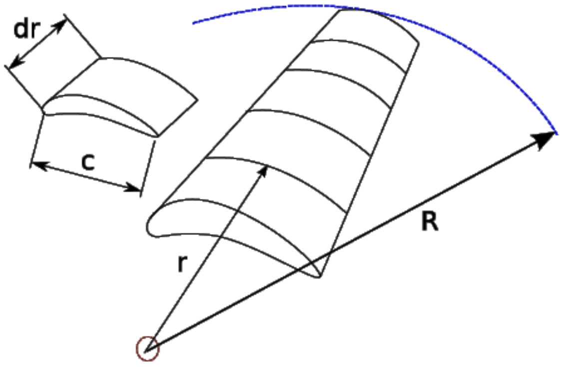


Figure 2.3: The blade element model (4)

Relative flow

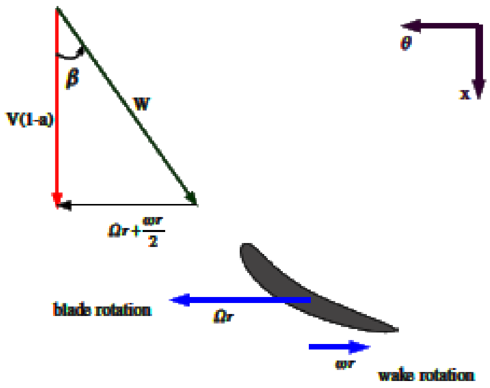


Figure 2.4: Flow onto the turbine blade (4)

We have said that the blade rotates with the speed Ω, and the average rotational flow over the blade due to wake rotation is$\frac{\omega}{2}$. Therefore, the average tangential velocity that the blade experiences is

$$\Omega r + (\frac{\omega}{2})r = \Omega r + \Omega \acute{a} r = \Omega r(1+\acute{a}) \tag{2.27}$$

recalling $U_2 = U_1(1-a)$

$$\tan\beta = \frac{\Omega r(1+\acute{a}}{U_1(1-a)} \tag{2.28}$$

the local tip speed ratio is defined as

$$\lambda_r = \frac{\Omega r}{U} \tag{2.29}$$

so the expression for $\tan\beta$ can be simplified to

$$\tan\beta = \frac{\lambda_r(1+\acute{a})}{(1-a)} \tag{2.30}$$

from the figure above the following relation is induced

$$W = \frac{U(1-a)}{\cos\beta} \tag{2.31}$$

Forces On Blade Elements

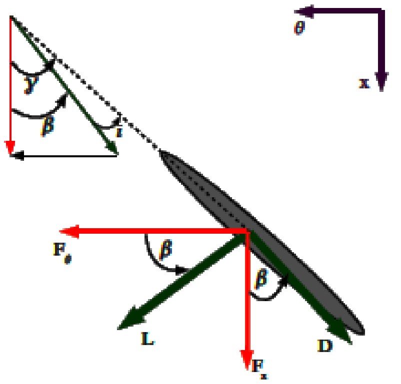


Figure 2.5: Forces on the turbine blade(4)

Lift and drag force are perpendicular and parallel to the incoming flow as showed in the figure. Therefore from simple calculation we can get the tangential and axial forces

$$dF_\theta = dL\cos\beta - dD\sin\beta \tag{2.32}$$

$$dF_x = dL\sin\beta + dD\cos\beta \tag{2.33}$$

where dL and dD are the lift and drag forces on the blade element respectively and they can be found from the definition of lift and drag coefficient as follow

$$dL = C_L\frac{1}{2}\rho W^2 cdr \tag{2.34}$$

$$dD = C_D\frac{1}{2}\rho W^2 cdr \tag{2.35}$$

Then for N blades, the above equations combined to give

$$dF_X = N\frac{1}{2}\rho W^2(C_L\sin\beta + C_D\cos\beta)cdr \tag{2.36}$$

$$dF_\theta = N\frac{1}{2}\rho W^2(C_L\cos\beta - C_D\sin\beta)cdr \tag{2.37}$$

We can get the torque dT by simply multiplying the tangential force with the radius

$$dT = N\frac{1}{2}\rho W^2(C_L\cos\beta - C_D\sin\beta)crdr \tag{2.38}$$

The equation can be simplified to more important form by substituting β and W which is expressed in terms of induction factors in the above equation.

$$dF_X = \acute{\sigma}\pi\rho\frac{U^2(1-a)^2}{\cos^2\beta}(C_L\sin\beta + C_D\cos\beta)rdr \tag{2.39}$$

$$dT = \acute{\sigma}\pi\rho\frac{U^2(1-a)^2}{\cos^2\beta}(C_L\cos\beta - C_D\sin\beta)r^2dr \tag{2.40}$$

Where $\acute{\sigma}$ is called the local solidity and defined as

$$\acute{\sigma} = \frac{Nc}{2\pi r} \tag{2.41}$$

2.3.4 Blade element momentum equation

We now have four equations, two derived from momentum theory which express the axial thrust and the torque in terms of flow parameters (Equations 2.15 and equation 2.24). We also have two equations derived from a consideration of blade forces which express the axial force and torque in terms of the lift and drag coefficients of the airfoil (Equations 2.39 and 2.40). By equating the corresponding equations from the momentum theory and the blade element theory, the following useful relationship will be derived which is necessary for the blade design procedure

$$\frac{a}{(1-a)} = \frac{\acute{\sigma}[C_L\sin\beta + C_D\cos\beta]}{4\cos^2\beta} \tag{2.42}$$

$$\frac{\acute{a}}{(1-a)} = \frac{\acute{\sigma}[C_L\cos\beta - C_D\sin\beta]}{4\lambda_r\cos^2\beta} \tag{2.43}$$

2.4 Classification of wind turbines

Wind turbine can be classified based on different criteria, thus one wind turbine may differ in some features with other wind turbines.

2.4.1 Wind turbine generator configuration

By considering the rotating axis of the rotor blade, wind turbines are further divided into horizontal axis and vertical axis wind turbine

A. Horizontal axis wind turbines

Now a days most of commercial wind turbines belongs to the horizontal axis type. Its rotating axis of the rotor blade is parallel to the wind stream. Comparatively it has high turbine efficiency with high power density and the cost per unit power output is low. It has high starting performance compare to the vertical type which means the blade starts easily or starts with low cut in wind speed. In order to support the generator and nacelle, horizontal axis wind turbine need strong tower. Thus, because of its high tower maintenance is very difficult. Based on the configuration of the wind rotor with respect to the wind flowing direction, the horizontal-axis wind turbines can be further classified as upwind and downwind wind turbines.

Up wind turbines

The majority of horizontal-axis wind turbines being used today are upwind turbines, in which the wind rotors face the wind. The main advantage of upwind designs is to avoid the distortion of the flow field as the wind passes though the wind tower and nacelle(14). It avoids the wind shade behind the tower. Therefore, it needs a yaw mechanism to keep the rotor facing the wind (15).

Down wind turbines

For a downwind turbine, wind blows first through the nacelle and tower and then the rotor blades. This configuration enables the rotor blades to be made more flexible without considering tower strike. However, because of the influence of the distorted unstable wakes behind the tower and nacelle, the wind power output generated from a downwind turbine fluctuates greatly. In addition, the unstable flow field may result in more aerodynamic losses and introduce more fatigue loads on the turbine. Furthermore, the blades in a downwind wind turbine may produce higher impulsive or thumping noise (14).

B. Vertical axis wind turbine

The blades of the vertical-axis wind turbines rotate with respect to their vertical axes that are perpendicular to the ground. Because vertical axis wind turbines accepts wind from any direction, yaw control mechanism is not needed. Unlike to the horizontal axis type its generator, gearbox, and other turbine main components can be set on the ground and this makes it simplifies the design, construction and also the maintenance process. But the starting performance of this type of turbine is very low. It must use external energy resource to rotate the blade during initialization and the blade experiences uneven load that cause a lot of stress on them. Because the axis of the wind turbine is supported only on one end at the ground, its maximum practical height is thus limited. Its power coefficient is much lower than the horizontal type. Thus, it the takes a small percentage on today wind turbines. The advantage on wind speed as height is increases does not work here for the reason its installation on the ground. Wind turbines can be classified according to the turbine generator configuration, air flow path relatively to the turbine rotor, turbine capacity, the generator-driving pattern, the power supply mode, and the location of turbine installation. The vertical axis wind turbine can be divided into two major type

Darrieus wind turbine

This is the first vertical axis wind turbine developed in France in 1927 by George Darrieus. It is the only vertical axis turbine that has ever been manufactured commercially at any volume. it is characterized by its C-shaped rotor blades, His style of vertical axis machine uses aerodynamically shaped wings to add some lift effect that is generated from the airfoil blades during rotation (15), (21).

Savonius wind turbines

Savonius wind turbines are drag based wind turbines consisting of two to three scoops. These turbines have an ‘S’ shaped cross section when looked from above. As they move along the wind, they experience lesser drag and this difference in drag helps these turbines to spin. Due to the drag, the efficiency of these turbines is less when compared to other types of turbines (21).

2.4.2 Drive type

A. Gear derived wind turbine

To produce a meaningful power frequency, the rotational speed of the blade,which is low, has to be increase by the gear system. Thus we can get high power output. a regular geared drive wind turbine typically uses a multi-stage gearbox to take the rotational speed from the low-speed shaft of the blade rotor and transform it into a fast rotation on the high-speed shaft of the generator rotor. Even if the gear helps to produce high power, it significantly lower wind turbine reliability and increase turbine noise level and mechanical losses.

B. Direct drive wind turbines

By eliminating the multi-stage gearbox from a generator system, the generator shaft is directly connected to the blade rotor. Therefore, the direct-drive concept is more superior in terms of energy efficiency, reliability, and design simplicity.

2.4.3 Load type

A. Ongrid wind turbines

On this type of wind turbine the power generated tied to the grid system. Most of medium size and almost all large size wind turbines are grid tied wind turbines. The basic advantage is there is no a storage problem.

B. Off-grid wind turbines

In contrast to large scale wind turbines most of small wind turbines are off-grid used for different applications like for residential home, farms, telecommunication, and other applications. Off-grid wind turbines are used in connection with storage batteries, diesel generators, and photovoltaic systems for improving the stability of wind power supply.

2.4.4 Location of turbine installation

A. Onshore wind turbines

This type of turbines are turbines installed on land areas unlike to the offshore type which is installed in water surface. There are number of advantages over the offshore type. Onshore wind turbines have lower cost of foundations, easier integration with the electrical grid network, lower cost in tower building and turbine installation comparing to the offshore one, and its is convenient access for operation and maintenance.

B. Offshore wind turbines

Since 1990s the development of offshore wind turbines are faster than the onshore type for the reason that water surfaces have excellent wind resources in terms of wind power intensity and continuity (14). Aside to making high power they operate more hours each year compared with the same turbines installed onshore. The low roughness of sea surfaces makes offshore wind turbines to yield 50% more energy to that of the onshore one. But in contrast to onshore type the construction and installation of a foundation requires 50% more energy than the onshore wind turbines. It should be remembered, however, that offshore wind turbines have a longer life expectancy, around 25 to 30 years, than onshore turbines. The reason is that the low turbulence at sea gives lower fatigue loads on the wind turbine (22). The resource assessment in offshore turbines are very difficult because collecting data remotely is a big challenge.

2.4.5 Wind Turbine Capacity

the classification of wind turbine is not restricted but classifying in large and small scale is common classification that argued different research. the other classification could be categorized into this broad categories. considering their rated capacities Wind turbines can be divided into a number of categories in view of their rated capacities: micro, small, medium, large, and ultra-large wind turbines.

Micro-scale wind turbines

Though a restricted definition of micro wind turbines is not available, it is accepted that a turbine with the rated power less than several kilowatts can be categorized as micro wind turbine. Micro wind turbines are especially suitable in locations where the electrical grid is unavailable. They can be used on a per-structure basis, such as street lighting, water pumping, and residents at remote areas, particularly in developing countries. Because micro wind turbines need relatively low cut-in speeds at start-up and operate in moderate wind speeds, they can be extensively installed in most areas around the world for fully utilizing wind resources and greatly enhancing wind power generation availability.

Small-scale wind turbine

Small wind turbines have been extensively used at residential houses, farms, and other individual remote applications such as water pumping stations, telecom sites, etc., in rural regions. Distributed small wind turbines can increase electricity supply in the regions while delaying or avoiding the need to increase the capacity of transmission lines.

Large-scale wind turbines

Megawatt wind turbines up to 10 MW may be classified as large wind turbines. In recent years, multi-megawatt wind turbines have become the mainstream of the international wind power market. Most wind farms presently use megawatt wind turbines, especially in offshore wind farms.

ultra large scale wind turbines

Ultra-large wind turbines are referred to wind turbines with the capacity more than 10 MW. This type of wind turbine is still in the earlier stages of research and development.

2.5 Small Scale Wind Turbines

Technically, small scale wind turbine is defined in several ways. The IEC, defines SWTs in standard IEC $61400-2$ as having a rotor swept area of less than $200m^2$, equating to a rated power of approximately 50kW generating at a voltage below 1000V AC or 1500V DC. But in addition to this standard, several countries set up their own definition. Most of small scales wind turbines have 3-10m diameter that can produce a power up to 20KW. In addition to the power difference, there are some features that small wind turbines may experiences over that of the larger one.

- They may not be sited on windiest area. They can be located wherever the power is required. It can be to adjacent of the owner's home.
- Unlike to large scale wind turbines which uses mostly doubly fed induction generators (DFIGs), small wind turbines use permanent magnet generator which have a significant resistive torque that must be overcome aerodynamically before the blades will start turning (3).
- Especially in low power producing small wind turbines, there is no wind speed controlling device to measure the wind speed and direction. Instead of complicated yawing mechanism small scale turbine may uses a small sheet metal tail for adjusting the turbine towards the wind direction.
- Furling is used in many small wind turbines for controlling the blades during overspeed. Whereas braking system and pitching the blades around its own axis is used for large wind turbines.

The classification of Wind turbines for small scale and large scales are basically based on the same aspects. Generally, from the wind turbine we have seen above, horizontal axis wind turbine is preferred for our study. This is because of the drag type vertical axis wind turbine has low efficiency and its self-starting performance is much lower than horizontal axis wind turbines.

2.5.1 Composition of small-scale wind turbines

Generally, all wind turbines are composed of a rotor, generator and tower. However, wind turbine has different type and classes, its composition is also may be different. Large scale wind turbines have complex composition than small scale wind turbines. Common small-scale wind turbines may have the following components;

Rotor

Rotor is the most important component in many standpoints like performance and overall cost (3). It includes the blade and the supporting hub. The blade is basically designed in order to capture wind energy and convert it into rotating mechanical energy. Most of the time wind turbines classification depends on the type, size and orientation of the rotor. Since rotor is energy converter part of the system it has to be strong enough to stand steady and resist randomly changing loads. Therefore, performance and structural integrity are the fundamental issue to be considered. The hub part transmits the power and loads from the blades to the main shaft. The rigid type hub is employed in most of small scale wind turbine for its simplicity which supports the blade I fixed position relative to the main shaft (23).

Generator

A generator converts the mechanical power from the rotating wind blades to electrical power. Among the most common generators in large wind turbines are Induction generators and synchronous generators (24). Most small wind turbines use direct drive generators, which are actually special synchronous generators with enough poles to enable generator work well at the same speed of wind turbine rotor (24). Because there is no gearbox required with these generators, the reliability of the system is generally better than when a gearbox is included.

Nacelle

Nacelle is the housing for the generator and bearings and assembly to the tail. It protects these components from sunlight, rain, ice and snow.

Tail Assembly

Most small wind turbines are pointed into the wind using a tail assembly. A tail assembly usually consists of tail fin and tail boom, which are the primary components of the yaw system, keeping the turbine pointed into the wind. Larger turbines generally dispense with a tail because as the turbine size increases, the weight and loads associated with a tail become excessive. Instead, most large turbines use an active yaw system in which geared motors point the turbine into the wind based on the readings of wind direction sensors mounted on the nacelle.

2.5.2 Small Scale Wind Turbine Blade Materials

Materials that can be used for small scale wind turbines are vary from large scale blades. It has been noted that small blades are made from a wider range of materials using a wider range of manufacturing methods (25). Among the materials carbon fiber, fiber glass and timber take the leading for manufacturing small wind turbine blades. fiber glass has high stiffness and tensile strength which makes it better from the other materials. It is a low-cost, easily knitted and woven into desired textiles to meet different engineering requirements (3). Carbon fiber is also becoming more popular because it has higher modulus, lower density and higher tensile strength than fiber glass and it is less sensitive to fatigue. However, carbon fiber is more expensive than fiberglass and it is difficult to align the fibers (23). Recently fiber reinforced composites are the promising materials which has nearly close properties with the fiber glass.

In addition to this materials timber is also have a great role for small wind turbines. Blades shorter than about 1.5 m can be made wholly from timber. These blades were hand-carved and have large variations in mass and inertia, J. Timber has good strength and its failure due to fatigue is very low. The limitation on length of solid timber blades is the cost of knot-free blanks. Timber blades can be manufactured using a number of processes. These include, in order of decreasing sophistication;

- Special-purpose computer numerically controlled (CNC) routers;
- Copying from a master in a copying machine; and
- Hand carving

Even if CNC routers are accurate for manufacturing timber blades, it is very expensive and sophisticated. Accuracy problems are exacerbated by the dominance of blade pitch in both copying machines and hand carving method.

2.5.3 Issues Concerning on Small Scale Wind Turbine

It is clear that there is technical, social and environmental issue related to different projects reacted from local community and easily figured by the professionals. Therefore, it is appreciable and professional responsibility conducting appropriate technical studies on each issue, addressing the problem to minimize the impact, and provide accurate and consistent information (23). likely, there are different issues raised related to small scale wind turbines that needs study and responses. (3) and (26) highlight other social issues that have been raised in the past, including shadow flicker, safety, electromagnetic interference, noise, and environmental concerns.

Noise

Noise pollution is an inherent issue with wind turbines, but one that has seen extensive research in recent years, leading to a general alleviation of the problem. The noise produced by a turbine can be attributed to mechanical and aerodynamic factors. The simplicity of their design is a characteristic that affords SWTs fewer mechanical parts, and hence, less mechanical noise than their larger counterparts. However, larger rotor speeds required to produce energy, mean that aerodynamic noise is increased.

Safety

(3) identify that the primary hazards associated with wind turbines are related to the rotation of the rotor, the possibility of public access to potentially dangerous machinery, and the generated electricity. The identifiable hazards include;

- Blade throw – failure of a blade may result in the blade being thrown.
- Falling ice or thrown ice – in cold climates, accumulated ice also has the potential to be thrown from the blade
- Tower failure – most likely caused by extreme winds
- Attractive nuisance – the public may be curious, and want to touch, open, climb or otherwise interfere with the machine.
- Fire hazards – particularly when the turbine is located in an arid and remote location where fuel may grow around the turbine uncontrollably.
- Worker hazards – machine maintenance involves certain hazards, and these can be magnified if the person maintaining the machine is not a trained professional.
- Electromagnetic fields – caused by the flow of a current through a conductor.

Electromagnetic Interference

(26) identifies electromagnetic interference of navigational or communication related systems as a potential issue. According to Hau, turbine siting and rotor material are the main causes of interference, with steel rotor blades particularly problematic. However, this is not significant for modern small wind turbines for the reason that most of them are made of carbon fiber, timber, and fiber glasses which negate any potential problem concerning electromagnetic interference.

Enviromental

Its known that small wind turbines do not produce pollutants, emits GHGs or necessitates the destruction of habitats to operate. As an environmental impact of small wind turbines, the hazard to birds and bat species can be raised. Any tall structure poses a hazard to birds or bats, and in particular, the moving blades have been known to cause deaths. But the negative contribution of small scale wind turbine on the environment is very low perhaps they have a little contribution in dispersing carbon dioxide in the atmosphereAWEA2008.

2.5.4 Starting Performance of Small Wind Turbine

Sometimes, at low wind speed, modern commercial wind turbines shows low efficiency for electricity generation. This may be the designed blades are tested only in the specified wind speed and turbulence model. For this reason, various researches are conducted in order to maximize the efficiency of the blade. Among those researches, some of them are concerned about the starting performance of the small-scale horizontal axis wind turbine. The devotion of small-scale wind turbines to produce a useful power in low wind speed region is in question for most of commercial wind turbines for the reason that the blades are manufactured with a single airfoil section, no pitch adjustment, and the design is on the basis of peak power production. But as researches showed "the best power producing blades had relatively poor starting performance" and this could affect directly the energy that we can get from the system. Therefore, in order to get maximum energy production, the starting performance of the turbine should be optimized.

Starting time is the time required to reach power producing angular velocity from rest at the user prescribed wind speed. As aerodynamic torque is reduced, an increase in the starting time is expected and the blades might not start at all in some cases. This is because starting is mainly depending on the aerodynamic torque generated near the hub region of the turbine and this can have a large effect on the overall energy production of a turbine at the particular site. The torque decreases due to in appropriate angle of attack. This leads to a substantial idle time at both high and low wind speed. When the angles are reduced to those giving high lift to drag ratios, the blade accelerates rapidly to complete the starting sequence by producing significant amounts of power. There may have different solution for improving the starting performance of a wind turbine some of these solutions are

- Redesigning the blade for the proper air density, aerodynamic torque, airfoil selection.
- Changing the characteristics of the generator

Among this increasing the aerodynamics torque to the optimal level takes more percent. There are a number of ways to increase this torque. Increasing the number of blades is one option but the disadvantage is that it also introduces additional inertia to the rotor.

Secondly, by increasing the pitch angle, the blade would generate more torque as the blade experiences a smaller angle of attack. This also reduces the idling as the blade produces a higher lift-to-drag ratio(27). However, with the increase in pitch angle the turbine performance curve is shifted towards a lower tip speed ratio and so the turbine will stall earlier resulting in unsatisfactory performance at higher wind. The other factor involving in increasing the aerodynamic torque is the rotor inertia which is related to the blade geometry and material. Apart from the material used the blade inertia is directly related to the blade size. The size of the rotor is determined by the chord distribution and airfoil shape. The chord distribution is normally designed using established design procedures from the airfoil chosen. Therefore, it is reasonable to conclude that obtaining an inertia reduction is dependent on the airfoil employed. Researches are conducted to optimize the starting performance of a turbine with a little reduction of the power production.

For most of researches taken on the small scale wind turbine is an efficiency improvement by changing different input parameters and designing mechanism. Mentioning the low efficiency of commercial wind turbines in low wind speed region, (12) tries to design a turbine that have a better efficiency to that of the commercial one. on his research, he used a single FD2.7-500 airfoil section with 3-phase-500W synchronous generator at a design wind speed of 6m/s and tried to improve the airfoil with its maximum camber, airfoil thickness, and changes the pitch angle. The turbine set is installed in mini truck for recording data as it starts to move and experiment was conducted by testing both the commercial blade and the new designed one and come up with the efficiency of 27% unlike the commercial wind turbine which is 10%. But the main problem is on the way of trying to increase efficiency of small wind turbine, the starting time of a blade will be affected. Increasing the camber of an airfoil section might have a positive impact on power production but it increases the inertia of the blade which have a great roll in decreasing the aerodynamic torque.

The first investigation on starting performance of small wind turbine blade is conducted by (28). The research was to present an analysis of typical sequences and develop a framework which can be used to improve the starting characteristics of small horizontal axis wind turbine. They take three action in order to observe how the wind turbine behave in high and low wind speed condition at the starting

- Study the implication of pitch rate on the increasing of the lift coefficient.
- Measure the starting and idling time of the turbine
- Rebuilt the blade attachment for lower friction and smooth pitching

Soon after they begin rotating, the blades can generate unexpectedly high torque. At the same time, the non- dimensional pitch rate and reduced frequency are too small to suggest a significant increase of the torque through the effects of unsteadiness. The torque then decreases due to inappropriate blade angles of attack. This leads to a substantial "idle time" at both high and low wind speed, in which the rotating blades are accelerating only slowly and the angles of attack are slowly decreasing. When the angles are reduced to those giving high lift: drag ratios, the blades accelerate rapidly to complete the starting sequence by producing significant amount of power. At low wind speeds, about 4 m/s, a gust is apparently required to complete the starting sequence. Finally, they come up with the conclusion that the idle time at low wind speed was high. Thus, the blade starts to rotate after 30sec and for a given blade and wind speed, the maximum torque depends only on the tip speed ratio.

The second research conducted on the starting performance of small wind turbine is again observation based and held by A.K.Wright and D.H.Wood. 3-bladed 2m diameter blade with 600w permanent magnet was investigated in order to measure the starting performance of the blade in the field test and compare with the blade element analysis. From previous work the resistive torque and moment of inertia was characterized accurately and the blade pitched by 5^0 (5).

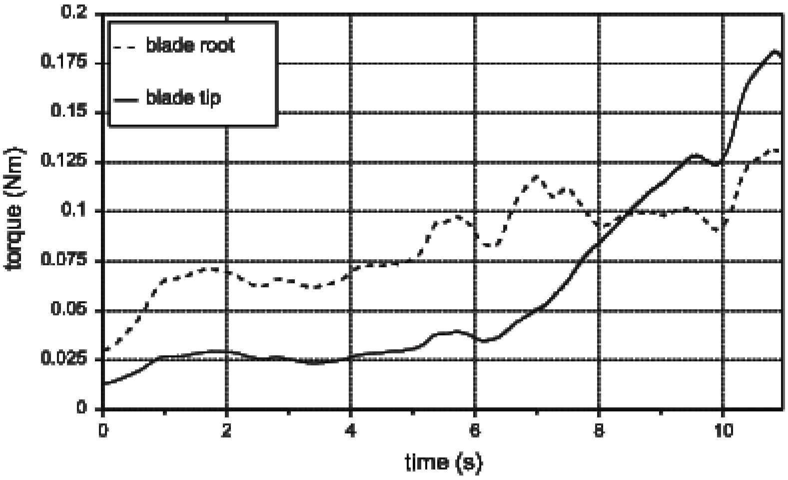


Figure 2.6: Torque generated by inner and outer blade elements for high wind speed start(5)

The starting behavior is predicted by the blade element analysis using a combination of interpolated airfoil data and generic equation for lift and drag at high angle of incident. As the Experiment for high and low wind speed start shows The average starting speed was 4.6m/s using the composite airfoil data and 5.6m/s using the equation and The average start time Ts, was 28s. the relation of wind speed and torque with starting time is showed in the figure 2.7 and fig. 2.6 . Finally, they concluded that the blades may be optimized for

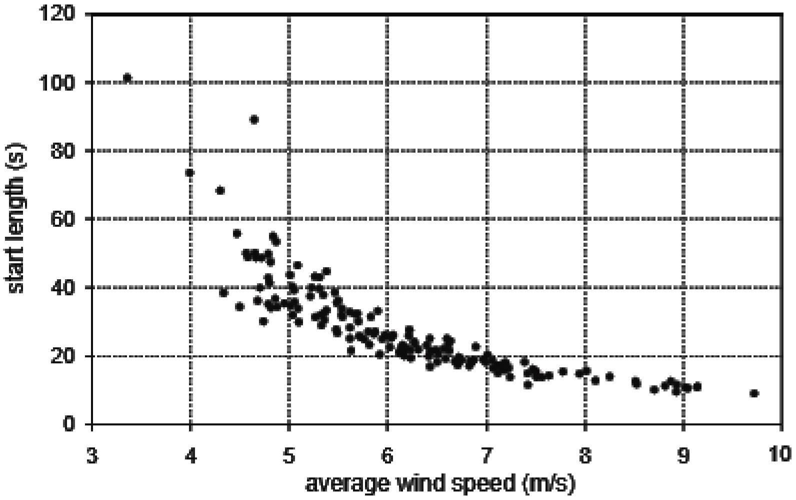


Figure 2.7: Starting time and the average wind speed sequence(5)

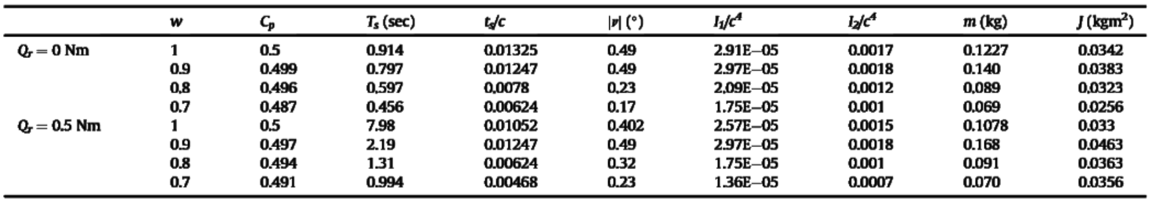
starting performance through the shape (pitch, twist, and chord) of the hub region and for the maximum power through airfoil selection for the tip.

After the observation of the starting performance of small wind turbines is finished some researches are showed up with a solution for optimizing the blade in order to have relatively a good starting performance with a considerable power production. As the previous researches concludes, for optimizing the blade pitching of the blade, twist and chord distribution have a great role. Therefore the coming researches determined on changing this parameter for the specified goal.

To generalize the study by using recent advances in knowledge of starting performance to improve the computational formulation, wood uses two bladed turbines designed at a speed of 10m/s. Single airfoil section is employed through out the blade section (13). The research is conducted for comparing the geometry of best power extraction blade obtained from evolutionary optimization with the arising from standard blade element theory and the effect of optimizing blades for starting performance on power production. The conclusion is it is possible to select (design a blade) which produce within 1% reduction of power super blade but starts in a time that is over a factor of two shorter and the optimized blade has larger value of pitch and chord near the hub region but the blades are similar near the tip.

The percent reduction of power production and starting time is investigated again by factor in the structural integrity of the optimized blade (1). For zero resistive torque(Qr) and W=0.7, Cp and Ts decreased 2.6% and 50% respectively in comparison with W=1. where 'W' is the weight given to the objective to be optimized. For Qr=0.5Nm, Cp and Ts decreases 1.6% and 87% respectively. In this study, the output power and the starting time were calculated by the BEM theory and a simple beam theory was employed to compute the stress and deflection along the blade. Genetic algorithm was employed for optimizing 3-bladed 1.06 diameter turbine which have the same airfoil section through out the blade. As we can see from the results of the above researches the weight(w) given to the two parameter has a great role in changing each value of the design parameter(Table 2.1). If more weight is given to the power production which is w=1, the power coefficient value is as expected but as the weight decrease down to the half value, there is a small change in power production and high percent change in the starting time. the other parameters which shows a considerable changes as the weight change are the thickness and the inertia of the blade.

Table 2.1: The effect of weight given to power production and starting performance(1)



	w	C_p	T_s (sec)	t_s/c	$\|\nu\|$ (°)	I_1/c^4	I_2/c^4	m (kg)	J (kgm^2)
$Q_r = 0$ Nm	1	0.5	0.914	0.01325	0.49	2.91E–05	0.0017	0.1227	0.0342
	0.9	0.499	0.797	0.01247	0.49	2.97E–05	0.0018	0.140	0.0383
	0.8	0.496	0.597	0.0078	0.23	2.09E–05	0.0012	0.089	0.0323
	0.7	0.487	0.456	0.00624	0.17	1.75E–05	0.001	0.069	0.0256
$Q_r = 0.5$ Nm	1	0.5	7.98	0.01052	0.402	2.57E–05	0.0015	0.1078	0.033
	0.9	0.497	2.19	0.01247	0.49	2.97E–05	0.0018	0.168	0.0463
	0.8	0.494	1.31	0.00624	0.32	1.75E–05	0.001	0.091	0.0363
	0.7	0.491	0.994	0.00468	0.23	1.36E–05	0.0007	0.070	0.0356

In order to have the fastest blade, the thickness and inertia of the blade should be decreased. Different materials were tested for structural integrity of the blade which is designed specifically for starting performance. For all materials at all weight of optimization, the minimum thickness $s = 0.01c$ was sufficient to ensure structural integrity. E-glass and flax/polyester blades, the better performing airfoil gave better blade designs because the minimum shell thickness is sufficient to maintain structural integrity (7).

The effect of starting performance is basically shown in the annual energy production of the wind turbine. Since the annual energy production is directly related to the working hour of the turbine, it is highly affected by the time that the wind turbine starts to give power and stops. the fastest blade starts, the more annual power production will be.

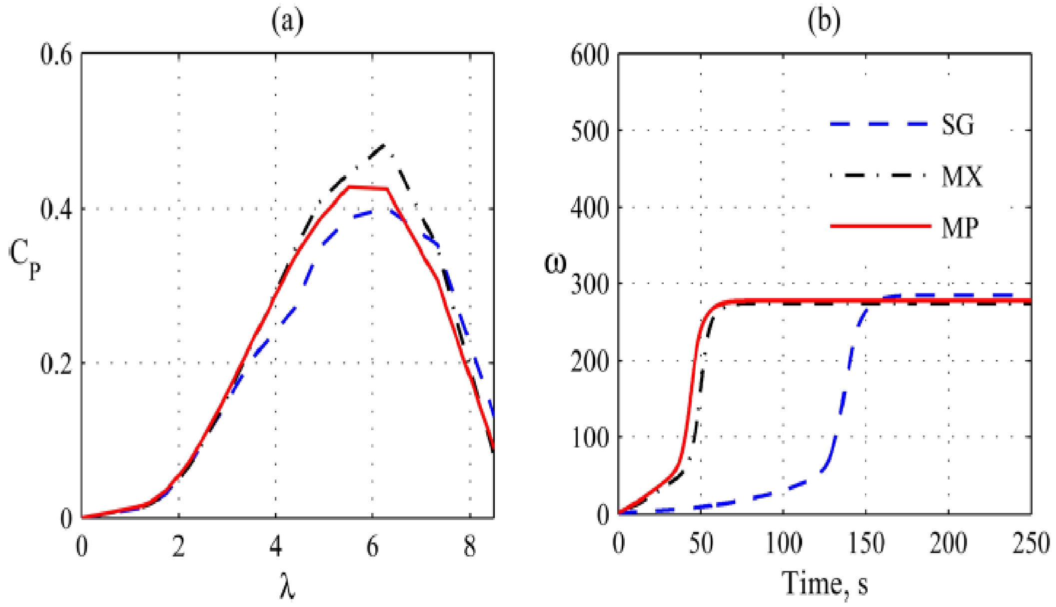


Figure 2.8: Power coefficient and start up sequence under steady wind condition. Where SG is single airfoil designed blade, MX is mixed airfoil blade(5^0), and MP is mixed airfoil blade with pitch angle greater than MX(6^0)(6)

Including annual energy production, (6) investigated the effected of load type integrated to the wind turbine as we trying to optimize for a better starting performance and a considerable power production. Unlike to the other researches on small wind turbines, the airfoil section is not single. Two promising airfoil sections(SD7062 and SG6043) are selected for mixing. The reason for combining two airfoil section was in order to get a low blade inertia and a better power production (6). First the effect of individual blade of each airfoil sections are investigated and compared to the mixed airfoil one figure 2.8.

Then the effect of different parameter like inertia, torque, pitching on increasing angular rotation are investigated by the blade with mixed airfoil section and pitched by 6^0 (Fig. 2.9).

Different load type, resistive load, battery load, and grid load, have an effect on starting and annual energy production.Net changes in annual energy production were ranges 4%-40% depending on the load types and site condition and it is proved that the starting ability has a direct effect on the duration that the turbine can operate and consequently its overall energy output. As we can see from fig 2.8 The mixed airfoil blades have a better starting performance under steady wind and Increasing the pitch angle also further shortens the idling period but doesn't significantly affect the rotor acceleration.

Among the research conducted in the area of starting performance some of them are observations that how small wind turbine blades behave in starting in different conditions and the others tried to optimize the starting time specifically to decrease the long idling period created. Some of the parameters(conditions) that are taken in those researches are

- Optimizing chord and twist distribution
- Hollow blade to minimize the moment of inertia

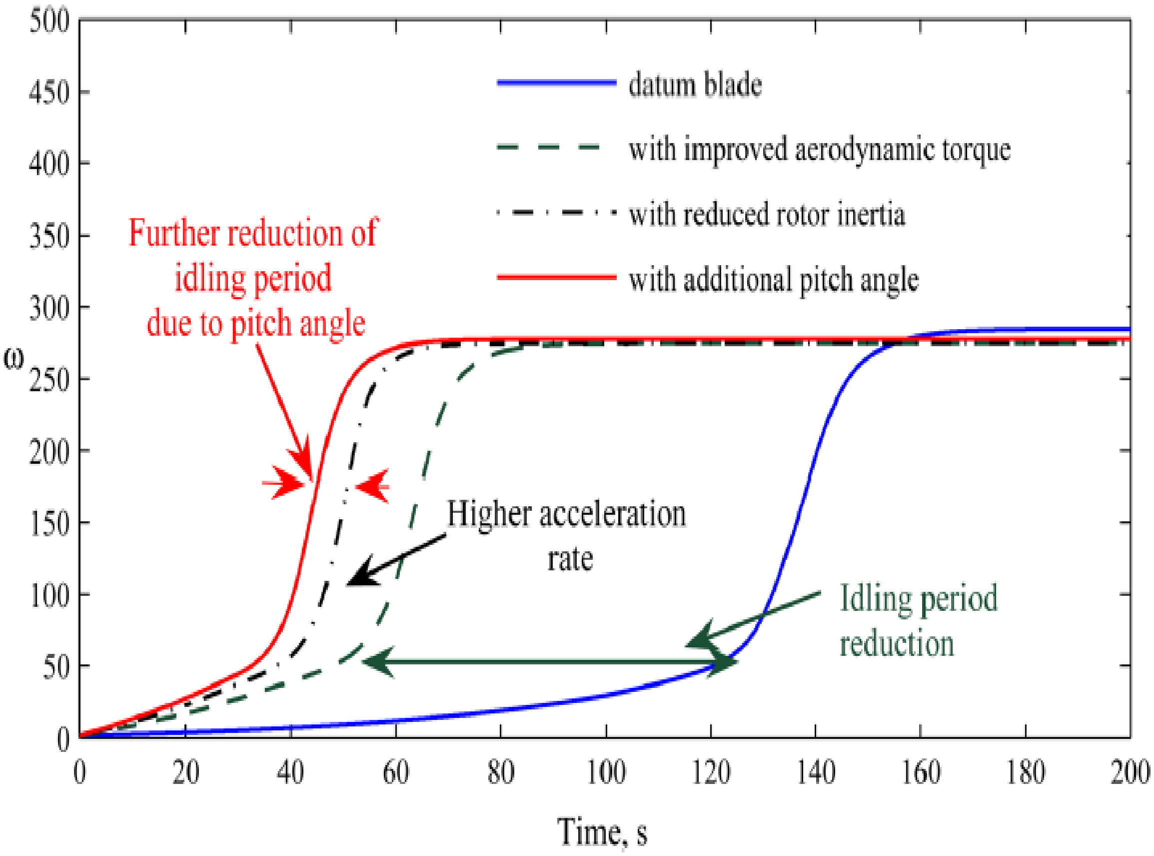


Figure 2.9: Parameters contributing to starting performance(6)

- Changing the airfoil
- Using mixed airfoil
- Using different materials

In addition to this the effect of load type is also considered. However, for those optimized blades to have a good starting performance experimental tests are not conducted for most of the researches and effect of using different airfoils for designing the blade is not investigated yet, investigation on the effect of blade number is not enough, and some comparative analysis should be taken for a better conclusion.

Chapter 3

Design of baseline wind turbine blade

In this section, the non optimized wind turbine blade is designed and the reason why blade number, wind speed , blade radius, and blade airfoil selected is described. The main objective of this section is designing a non optimized blade which is used for analyzing the effect of optimized blade on the starting and power performance.

3.1 Preliminary Design

In most cases blades were designed to be the best for power production but this leads to the blade to start slowly with large starting wind speed and the idling time becomes longer. This is because a blade designed to have high coefficient of performance for a given wind speed have larger blade radius and experiences different chord and twist distribution. Therefore, as this radius increases the blade moment of inertia increases which makes the blades not even to rotate for the specified wind speed by increasing a resistive torque. In addition to increasing resistive torque, the blade experiences high angle of attack which leads to early stall and generate only small amount of torque. Even if the starting time and power production are indirectly related recent researches are showing up on designing a blade that have low starting time with a little reduction of power production. To make this right a genetic algorithm was used in order to optimize the blade by altering different parameters. First the blade chord and twist distribution will be computed by a standard blade element momentum theory and optimization takes place by multi objective genetic algorithm optimization techniques. For better analysis we select two different blade with different input parameters. The design by BEM is conducted in order to compare the geometry of the blade with the optimized one. In order to decrease the blade inertia, the best performing airfoil will be selected from the airfoils designed specifically for low wind speed blades and a material that have low density is selected as mentioned in (6),and (7).

3.1.1 Determining input parameter

Blade speed and radius

Basically, the power that can be gained from a specific site is mainly depend on the wind speed distribution. Therefore, it is easy to estimate the power that can be traced from the regions that have low wind speed distribution easily from the power formula. Even if the specified range of wind speed is differing from document to documents, most of them agreed that low wind speed is averaged to 5m/s (28). In almost all of the research conducted in starting performance the design wind speed is taken 10m/s for the area that have low wind speed.

But as the design wind speed increases the blade radius decrease and the starting torque, and the power output will decrease. Therefore, if our goal is to increase the starting torque, we have to increase the blade radius for the reason that they are highly related to each other. As compared the power that we can get from 6m/s and 10m/s from different blade radius, we can get more power at 10m/s for comparatively low blade radius But in both cases, we figure out that as the radius of the blade increases the power also increases because power is directly related to the square of the blade radius. But to decide the size of the blade radius there are different parameters that have to be consider in addition to the power.

Because this paper aims to design a small wind turbine blade that have low starting time and better power performance at the same time, our selection should direct the blade to have low starting time and a better power performance. The reduction of rated wind speed results an increase in the wind blade radius in order to extract more energy from low wind speeds (29). This makes the wind blade to increase its weight. From the Table 3.1 which is abducted from (30), the increase in blade radius highly affect inertia of the blade rather than any other parameters. When the wind blows, the angular acceleration(the rate of increase of rotor speed), is expressed by the aerodynamic torque divided by the inertia of blade.

Table 3.1: Dependence of important parameters on blade radius

(30)

parameter	dependence
`Reynold number`	R
`Power output`	R^2
`Centrifugal force`	R^2
`Starting torque`	R^3
`Inertia of the blade`	R^5

$$\alpha = \frac{Q}{J} \tag{3.1}$$

Therefore, starting can be maximized by increasing the aerodynamic torque and minimizing the blade inertia by reducing the blade radius. But if we design the blade with low rated wind speed, the rotor may not even starts to rotate at all or the idling period will be high because of the weight(inertia) it develops from the increase of blade radius.

Choosing number of blade

The effect of number of blades on the power production and starting time improvement is investigated(2). The result of the research shows that the more powerful blade was found for N=4,5 rather than three bladed turbines for the reason that as the blade number increases the aerodynamic torque will increase which overcome the resistive torque. But this output will be different in different blade material that highly affect the inertia of the blade. The selection of blade number has to depend not only on the aerodynamic torque, economic feasibility and density of the blade material should be taken in account. For small turbines (smaller than 50 ft) rigid, three-blade rotors are inexpensive and simple and yield the lowest system cost. As the turbines become larger, blade weight (and hence cost) increases in proportion to the third power of the rotor diameter while power output increases as the square of the diameter.

Table 3.2: Relation of tip speed ratio and number of blade

λ	B
1	$8-24$
2	$6-12$
3	$3-6$
4	$3-4$
>4	$1-3$

Select an airfoil section

As researcher investigated starting performance, specifically the long idling period of small wind turbine blade is affected by the aerodynamic torque generated near the hub region and the power is affected by the torque generated from the tip region (13). Because small wind turbines experience high angle of attack and very low Reynold number, the lift and drag values are uncertain and unsatisfactory. This lift and drag values are the main parameters for the aerodynamic torque of a wind blade. In order to produce a significant amount of power, the blade should considerably accelerate by reducing the angle of attack to those giving high lift to drag ratio.

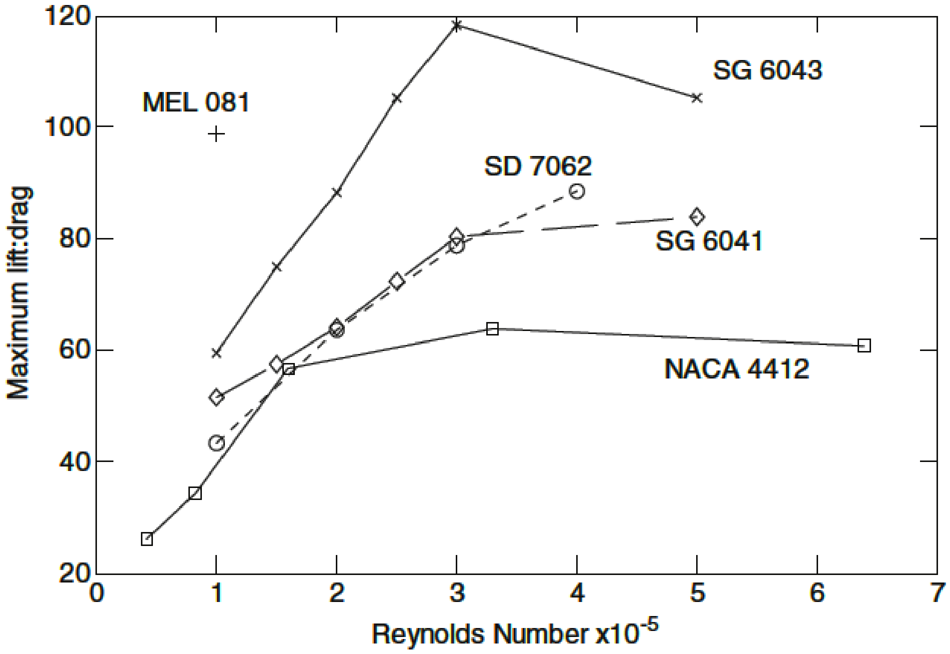


Figure 3.1: Airfoil lift to drag ratio at low reynold number (7)

Producing high torque without introducing additional inertia and sacrificing the power production is highly depends on the selection of airfoil. Therefore, to achieve this goal a careful selection of an airfoil shape is the best action in optimizing the blade for starting performance and also for power production. In most cases small wind turbines uses a single airfoil for simplicity and ease of manufacturing but when it compares to the mixed airfoil blades, its performance is very low for starting performance and power production. mixed airfoils have a high percent reduction of moment of inertia of the blade in addition to the power production.

As selig. investigated the airfoil performance using an unsteady two-dimensional Reynolds-averaged Navier–Stokes (RANS) solver, SG6043 and SD7062 airfoils are the promising airfoil emerged to design a blade for starting performance and also a best power production performance for small wind turbine with low Reynold number (31).

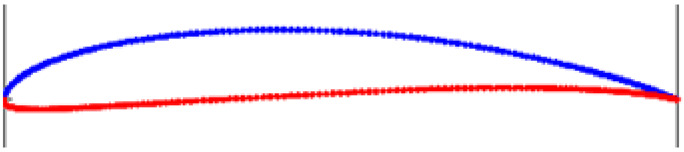


Figure 3.2: SG6043 airfoil shape

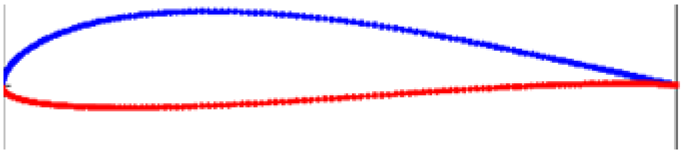


Figure 3.3: SD7062 airfoil shape

The SG6043 was designed by Selig and Giguere for small wind turbine applications. Its thickness and camber are 10 and 5.5, respectively, and it has a high lift-to-drag ratio. The $SD7062$ was designed for gliders by Selig and Donovan at the University of Illinois. It exhibits high lift and low drag at low speed. It has a thickness of 14 and camber of 4. This airfoil is thicker than the $SG6043$ and can be employed for root sections (7). These two primary airfoils having the highest design lift coefficients ($SD7062andSG6043$) yielded enhanced lift-to-drag performance over many other low Reynolds number airfoils. $Reynoldnumber$ is the most important parameter for defining the characteristics of the fluid flow. It is dependent on the speed and the cross section of the airfoil.

3.1.2 Single Airfoil Design

This design is basically aims to show the difference in chord, twist, and power created between the optimized blade and the blade designed by blade element momentum analysis. After designing the blade by BEM theory, the optimization will take place in order to achieve a best performing blade compared to the designed one. therefore, the input parameters for the two blades will be listed.

Betz's law theory is used for the preliminary design and mat lab is used for the complex mathematical equation and process (32). The input parameter listed in Table 3.3 and Table 3.4 is used as the initial input parameter for the design. The output results are chord and twist distribution and the power can be achieved from the two blades.

Table 3.3: Input parameter for initial design of Blade 1

λ	6
`number of blade`	3
`diameter`	1.69
`r/R`	0.0472
`minimum chord`	0.04
`maximum chord`	0.2
`mechanical and electrical efficiency`	0.85
`start value of` α	0
`finish value of` α	20

Table 3.4: Input parameter for initial design of Blade 2

λ	6
`number of blade`	3
`diameter`	1
`r/R`	0.0313
`minimum chord`	0.06
`maximum chord`	0.2
`mechanical and electrical efficiency`	0.85
`start value of` α	0
`finish value of` α	20

3.1.3 Mixed Airfoil Design

The basic need of designing the blade from a mixed airfoil sections is to investigate the effect of mixed airfoil blade on the starting performance of a small wind turbine and to compare its starting performance with the optimized blade.

The airfoils used here is SD7062 and SG6043 which have high lift to drag ratio from the other airfoils designed for the purpose of small wind turbine. since SD7062 is thicker than SG6043, it is employed for the root section with the proportion of 1/5. This is because as the proportion of the airfoil section increases, the blade profile become more twisted in order to achieve the desired power. The other thing is a big care should be given for the airfoil selected to be mixed together to get one blade for the reason that some airfoil does not much with the other one in chord distribution and this makes the blade to have rough structure which might affect the manufacturing in addition to its effect on the torque and power of each blade section and on the overall blade length.

In addition to this the air density and viscosity is taken as the input parameter for the design. As different investigation shows the chord and twist distribution of a blade is large at the root section and decreases towards the blade radius. The out put from our design by BEM theory approve this.

From Figure 3.5 we can observe that the maximum chord and twist is a not restricted to observe the effect of giving range to the chord and twist value of the blade on the starting

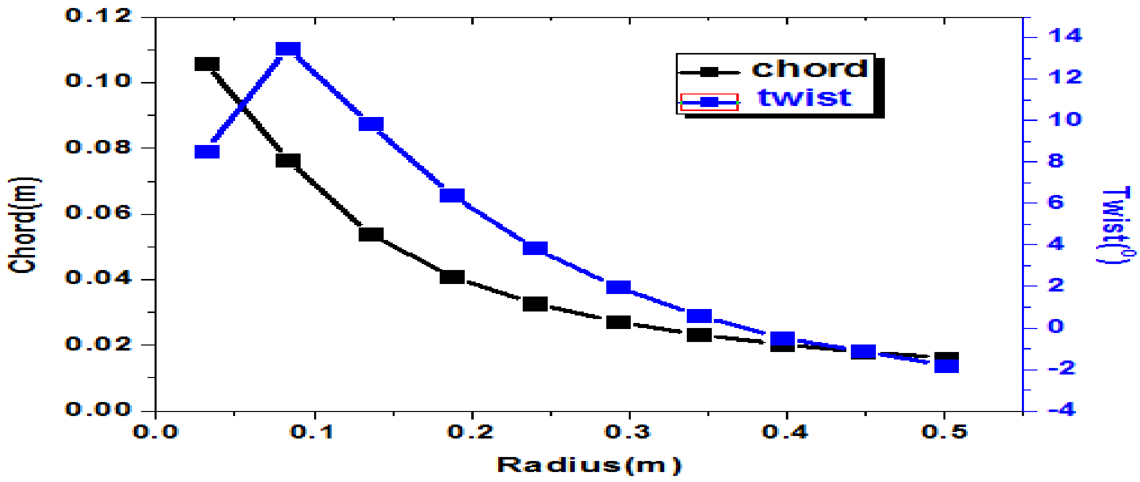


Figure 3.4: Chord and twist distribution of Blade 2 designed by BEM theory

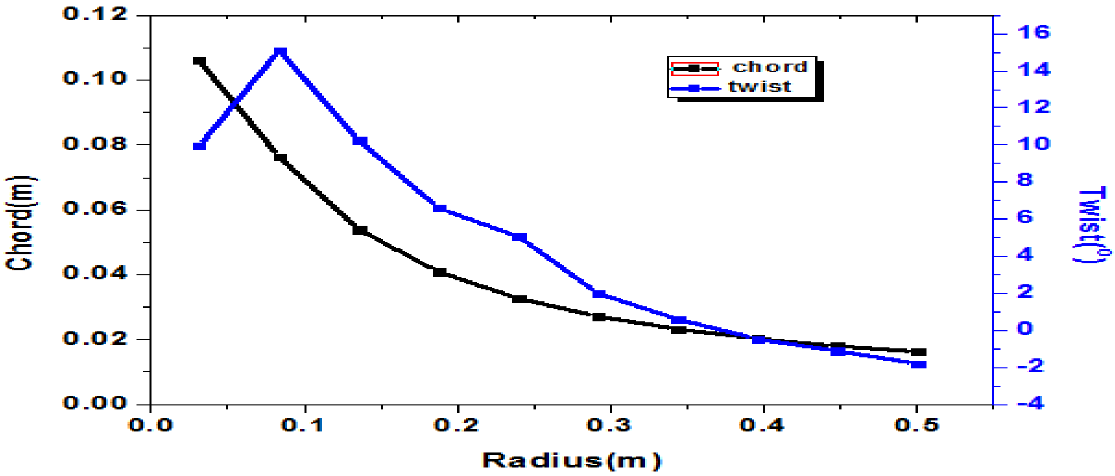


Figure 3.5: Chord and twist distribution of mixed airfoil blade designed by BEM theory

and power performance of wind turbine. The power that can be generated from the ***Blade*1** is 0.393kW and the power coefficient is 0.42.

Chapter 4

OPTIMIZATION OF THE BLADE WITH GENETIC ALGORITHM

This chapter includes the description of optimization technique, necessary modeling and input parameters for the optimization. Desciption of small wind turbine rotor design code(SWRDC) is also included in this chapter.

4.1 Optimization

Optimization is a mathematical technique for finding a maximum or minimum value of a function of several variables subject to a set of constraints. Optimizing a function give so many advantages like finding the better (optimal design), faster design evaluation, for trade off analysis.

Evolutionary algorithm is derived from the classic evolution theory, which are implemented on computers in the majority of cases. These population dynamics follow the basic rule of the Darwinist evolution theory, which can be described in short as the “survival of the fittest”. The most important evolutionary algorithm methods are Genetic Algorithms (GA), Genetic Programming (GP), Evolutionary Strategies (ES), Evolutionary Programming (EP) and Learning Classifier Systems (LCS).

Given an optimization problem, we create a population of candidate solutions, which we call individuals. Some solutions are good, and some are not so good. The good individuals have a relatively high chance of reproducing, while the poor individuals have a relatively low chance of reproducing. Parents beget children, and then the parents drop out of the population to make way for their offspring. As generations come and go, the population becomes more fit. Sometimes one or more "supermen" evolve to become highly fit individuals that can provide near-optimal solutions to our engineering problem, this is how genetic algorithm works.

Therefore, before the optimization technique starts there is modeling which are inputs for the optimization. Since we are trying to optimize two indirectly dependent parameters, we have to model both individually and then our objective function takes the leads for the last optimization technique by factor-in both parameters.

4.1.1 Aerodynamic modeling

Aerodynamically the blade torque, twist and chord distribution, aerodynamic forces and many other parameters can be calculated from blade element momentum theory. Since the design aims to achieve a best wind turbine blade which is the fastest to start and a better power coefficient correspondingly, taking the power coefficient modeling is enough. The other mathematical procedures to get the profile of the blade (chord and twist distribution) is held by the optimization technique. This is because the blade designed aerodynamically by the blade element momentum theory give the best power producing blade but the slowest to start which contradict our design goal (1).

$$Cp = P/(1/2)\rho AU^3 = Q\omega/(1/2)\rho AU^3 \tag{4.1}$$

Where Q is used as the representation of torque through out this paper

4.1.2 Starting time modeling

In order to have a blade with a fast-starting time, the aerodynamic torque should be maximized and the blade inertia should be low as much as possible. The aerodynamic torque acting on the blade could be found by employing the generic flat plate expression for the aerodynamic coefficients at high angle of attack.

$$Q = N\rho U^2 R^3 \int_{r_h}^{1} (1+\lambda_r^2)^{\frac{1}{2}} cr \sin\theta_p(\cos\theta_p - \lambda_r \sin\theta_p) d_r \tag{4.2}$$

Where N is number of blades,λ_r is local tip speed ratio, θ_p is twist angle,c is chord length, and r is local radius. following the aerodynamic torque, the starting capability is expressed by the rotor acceleration. The angular rotation of a rotating blade has to exceed the angular rotation of the generator in a specific time to produce usable power. As the increment of angular rotation in order to exceed the generator's angular velocity is slows down, the idling time become longer which means the angular acceleration of the rotor is very small. This can be related to the torque produced and the moment of inertia of the blade

$$\alpha = \frac{Q - Q_r}{J} or \frac{d\lambda}{dt} = \frac{R(Q - Q_r)}{JU_\infty} \tag{4.3}$$

Q_r is resistive torque towards the rotation of the blade created by mainly the generator which is called the cogging torque. The cogging torque created by permanent magnet generators depends on many factors such as rated size and configuration. Noise and mechanical vibration may be excited by the cogging torque. This type of vibration may threaten the integrity of the mechanical structure of improperly designed small wind turbine. In high wind speed, the amount of torque and the kinetic energy stored in the rotor is sufficiently large that the cogging torque is insignificant (33). But If the blade size is small any torque resistive to the rotation have a great impact on the starting performance of the blade. It has been reported that typical cogging torques of permanent magnet generators rated from 500W to 1.5kW are 0.3 to 0.6 Nm, respectively (34). Therefore, based on this the cogging torque for the generator rated less than 500w is not exceed 0.3Nm.

The moment of inertia is dependent on the airfoil, the size of the rotor, and the blade material used (35). The blade material for this design is the same through out the blade cross section but the airfoil is mixed and in order to reduce the inertia hollow blade is preferred by considering the structural integrity of the material. (7) said that for most materials, the minimum thickness sufficient to ensure the structural integrity of the blade is not more than 0.1*chord. Therefore, the inertia of the blade is the difference between the inertia of the inner surface which is gained by subtracting the thickness from the original and the original

Table 4.1: The value of A for different airfoils

airfoil	A
SD7062	0.08818
SG6040	0.10411
SG6041	0.06955
SG6042	0.06916
SG6043	0.06850
NACA0012	0.08213
NACA4412	0.08211

one itself.

$$J = N\rho_b AR^5[\int (cr)^2dr + \frac{A}{12}(\int c^4cos^2\theta_pdr + A^2\int c^4sin^2\theta_pdr)] \tag{4.4}$$

4.1.3 Objective function

The objective function determines the chord and twist distribution that gives the highest power coefficient and the fastest starting blade.

$$maximize : (w\frac{Cp}{maxCp} + (1-w)\frac{min(t_s)}{t_s}) \tag{4.5}$$

Where w, is the weight given to each objective which ranges ($0 \leq w \leq 1$). as w tends to shift to 1 the blade is optimized to have high power coefficient. The chord and twist distribution through out the blade are the design variables of the optimization problem. The maximum chord is often fixed. The minimum and maximum chord corresponds to 30mm and 300mm respectively which is considered the smallest section that can be manufactured accurately (13). the maximum and minimum twist are often fixed by similar consideration.

Table 4.2: Input parameters and the characteristics of design variable of Blade 1

`N` =3	`Airfoil` =SG6043
`R` =0.8466	r_h =0.04
`maximum chord` =0.2	`minimum chord` =0.04
`number of blade element` =15	`number of design variable` =30
`maximum twist` =20	`minimum twist` =0

4.1.4 Small Wind Turbine Rotor Design Code (SWRDC)

This is a design code which can be integrated to the MATLAB as one tool in order to design a small wind turbine blade which is optimized either in single objective or multi- objective.

Table 4.3: Input parameters and the characteristics of design variable of Blade 2

`N` =3	`Airfoil` =SG6043
`R` =0.5	r_h =0.0313
`maximum chord` =0.2	`minimum chord` =0.06
`number of blade element` =10	`number of design variable` =20
`maximum twist` =20	`minimum twist` =0

Table 4.4: Input parameters and the characteristics of design variable of Blade 3

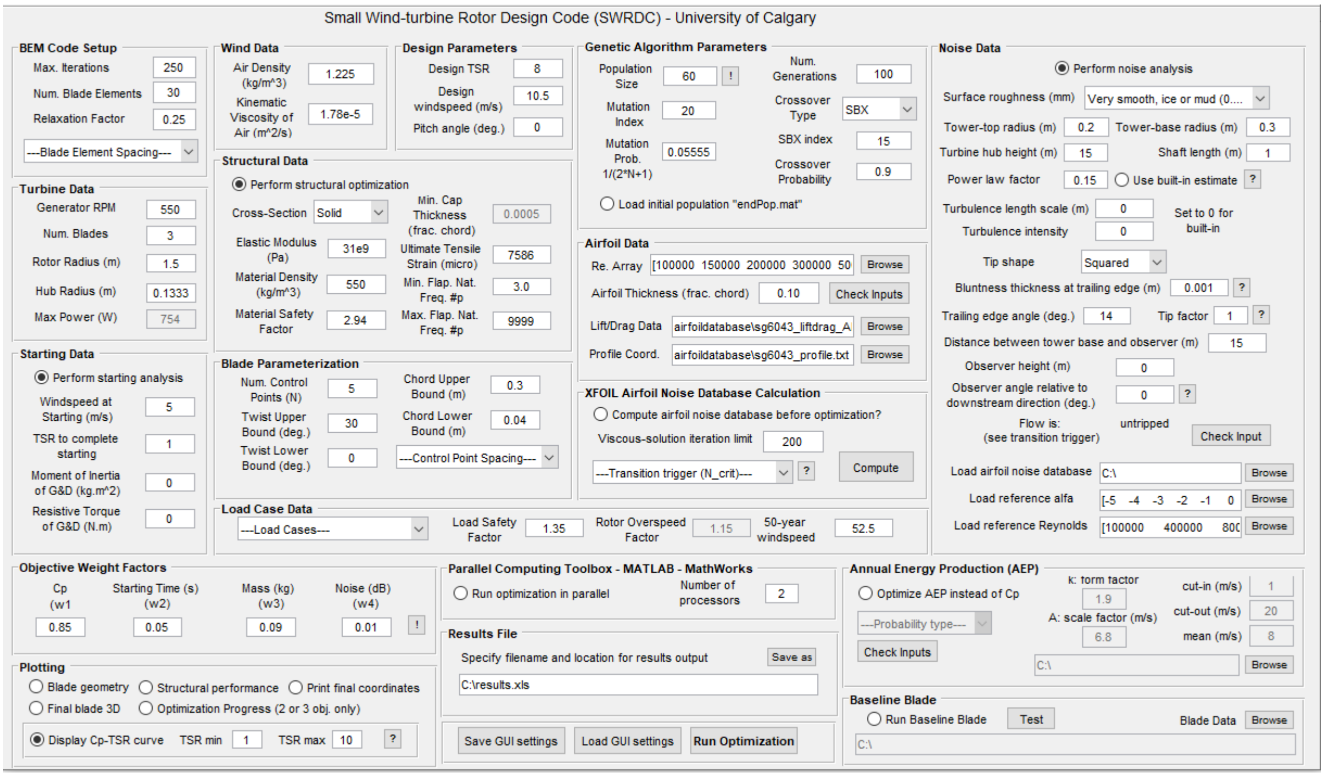
`N` =3	`Airfoil` =SD7062
`R` =0.5	r_h =0.0313
`maximum chord` =0.18	`minimum chord` =0.08
`number of blade element` =10	`number of design variable` =20
`maximum twist` =20	`minimum twist` =0

The tool developer tries to develop a computer method for the design of small-scale wind turbine blades. In this tool one can optimize the bade starting time, power coefficient, noise, and mass. The tool uses genetic algorithm, blade element momentum theory, simple euller-bernoulli beam theory and a starting performance model of small turbine blades which early developed by David wood, and a noise model of Zhu to design a small scale, variable speed and fixed pitch horizontal axis wind rotors(36). Under our scope the starting time performance and power coefficient is concerned for the design and the structural analysis and noise reduction analysis are not considered. The whole input parameters for the design is specified in the design section

In order to get appropriate result, the input parameter on the tool have to be fill with the correct and reasonable value. The first requirement is to fill the number of iteration and relaxation factor. For the appropriate aerodynamic calculation, it is recommended to take the number of iteration 200+ along with a small value of relaxation factor which is < 0.2. but for rough and quick calculation we can use the opposite.

The optimization algorithm in SWRDC is genetic algorithm which can be controlled by different parameter specified in the GUI. The first parameter is population size which determines the the number of individuals for each generation. It has a direct relation with the computation time, as the population size increase the time for computing each generation will increase. Therefore it is recommended to use population size greater than 100. The second parameter is the number of generation which is the maximum number of generation that the genetic algorithm will run before it terminates. Same to the population size ,increasing the number of generation will ensure the algorithm to converge to the optimal blade design. Therefore large number of generation is recommended which is greater than 50.

To create children and potentially superior individuals, the GA utilizes the crossover and mutation operators. Each operator contains settings which can be controlled by the user. These settings can significantly influence the performance of the GA. For Crossover Type, either SBX or Uniform can be selected. For the SBX, the crossover is performed between two parents and requires a SBX index. The SBX index controls the probability of creating



Small Wind-turbine Rotor Design Code (SWRDC) - University of Calgary

BEM Code Setup
Max. Iterations 250
Num. Blade Elements 30
Relaxation Factor 0.25

Turbine Data
Generator RPM 550
Num. Blades 3
Rotor Radius (m) 1.5
Hub Radius (m) 0.1333
Max Power (W) 754

Starting Data
● Perform starting analysis
Windspeed at Starting (m/s) 5
TSR to complete starting 1
Moment of Inertia of G&D (kg.m^2) 0
Resistive Torque of G&D (N.m) 0

Wind Data
Air Density (kg/m^3) 1.225
Kinematic Viscosity of Air (m^2/s) 1.78e-5

Design Parameters
Design TSR 8
Design windspeed (m/s) 10.5
Pitch angle (deg.) 0

Structural Data
● Perform structural optimization
Cross-Section Solid
Min. Cap Thickness (frac. chord) 0.0005
Elastic Modulus (Pa) 31e9
Ultimate Tensile Strain (micro) 7586
Material Density (kg/m^3) 550
Min. Flap. Nat. Freq. #p 3.0
Material Safety Factor 2.94
Max. Flap. Nat. Freq. #p 9999

Blade Parameterization
Num. Control Points (N) 5
Chord Upper Bound (m) 0.3
Twist Upper Bound (deg.) 30
Chord Lower Bound (m) 0.04
Twist Lower Bound (deg.) 0

Load Case Data
Load Safety Factor 1.35
Rotor Overspeed Factor 1.15
50-year windspeed 52.5

Genetic Algorithm Parameters
Population Size 60
Num. Generations 100
Mutation Index 20
Crossover Type SBX
SBX index 15
Mutation Prob. 1/(2*N+1) 0.05555
Crossover Probability 0.9
○ Load initial population "endPop.mat"

Airfoil Data
Re. Array [100000 150000 200000 300000 50
Airfoil Thickness (frac. chord) 0.10
Lift/Drag Data airfoildatabase\sg6043_liftdrag_A
Profile Coord. airfoildatabase\sg6043_profile.txt

XFOIL Airfoil Noise Database Calculation
○ Compute airfoil noise database before optimization?
Viscous-solution iteration limit 200

Noise Data
● Perform noise analysis
Surface roughness (mm) Very smooth, ice or mud (0....
Tower-top radius (m) 0.2
Tower-base radius (m) 0.3
Turbine hub height (m) 15
Shaft length (m) 1
Power law factor 0.15
○ Use built-in estimate
Turbulence length scale (m) 0
Turbulence intensity 0
Set to 0 for built-in
Tip shape Squared
Bluntness thickness at trailing edge (m) 0.001
Trailing edge angle (deg.) 14
Tip factor 1
Distance between tower base and observer (m) 15
Observer height (m) 0
Observer angle relative to downstream direction (deg.) 0
Flow is: (see transition trigger) untripped
Load airfoil noise database C:\
Load reference alfa [-5 -4 -3 -2 -1 0
Load reference Reynolds [100000 400000 80(

Objective Weight Factors
Cp (w1 0.85
Starting Time (s) (w2) 0.05
Mass (kg) (w3) 0.09
Noise (dB) (w4) 0.01

Plotting
○ Blade geometry ○ Structural performance ○ Print final coordinates
○ Final blade 3D ○ Optimization Progress (2 or 3 obj. only)
● Display Cp-TSR curve TSR min 1 TSR max 10

Parallel Computing Toolbox - MATLAB - MathWorks
○ Run optimization in parallel
Number of processors 2

Results File
Specify filename and location for results output
C:\results.xls

Annual Energy Production (AEP)
○ Optimize AEP instead of Cp
k: form factor 1.9
A: scale factor (m/s) 6.8
cut-in (m/s) 1
cut-out (m/s) 20
mean (m/s) 8
C:\

Baseline Blade
○ Run Baseline Blade
Blade Data
C:\

Figure 4.1: Small wind turbine rotor design code
(36)

near parent solutions or distant solutions as children. When Uniform is selected, a random binary vector is created and selects the genes where the vector is 1 from the first parent and the genes where the vector is a 0 from the second parent, and combines the genes to form the child. The Crossover Probability controls whether two parents will be subjected to crossover or not, and is a parameter for both the SBX and Uniform crossover types. Mutation specifies how the GA makes small random changes to create mutated children, promoting the diversity of the population. The Mutation Index controls the intensity of the mutation (or the randomness) when altering the genes of a child. The Mutation Probability is the probability that each gene from a child will be mutated. A commonly used heuristic for Mutation Probability is 1/number of variables, where the number of variables in SWRDC is $2N + 1$. N is the number of control points as specified in the Number of Control Points (N) field on the Blade Parameterization panel.

Chapter 5

MANUFACTURING AND TESTING OF THE OPTIMIZED BLADE

In this chapter materials are selection, manufacturing of the wind turbine blade and the procedure followed to conduct experimental testing is described. Manufacturing the wind turbine consists the material selection, blade manufacturing and assembling the blade with the generator and some other supporting parts. Considering the specification of the available CNC machine, Blade 3 is selected to be manufactured for experimental testing process.

5.1 Material selection

Currently different materials are being used widely for the purpose of manufacturing small wind turbine blade. However, the selection process needs a big care giving the credit for the type of the designed blade and the manufacturing process. Wood, metals, glass fiber reinforced polymer, carbon fiber reinforced polymers, natural fiber reinforced polymer, and nano-composites are the most recommended materials in the market for small wind turbine blade among that glass fiber reinforced polymer and carbon fiber reinforced polymer take the leading in the manufacturing process but they are not abundant and difficult to manufacture compare to wood made blade. Furthermore, the weight and manufacturing complexity make metal to be not listed.

Figure 5.1: The bamboo used for blade manufacturing

Since the design is concentrated on the power production and starting performance side, the selection of material should consider the available manufacturing process, cost, and weight. Considering these, timber is preferable rather than the above listed material. Timber has different type with different properties and advantage. Among them bamboo was the promising material for small wind turbine blade. It is strong having high tensile strength, resistant to wrapping, and can be used for many different types of application like paper, flute, scaffolding, carving, etc.. . .

5.1.1 Manufacturing Method of bamboo plate

In order to make the designed blade from bamboo first the bamboo should be very thick to fit the specified size. The bamboo needs some machining process in order to get a flat surface since it is round.

- The round bamboo cuts out in the length of 1m.
- Split the bamboo to half.
- If the curve is still large, cut it into half again.
- Surface finishing process
- Thin bamboo plates glued to the height and width of the desired dimension
- After it is perfectly glued and get the necessary flat surface, it will finally be machined and send to CNC machine for further manufacturing.

Figure 5.2: Processing the bamboo for further machining process

However the processed plate have more weight than excepted. The bamboo thickness decreases to its length which means, the root section is very thick and starts from 25% of its length bamboo has thin round section.Therefore, it is preferable using root section of bamboo in order to get thick flat bamboo plate from the machining process but the big problem was in the root section there are heavy, hard and difficult to machine knots few mm apart from each other. This knots are the reason for the bamboo plate to weigh more than expected. since the thin bamboo plates to be glued together in order to give the desired dimension are many in number, more gluing fluid is used. This connecting fluid makes the weight of the plate become large.

Therefore, the material for the blade manufacturing process is changed to other type of timber which have nearly the same characteristics with bamboo, that is **Australian timber** .

5.2 Generator selection

Generator is an electrical machine which convert mechanical energy to electrical energy. The suitable generator type for the our design is PMG(permanent magnet generators) which have comparatively require low angular velocity and have varying rotational speed which enable to track optimum Cp for most wind speeds below the design wind speed from the other rotating electrical machine. However PMG has a great advantage on the starting performance of a wind turbine by reducing the idling period, it is not possible to easily access in the market.

The access of electrical generator for the desired specification is not bound to the type of the generator, it is not totally available to get generators used for the purpose of generating electricity from wind turbines. Therefore, the only choice is taking out the generator from other operating electrical machines and making a little modification to operate in the desired way like washing machine, car alternator, fuel operated generators.

Among those electrical equipment's a car alternator(80Amps 12v) is used here for the reason of its accessibility and ease of modification. The main purpose of an alternator in the car system is charging the battery, hence at the time car engine is not running lighting, radio, opening the window mirror and some other operations which needs electric is supplied from the stored battery. But first the alternator has to get some electrical energy from the battery in order to excite it self and create electromagnetic field for electric generation. After the excitation system is done the sign of battery will be off which means the alternator stops accepting energy from the battery and starts generating voltage back. The selected a car alternator is shown in the Figure

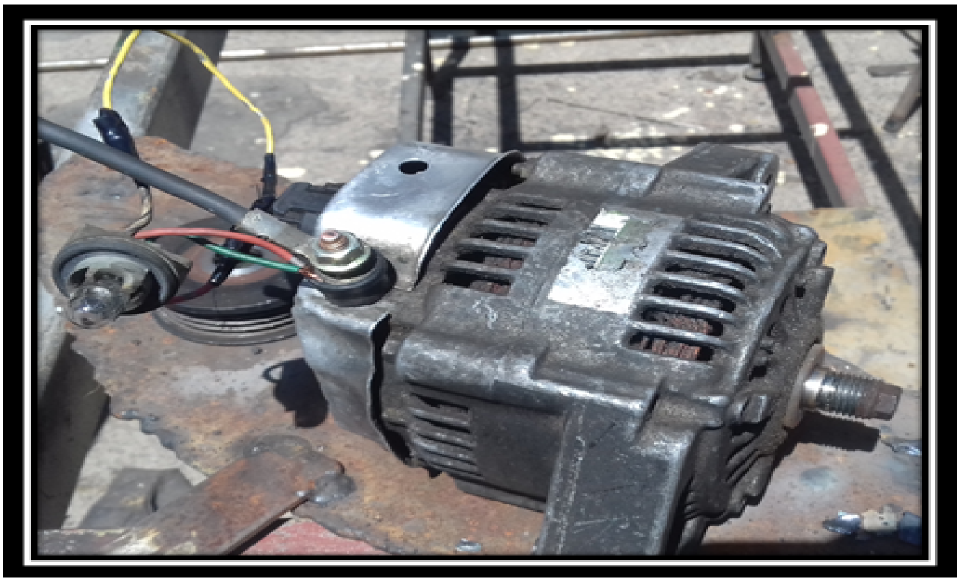


Figure 5.3: Car Alternator modified to operate for small wind turbine

5.3 Manufacturing wind turbine blade

As stated in the literature, small wind blades can be manufactured with three method. Among that manufacturing with CNC machine is the most recommendable choice because the problems showed in others method is resolved here i.e. the twist of blade is very difficult to form for the hand carving method and the size that can be manufactured with printing machine is limited. From the three designed blade, Blade 3 is manufactured for the experimental testing because its characteristic is more suitable to manufacture. The difficulty in manufacturing process was the access of finding CNC machine which have the specification fit for the designed blade. However, the lowest chord length that can be manufactured is 30mm, the machine is rare available in our country. In addition to that it was difficult to get CNC machine working with more than 500mm length. The available one can not operate blade that have lower than 60mm chord length, hence the lower limit of thickness of the tip part of the blade should be greater than 10mm.

5.3.1 Procedure followed for manufacturing the designed blade

- convert the designed blade to .stl format from previously designed format which is .step. this is because the software used for manuacturing (***Artcam***) can only import a 3D model object that are saved with .stl format.

- import the 3D model by the direction specified by Artcam software (i.e. import 3D relief).

- Since the machine works with XYZ coordinate, the blade has to be divided into upper and lower section.

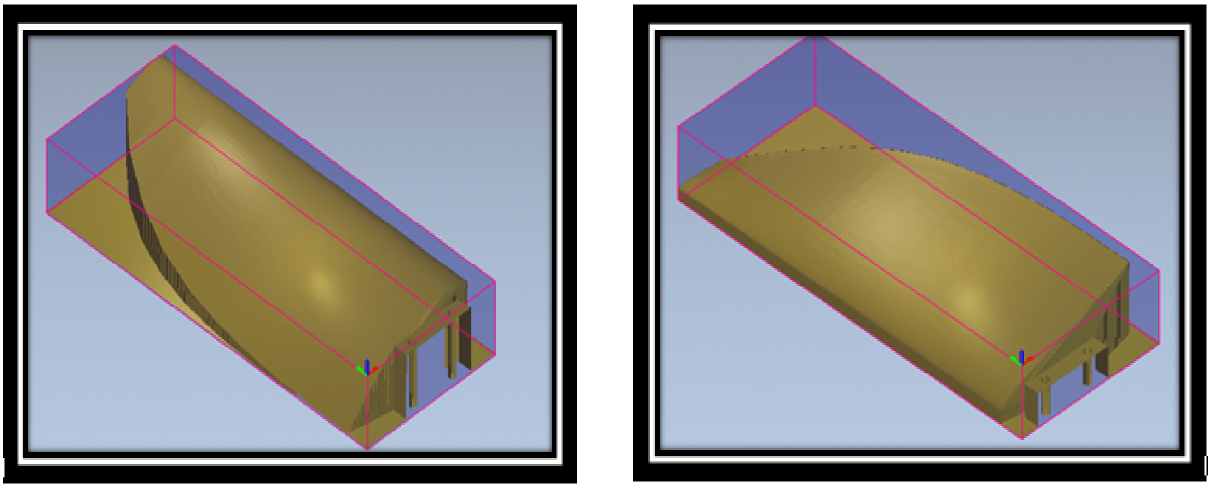


Figure 5.4: The upper and lower part of the blade to be manufactured

- Generate the G-CODE which is the code the machine read any objects to be manufactured. Every object is converted into xyz coordinate.

- Tightly fasten the Australian timber which is machined to the dimension desired for manufacturing

- Set the starting coordinate and the blade for cutting the surface.
- Because the cutting blade is not large enough to cut deep into the lower part of the object, the process can not be finish with a single step. Therefore first area clearance is needed in order to minimize to the step for the main manufacturing.

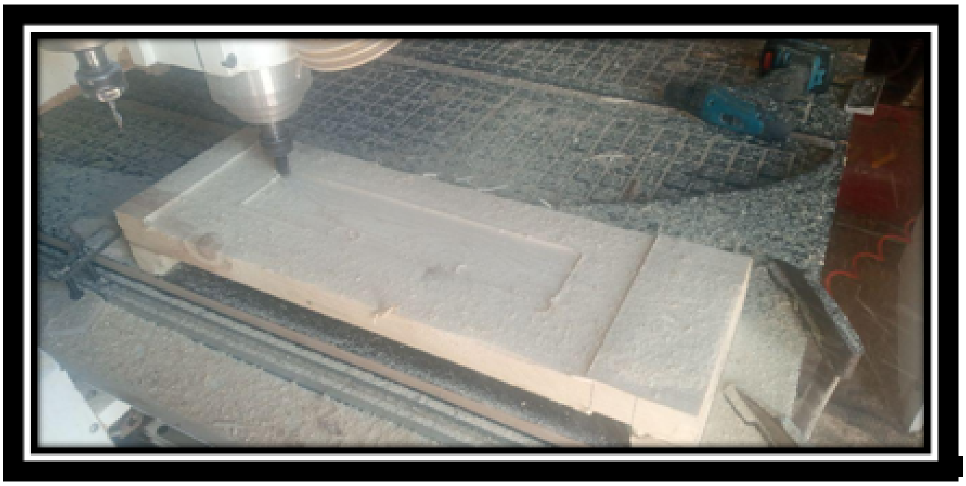


Figure 5.5: Area clearing process for the designed blade

- After the area clearance, the first upper section is manufactured
- By turning upside down and clearing some area , the second section which is the bottom surface is manufactured.

Figure 5.6: manufacturing of the designed blade with CNC machine

5.4 Assembly of the wind turbine

As stated in the literature section the component that comprise a horizontal axis small wind turbines are rotating blade, generator, tail section, tower. Therefore partial assembly of the wind turbine looks like as shown in the figure C.5 three leg with a base like part used instead of a single long and round tower for the reason that tower cannot be fastened or grounded in the building rather something stable is preferred as shown. Tail is also assembled in order to fit the turbine towards the wind direction. it is manufactured to be relatively large to be simply pushed by the wind pressure.

Figure 5.7: Assembled designed blade on the roof top of building

5.5 Experimental testing procedure and measuring devices

Among different types of tests , the power and starting performance is conducted which the scope of this research is up to power performance and the time at which the blade starts rotating. In order to held the testing procedure some measuring instruments are used.

5.5.1 Measuring instruments

Multi meter

multi-meter, also known by the name Volt-ohm meter, is one of the handheld electrical measuring instrument which is used to measure electrical voltage, current (amperage), resistor and other values. It has an analog and digital version which can also helps to detect faults and make complex diagnostics. Multi-meter is preferred for troubleshooting of electrical problems on different electrical machines like motor, appliances, circuits and power supplies.

Anemometer

Anemometer is a multi purpose measuring device which come on in different type and version. Among the different types of anemometer,**VANE Anemometer** is preferred for our experimental testing. Vane anemometer is used to measureair speed, air flow, air temperature and infrared temperature. It is multi-functional handheld equipment which give a quick response time. Most of vane anemometer works in the range of 0.4-30$\frac{m}{s}$ wind speed and $-10-60^0c$

Figure 5.8: Vane Anemometer

5.5.2 Experimental Testing procedure

In order to conduct the experimental testing all useful measuring devices have to prepared and the place at which the testing conducted has to be specified

1. In order to get a constant wind speed, it was preferable to set the experiment on moving vehicle hence as the vehicle drive with constant speed the speed of the wind will be approximately constant.

2. Put Anemometer in front of the rotating wind turbine blade..

3. In order to excite a car alternator there should high RPM , instead DC current is supplied to through the field coil to create electromagnetic system inside the generator.

4. When external voltage is supplied make sure it is done with the appropriate port that is the port coming from the brushes.

5. Connect diode on the positive side of the imported coil for the reason that no current coming back to the exciter and make it damage, since the function of diode here is controlling the flow of current direction.

6. 10 and 20Ω resister is used to draw high current from the generator, hence the power output gets higher value.

7. Use small DC lump in order to recognize the time at which the generator finish excitation and begin generating voltage, i.e. when the generator supplied external

DC current the bulb gives light and as soon as the generator it self start generating voltage the lump goes off.

Note:- Generated voltage is depends or might be controlled by the supplied DC or excitation current , this changes the strength of magnetic field created inside the generator.

Figure 5.9: Set up of the turbine for experimental testing on the moving vehicle

procedure followed to measure output voltage of the wind turbine

1. First select the range of DC voltage (i.e. 20v) by turning the selector dial to the DC voltage setting on the multi meter.
2. use the black probe for connecting to the negative terminal (i.e. body of the generator) while the red probe used for the positive terminal.
3. In order to measure the voltage drop across the resister connect the multimeter parallel to the circuit.
4. read value on the LCD display of the multi meter.

   The voltage might not exceed from the specified value by the generator but current drawn through the circuit increase as more load is connected to the circuit under measure.

procedure followed to measure output current of the wind turbine

1. connect the black probe to the COM and red to the 10 A DC which is the safe range for our measurement.
2. Turn the selector dial to the 10 DC A reading

Figure 5.10: Measuring the voltage drop from the generator with multi-meter

3. Connect the red probe with positive terminal of the generator and black probe to the resister, hence current pass to the multi-meter followed by the resister and goes back to the negative terminal of the generator.
4. Read current value from the LCD display of multi-meter **NOTE :-** measuring the current directly from the generator may cause the fuse to blow, therefore a multi-meter has to be connected seriously with a resister.

NOTE :- In order to measure the time at which the blade starts, simple timer is used from mobile phone. The timer turned on at the time of wind tunnel is on and measure the generator gives a voltage output.

From the experiment current voltage and starting time is measured, hence the electrical power from the wind turbine will be calculated. However to calculate the coefficient of performance that the turbine work should be calculated that is

$$C_p = \frac{P_t}{P_{avail.}} \tag{5.1}$$

The power extracted from the wind is obtained from the electrical power output calculated in the experimental testing.

$$P_t = \frac{E}{\eta} \tag{5.2}$$

Chapter 6

RESULT AND DISCUSSION

This chapter describe results of the optimization technique and the investigation of different parameters effect on the starting and power performance. Additionally result from the experiment and its comparison with optimization value are described.

6.1 Result From The Optimization Processes

A single SG6043 airfoil used for two blades to undertake the optimization technique. Two different blades with 0.5m and 0.846m blade radius and some different input parameters are optimized in order to investigate the effect of blade radius beside to ease manufacturing access. Besides to the size effect, the effect of airfoil in the performance of the blade is investigated by designing third blade which have the same radius with the second blade but with different airfoil section and some input parameter as listed in Table 4.4. The resistive torque,blade number , starting time, weighting factor are investigated in the analysis. Considering its effect on the blade radius and the power can be generated from the turbine while designing, 7m/s rated wind speed is taken. Furthermore, different input parameters for the optimization process is previously listed in the design section and now we expect the chord and twist distribution of a blade with various weighing factor from the software. The time at which each blade might start to rotate at 5 m/s and the power coefficient that each blade might give is also the output from the optimization process. But we have to remind that in small wind turbine the largest practical power coefficient a blade can achieve is around 0.48 (23).

Note:- SWRDC(software) is well developed and used by researchers for designing and optimizing small wind turbines. It is developed from different scientific concepts like genetic algorithm, blade element momentum theory (BEM), simple Euler-Bernoulli beam theory, a wood model for starting performance, and noise model of Zhu. Based on this code different researches are conducted specially for optimizing small scale horizontal axis wind turbines. Therefore, the objective to be optimized by this code are Coefficient of performance, Starting time, Annual energy production, and noise of the turbine. Among this Cp and starting time is optimized in this research. The governing equation for optimizing the two performance is

$$maximize : (w\frac{Cp}{maxCp} + (1-w)\frac{min(t_s)}{t_s}) \tag{6.1}$$

This shows that as the weight given to Cp increase the time at which the wind start decreases and vice versa. In order to understand concept behind this, mechanical power that can be generated from flowing wind and the overall surface which utilize the wind energy should be realized.

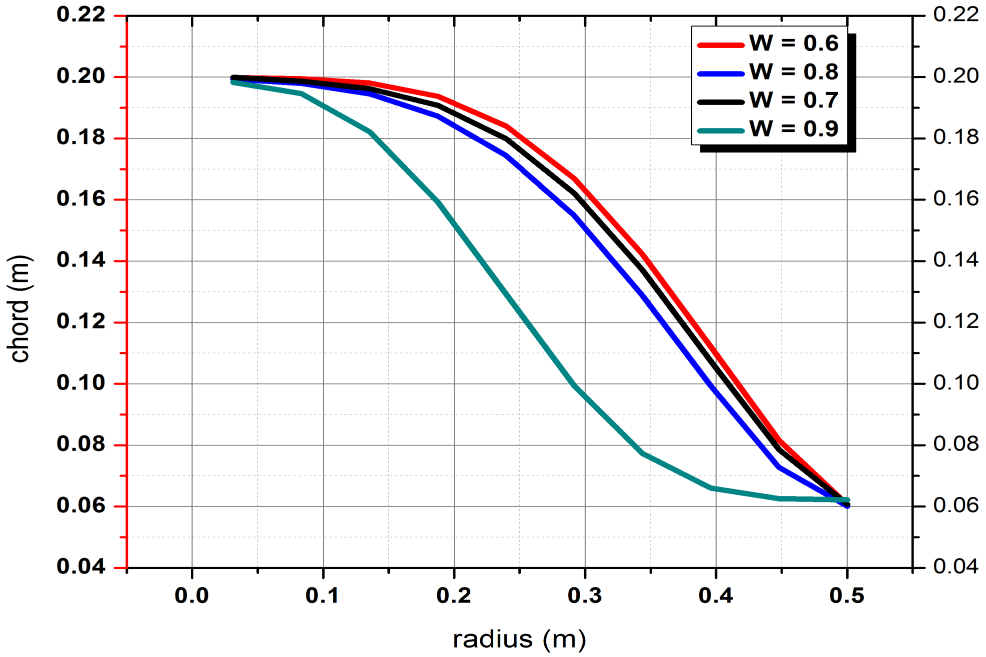


Figure 6.1: Optimized blade chord distribution with various weighing factor

As it observed from Equation 2.4 a wind turbine can absorb 100% of the available kinetic energy of the wind only if the downstream wind speed become zero by completely blocking the air flowing through the turbine. However, this condition is not possible to achieve. Therefore, maintaining the surface covered by the blade and the angle it is oriented plays a great role in giving the best extraction of wind energy. As the chord of wind turbine blade is much higher than the desired, it might absorb more energy from the wind which helps turbine to rotate but efficient conversion to mechanical power cant be achieved.

research shows that the power coefficient of wind turbine can significantly affected by chord length. The power curve rises first and degraded to its lower performance as the chord length increases (37).

Therefore, the algorithm choose optimum chord and twist distribution which can give remarkable decrease in starting time with out affecting the power performance of the wind turbine.

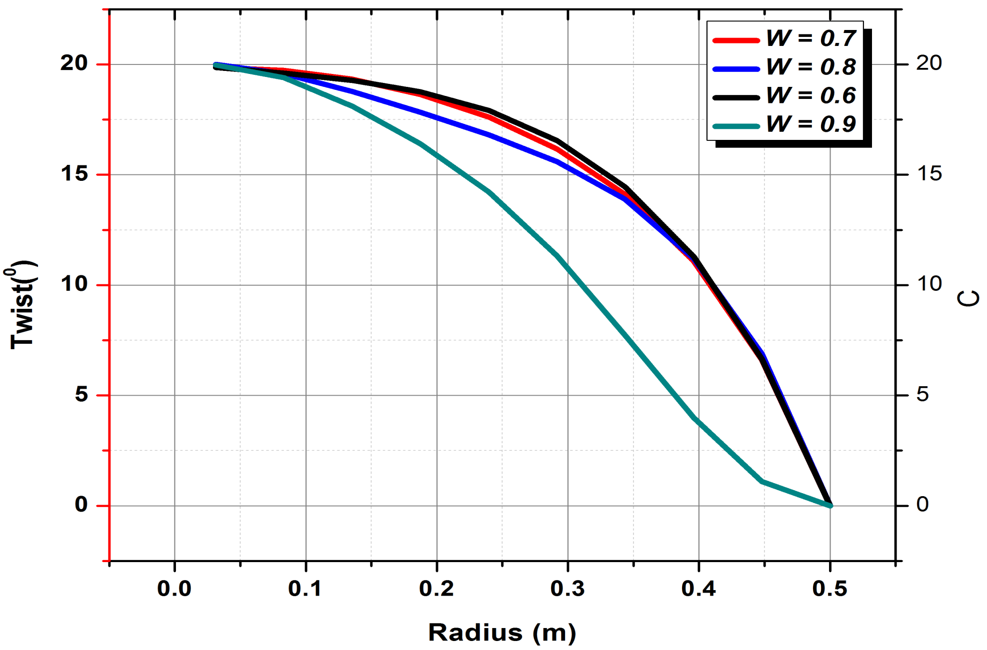


Figure 6.2: Optimized blade twist distribution with various weighing factor

As previously mentioned the turbine with high power coefficient experiences low starting performance. However, by using optimization technique specifically genetic algorithm the starting time can be reduced with a little percent reduction of the power performance. In order to start a blade too fast, the starting aerodynamic torque should be high enough and this depends on basically in the blade shape which is the chord and twist distribution of the blade. Therefore, the algorithm selects an optimal chord and twist value from specified range that gives low starting time with a relative power coefficient. Based on the previous documents, it is expected the blade might have high twist and chord value near the root section and nearly the same value to that of a non optimized blade in the tail section.

From the graph of chord and twist distribution, it can be seen that the chord and twist value of the optimized blade have a little increment as the weight given to the starting increases. But when we compare to the non optimized blade the distribution show clearly that there is a significant difference in blade shape specifically in the root section. As it shown in the Figure 6.4 and Figure 6.3 the optimized blade reach the limit boundary in both chord and twist value in order to give the desired output.

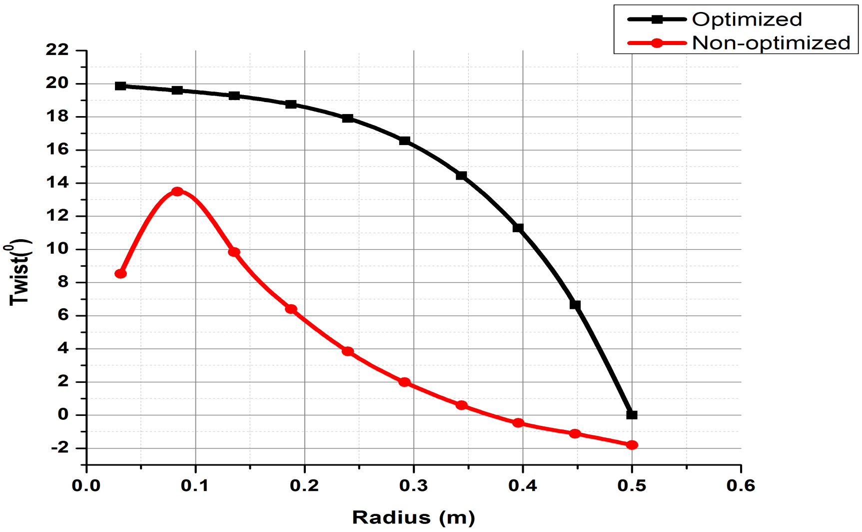


Figure 6.3: The twist distribution of optimized and non optimized blade

6.2 The effect of genetic algorithm parameters

6.2.1 Population size and Number of generation

Since the concept of genetic algorithm is directly conducted from biological analogy, most parameter of the selective breeding of plant or animal system is the same to any system which uses genetic algorithm. As we say offspring in plant or animal breeding it means characteristics that are determined at the genetic level. Population of these strings are often referred to in the genetic algorithm literature as chromosomes. By genetic crossover and mutation analogies, the strings are recombined again and again until the higher fitness string is produced. Therefore, the major task to be consider first is the population and secondly the method by which the string is selected. The two basic governing idea for selecting the population size are efficiency and effectiveness. As researches show too small population would not allow sufficient room for exploring the search space effectively, while too large population would so impair the efficiency of the method that no solution could be expected in a reasonable amount of time. Hence optimization which uses too large population size must validate the result with proper experimental results. Furthermore, the capacity of processor used for performing the optimization process is the big factor which affect the time we use for processing. It might take days for only one optimization if the processor is weak.

Here totally more than 15 effective optimizations were taken for each blade with a single optimization take hours to complete. As the number of population size and number of generations increases, the time to complete the optimization process also increases and once the computer for processing works above its capacity, it become more week for the next process. This was the big difficulty in the way of getting the information. Some research papers use very large number of generation and population size and get nearly 1sec starting time and very high-power performance which is not validated by experimental results. As an example (2) uses 500 number of generation and 2000 population size and get less than 3sec starting time and the power coefficient is above 50 which contradict the fact that small

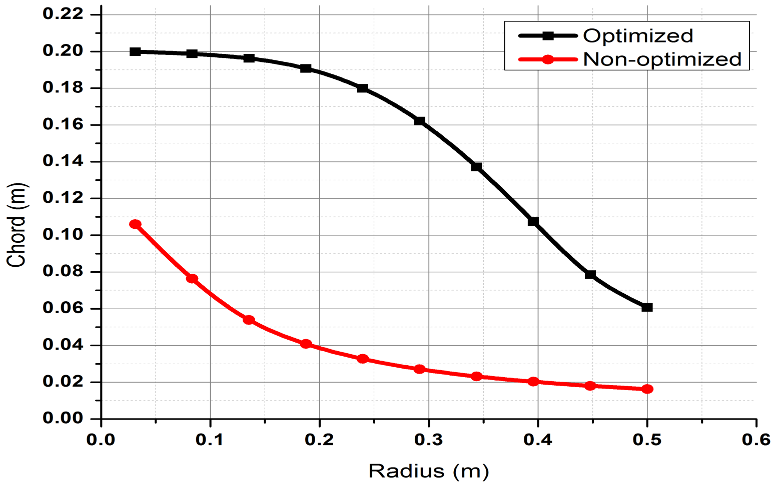


Figure 6.4: The chord distribution of optimized and non optimized blade

wind turbine power performance can't exceed 0.48(23).

6.3 The effect of weight on starting and power performance

Weight,W, is the percent given to the starting time and power coefficient in order to be optimized. Its effect in the chord and twist distribution is shown in Figure 6.1 and Figure 6.2 above. As more weight is given to power coefficient, the blade efficiency will be greater and the time to start gets higher. This cause the turbine to do not start at the specified starting wind speed.

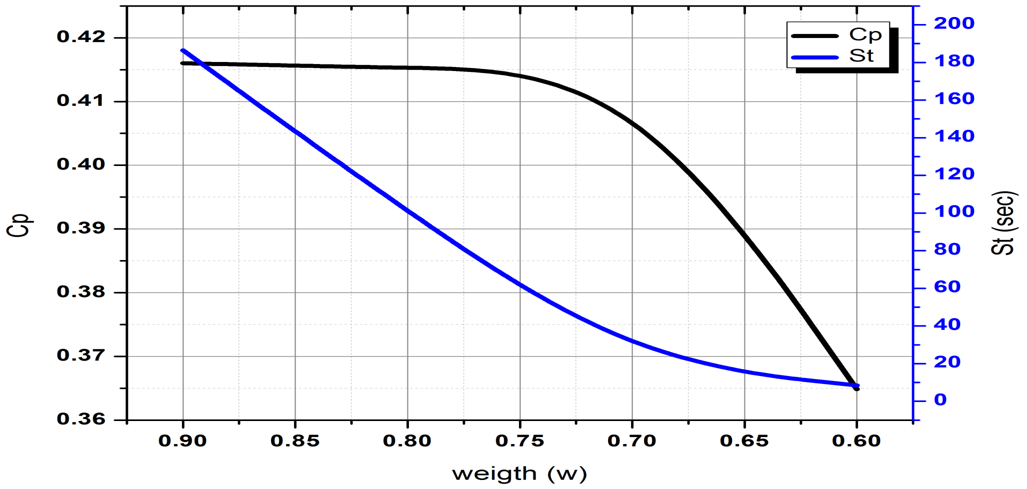


Figure 6.5: The effect of weight given to coefficient performance and starting performance

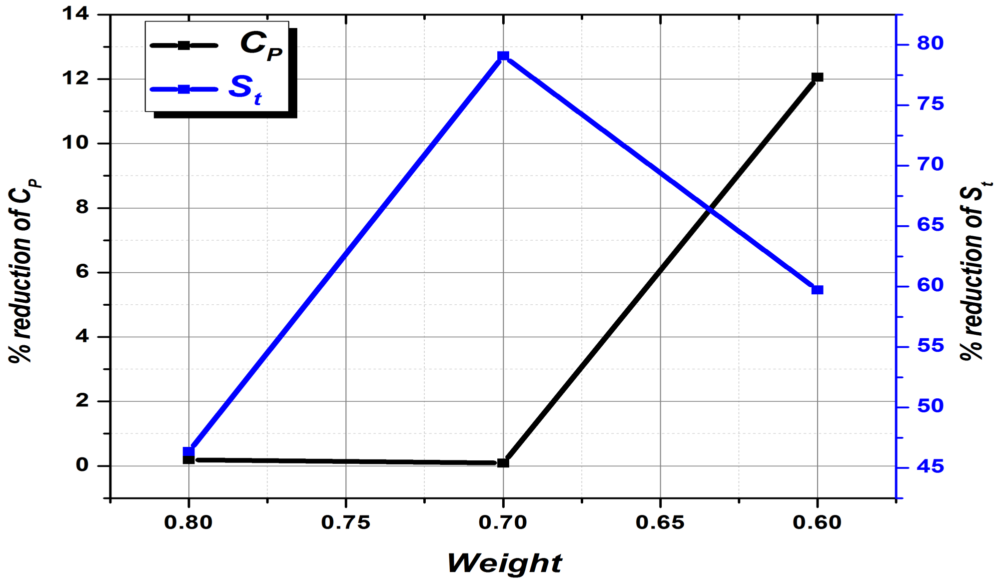


Figure 6.6: Percent of reduction of starting time and coefficient performance as the weight decreases

If we increase the weight of starting time, the blade starts early but the power coefficient decreases with a little percent. But from the Table 6.1 we can observe that further increasing the weight of starting time will cause high reduction in power performance. Since the chord of the blade is directly proportional to the starting time, the mass of blade experiences a little increment(i.e.solidity of the blade) because of large size chord generated while optimizing for the high starting performance. Starting time can not be decrease by further reduction of C_p because of the increasing mass and this eventually increases the starting time.

Table 6.1: The starting performance, power coefficient, and mass of different weight blades

`weight`	`Power coefficient`	`Starting performance(sec)`	`Mass(kg)`
$w = 0.6$	0.36484192	8.42654801	0.478478
$w = 0.7$	0.41486083	20.9212667	0.452717
$w = 0.8$	0.41523121	100	0.436027
$w = 0.9$	0.41602123	186.459234	0.442323

6.4 The effect of limiting the boundary of chord and twist value

Since chord and twist values are the final outputs of a designed blade, any action that makes changed in their value affects the performance of a blade. One of the action takes place in the optimization process is giving the upper and lower limit to the chord and twist value.

This is because in order to select a population their should be a limited range, If not the algorithm would select undesirable value in order to achieve the objectives set in the design process.

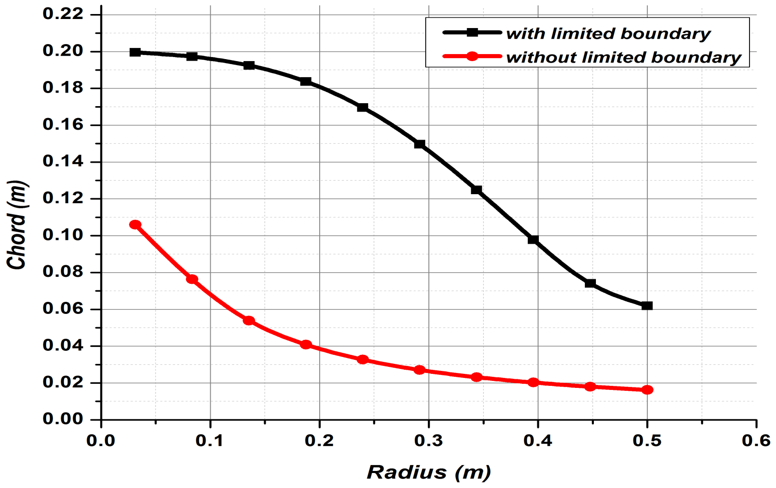


Figure 6.7: Chord distribution a blade with and without boundary condition

Two blades are designed without optimization process and the chord and twist value of the first one is not limited and gives coordinates that are difficult to manufacture. Considering the first effect the second blade design is given a boundary that can be manufactured in our country machinery access. The chord and twist distribution of the second blade reaches both the upper and lower limit in order to achieve the desired objectives. Chord and twist distribution of both the limited and non limited blades are shown in the graph hence the chord and twist distribution is changed, the performance of coefficient and starting time is affected. to illustrate the difference created in the performance the final blade is analyzed. As it observed from the above table, the effect of bounding the boundary of chord and twist value is clearly shown in the power performance and the mass of blade. The number 701 shown in the table indicates that both blades can not be rotated, but it doesn't means it can not rotate at all. This will be elaborated in the next sections.

Table 6.2: The starting performance, power coefficient, and mass of bounded and non bounded blades

Blade type	Power coefficient	Starting time	Mass
Bounded	0.36243	701	0.48084
Non bounded	0.41026	701	0.41372

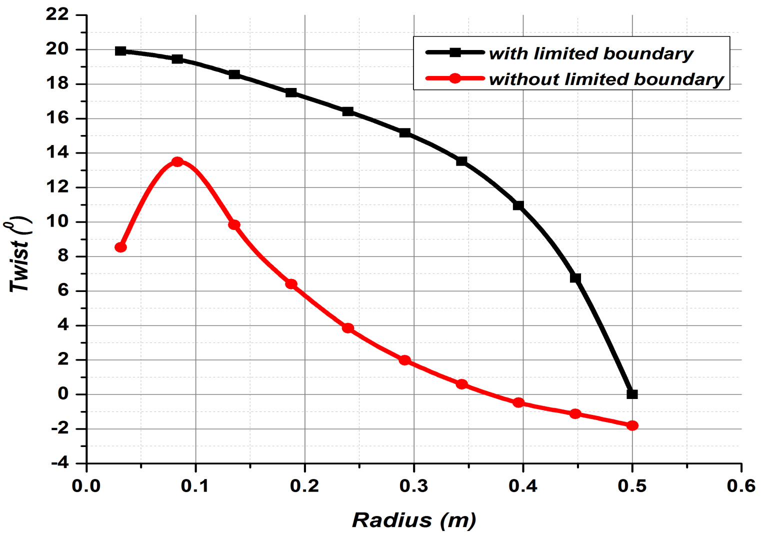


Figure 6.8: Twist distribution of a blade with and without boundary condition

6.5 The effect of airfoil on the blade performance

Airfoil is the main parameter which affects the performance of a blade besides to the effect it has on the starting time. Changing airfoil shape means increasing or decreasing the lift coefficient a blade has, hence the time to start wind turbine and its power coefficient will be highly affected. As shown in Fig 3.1 SG6043 has high lift to drag ratio compare to the other airfoil shapes, but here SD7062 is used to be manufactured for the reason that blade with SG6043 has thin blade sections which is difficult to manufacture in the available machine. Obviously there is an effect in the power and starting performance as the airfoil is changed.

Table 6.3: The effect of SG6043 and SD7062 airfoil blades in performance parameters

`Airfoils`	`Power coefficient`	`Starting time`
$\boldsymbol{SG}$**6043**	0.38195	701
$\boldsymbol{SD}$**7062**	0.36322	701

6.5.1 Comparing the performance of mixed and single airfoil blade

As Ingram(6) recommended a blade with mixed airfoil shape could perform better than the single airfoil shaped blade. The selected airfoils for mixed design have better lift to drag ratio other than other airfoil shapes recommended for small wind turbine.

Therefore, SD7062 is applied in the root section of the blade with 1/5 proportion for the reason that it is a little thicker than SG6043 hence it helps for structural integrity. The rest of the blade section is SG6043 which have high lift to drag ratio helps for better power performance and making the blade a little lighter , hence it starts so fast. Moreover, the combination of this two airfoil sections gives a better power and starting performance as shown in the table below.

Table 6.4: Comparing the performance of single and mixed airfoil shaped blades on starting and power.

Blade type	Power coefficient	Starting time
Single airfoiled	0.36243	701
Mixed airfoiled	0.43	701

In order to check the difference in starting time, the starting time wind speed is changed. Therefore, at $6\frac{m}{s}$ starting wind speed the single airfoil shaped blade starts at $44.719sec$ while the mixed airfoil shaped blade starts at $15.58sec$. This shows there is a big difference in the starting time and power performance when we changed our design from single airfoil to mixed one.

6.6 The effect of blade number on starting and power performance

Typically the number of blade is expected to increase the starting performance of wind turbine but the power coefficient might be reduced. This is the reason that water pump operated by wind have large number of blade. Increasing number of blade means the turbine has high solidity which is directly related to the concept of utilizing the wind energy which gives much larger output torque. Rotor will accept more energy from the wind if is multi-bladed. However, it will be predicted lower Cp value as the blade number goes high (38).

Therefore, three bladed wind turbine is preferable among the others by its best performance, structural strength, appearance of the wind turbine and also its economical feasibility. The output from the optimization validate what is known by different researches as it shown in the table 6.5.

Table 6.5: The starting time and power coefficient of different blade numbers

Blade number	Power coefficient	Starting performance(sec)
2	0.415976	701
3	0.41486083	20.9212667
4	0.32126	8.785576

6.7 The effect of starting data

6.7.1 starting wind speed value

Wind speed is the critical parameter which governs the power performance and the starting time of wind turbine. As we know the power of a wind turbine is directly related to cube of wind speed, this shows a little change in the wind speed will have a great effect in the power of turbine, hence the starting time of the turbine is highly affected.

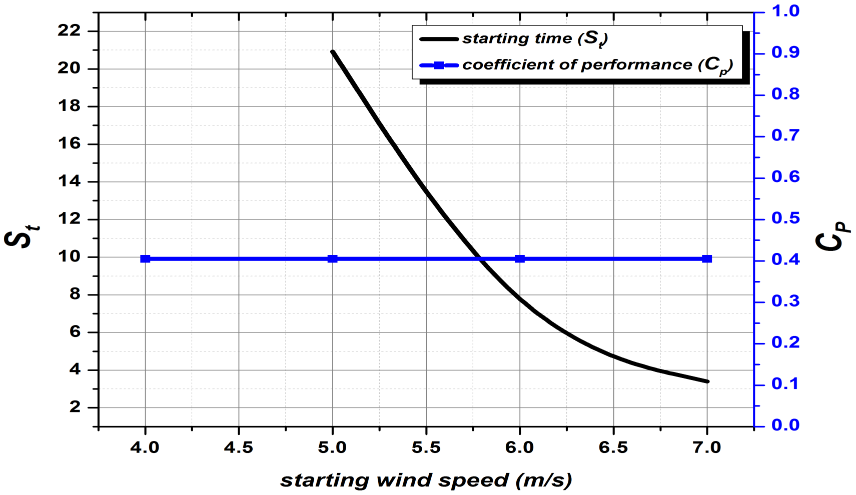


Figure 6.9: The effect of starting wind speed on power and starting performance

Table 6.6: The effect of starting wind speed data on power coefficient and starting time of Blade 1

`Starting wind speed`	$4m/s$	$5m/s$	$6m/s$	$7m/s$
`Starting time`	701	20.921267	5.596492	3.4
`Power coefficient`	0.404842	0.404842	0.404842	0.404842
`Mass`	0.478478	0.478478	0.478478	0.478478

As the table shows the selected blade cant start at $4\frac{m}{s}$ but when the starting wind speed is increasing its value increases, hence it starts earlier from the preceding wind speed. Since the aim is to design a an optimized blade specifically for low wind speed region, the starting time wind speed has be $5\frac{m}{s}$.

6.7.2 Resistive torque

In order to observe the effect of resistive torque, the first blade is investigated. The wind blade starts to rotate when it overtake the resistive torque and the resistance created by its moment of inertia of the blade and it begins to generate electricity when its angular acceleration reach the starting limit of the selected generator(Eq. 4.3). As shown in the table below, the starting time of the designed blade, when resistive torque considered, is very high. This shows as even if the cogging torque is very low, it has a great impact on the starting performance of a small wind turbine.

Table 6.7: The effect resistive torque on starting performance.

Resistive torque	Starting time
$\boldsymbol{R=0}$	2.636965
$\boldsymbol{R=0.5}$	20.921267

6.8 Result from experimental testing and Discussion

The main objective needed from the experimental testing is the time at which the blade starts and the electrical power generated by the turbine. Since to excite the generator a continuous and high rotation is needed, the performance test of the turbine is held on the moving vehicle. The value of starting time, voltage, current,and electrical power is tabulated in the Table 6.8.

Table 6.8: Result from the experimental testing

test no	Starting time (sec)	Voltage (V)	Current (A)	Electrical power $= IV(W)$
$Test1(4\frac{m}{s})$	12	5.2	1.4	7.28
$Test2(5\frac{m}{s})$	9	6.75	2.3	15.525
$Test3(6\frac{m}{s})$	5.9	8.9	2.65	23.585
$Test4(7\frac{m}{s})$	3.5	13.89	3	41.67

Therefore, at $5\frac{m}{s}$ power of the wind turbine is calculated 19.4watt by taking efficiency of the generator 0.8. since the power a wind flowing at $5\frac{m}{s}$ in the area of a 0.5m wind turbine is 60.1watt, the coefficient of performance of the tested wind turbine is **0.3228**.

6.8.1 Comparison of blade under experimental testing and the optimized blade

considering the manufacturing process and the best performing blade, blade 3 with a single SD7062 airfoil section and optimized at the weight of W = 0.7 is chosen because it achieves the best performing coordinate of chord and twist value on starting and power performance. Its starting time and coefficient of performance is 8.6345 and 0.335 respectively.

Therefore, from experimental result the tested blade shows a 3.61% error in coefficient of performance and 4.2% error in starting time. Moreover, it would be possible to get the best performing blade if a mixed airfoiled blade undergo optimization process, since it has high Cp in addition to its best performance in starting time. This high value of error in starting is comes from first the generator, since it needs to be excited it makes some delay on recording some seconds as it starts generating electricity. Beside to excitation the generator is used and maintained repeatedly, this makes it to do not perform as it is first manufactured. There is also some manufacturing difficulties while making parts and assembling the wind turbine which add some contribution on the performance of blade under experimental testing.

Chapter 7

CONCLUSION AND RECOMMENDATION

This chapter contains conclusion and recommendation part which is the conclusion from different analysis taken in the above chapter and recommend the issue to be address for the future researcher and a better practice to be done for whom planning to conduct experiments regarding small wind turbine.

7.1 CONCLUSION

In this research, blades which have single and mixed airfoil section is designed without optimization using a MATLAB code and blades which have different input criteria are designed with optimization process. small wind turbine rotor design code(SWRDC) is used to designed optimized blades. Starting time and coefficient of performance of a small wind turbine blade are the main objective of the research. The effect of each parameters used in the design code is investigated. After the result from both designing process the best acting blade is selected for manufacturing. Finally the manufactured blade is tested in the field and in the laboratory and the following conclusion is made.

1. As we give more weight to starting performance the percent decrease in time is considerably high i.e. relatively there is 88% reduction in starting time and only 0.279% Cp is reduced.

2. The second factor that highly affect the performance starting is the resistive torque of the generator. There will be 90.4% reduction of starting time if the generator resistive torque is 0.

3. Starting wind speed is the other big factor that affects the performance of wind turbine considerably. As the starting wind speed increases from $5\frac{m}{s}$ to $6\frac{m}{s}$, the starting time decreases by 73.24%.

4. Although the starting time decrease by 58% when the blade number increased from 3 to 4, the change in coefficient of performance is very high i.e. 22.74% reduction. Hence the wind turbine works with low performance.

5. As shown the result section, the only parameter that have a positive impact in both starting and power performance is changing the wind turbine from single to mixed

airfoil blade. The percent increase in power performance and reduction in starting time is 18.64% and 65% respectively.

6. It is proved here that airfoil shape of a blade can considerably affect the performance of a wind turbine. The selected airfoils (SG6043 and SD7062), even if they have relatively low difference in the lift coefficient, SD7062 has 5% reduction in coefficient performance from that of SG6043.
7. The last parameter investigated in the research is bounding the chord and twist value of the under design blade. As we bound the blade shape coordinate it shows 11.65% reduction in coefficient of performance but to achieve the desired best starting time shape of the blade is changed as shown the manufactured blade Fig. C.3.

7.2 RECOMMENDATION

During conducting this research there was many challenge that directly or indirectly affect the output. It will be better if one who tries to work on this area knows about the challenges and the best things made in this research. For a better estimation of starting and power performance of small wind turbine, the following recommendation gives a useful information and precaution.

1. It will be better if blade designed with mixed airfoil passes optimization process for starting and power performance, since it shows a better increase in both performance with out optimization.

2. Small wind turbine rotor design code(SWRDC) should be re coded by factor in some input parameters like option to design blade with mixed airfoil and the output should contain more detail contents.

3. To decrease the mass of the blade, its better if the design process consider making the blade hollow instead of solid.

4. The first difficulty faces in the research was manufacturing the designed blade, since it was difficult to get rotary CNC machine which is suitable for manufacturing the blade. Instead the usual xyz axis operating CNC machine was used but still operator is not available. This consume the most time of the research. Therefore, it will be better if workshops takes under consideration training and importing some critical machines.

5. The other big problem was finding a generator suitable for our design. There should be some way a student working on specifically in power generation gets either new or good working generators as their specification.

6. In order to test the wind turbine with relatively large size, the wind tunnel available in the laboratory should be improved.

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Appendix A

SD7062 and SG6043 airfoil data selected for designing blades

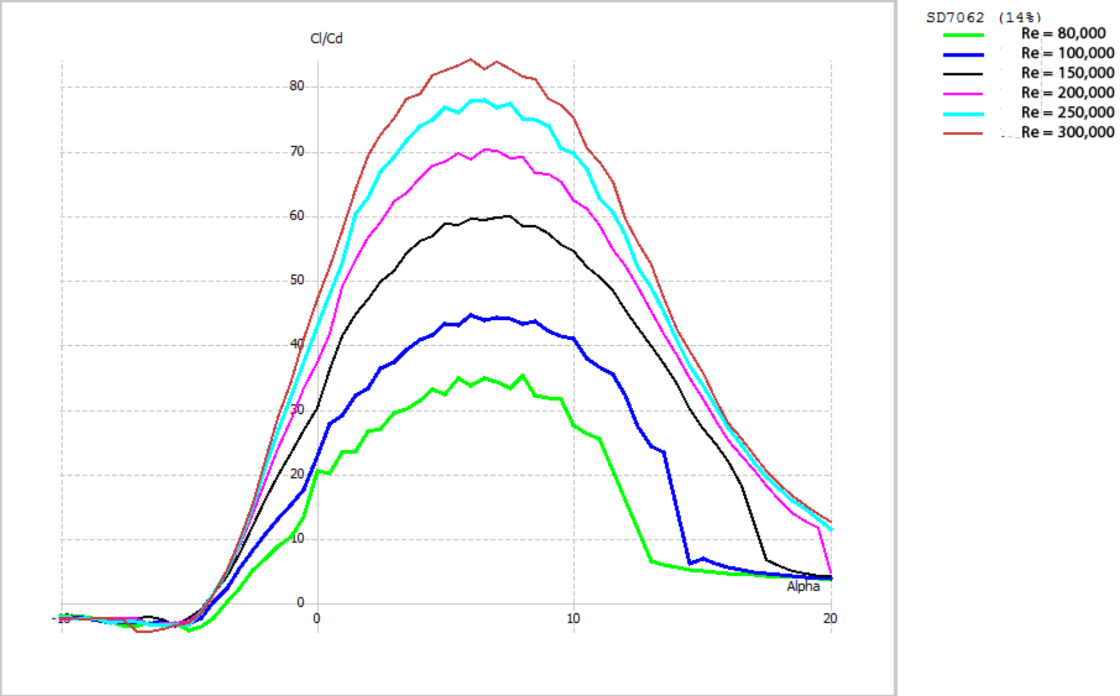

Figure A.1: Lift to drag ratio for SD7062

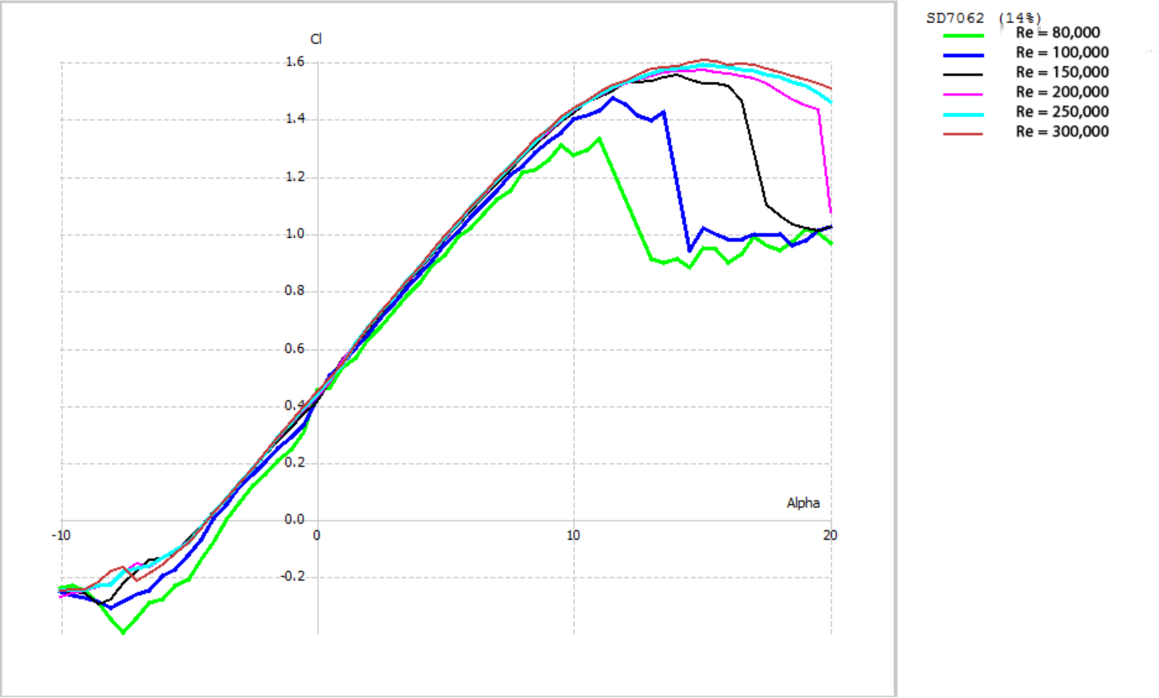

Figure A.2: Lift coefficient for SD7062

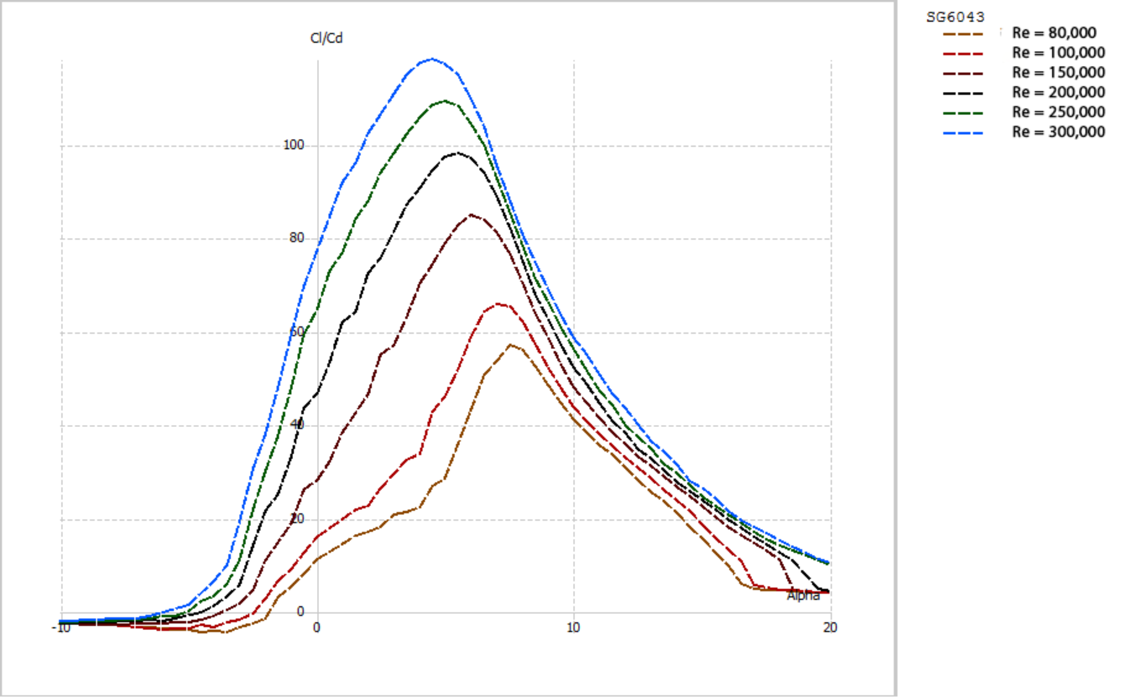

Figure A.3: Lift to drag ratio for SG6043

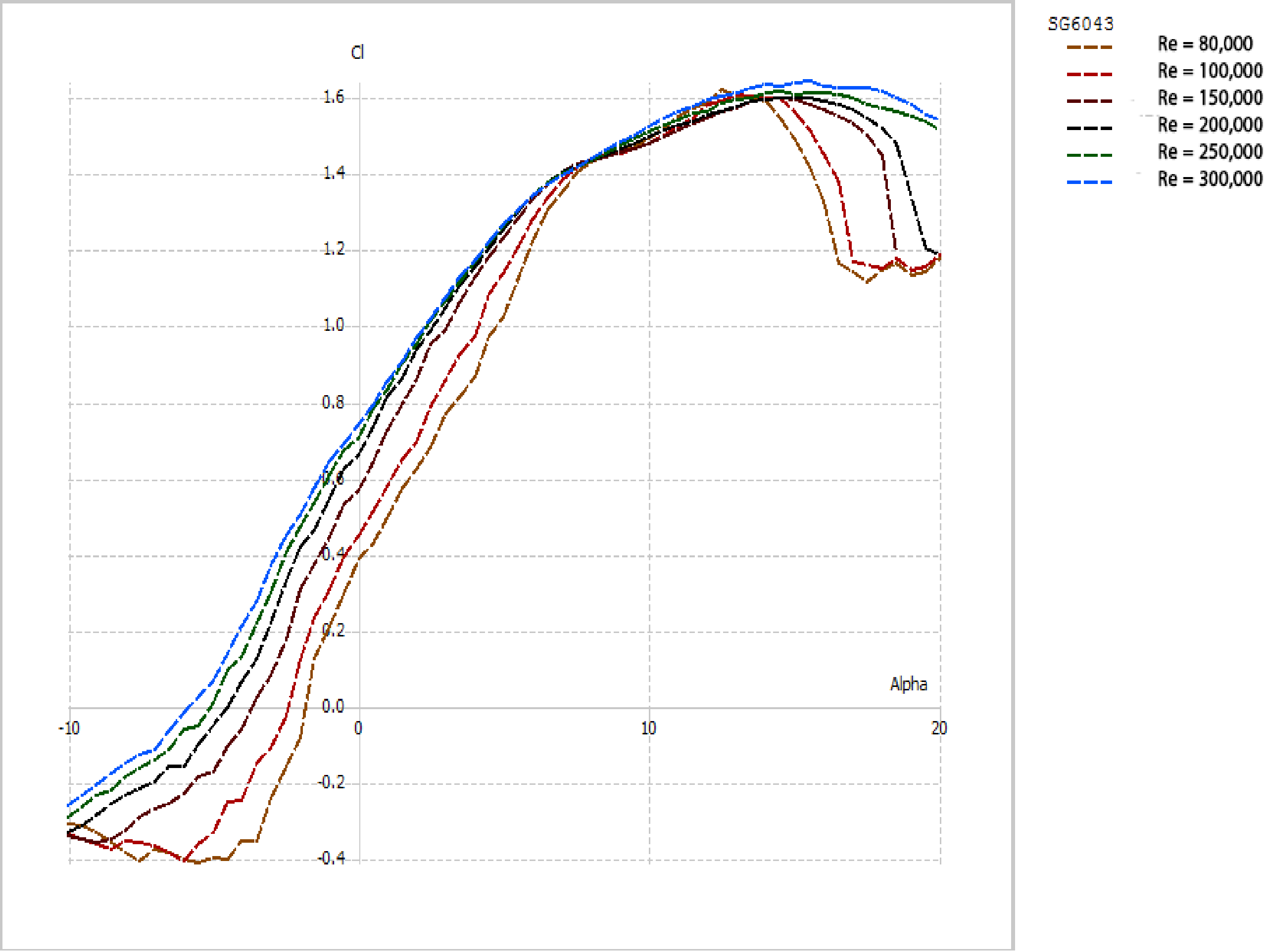

Figure A.4: Lift coefficient for SG6043

Table A.1: Input parameter for designing a blade with mixed airfoil section

λ	6
$numberofblade$	3
$diameter$	1
r/R	0.0313
$minimumchord$	0.06
$maximumchord$	0.2
$mechanicalandelectricalefficiency$	0.85
$startvalueof\alpha$	0
$finishvalueof\alpha$	20
$airfoil$	$SG6043andSD7062$

Appendix B

Matlab code

Listing B.1: matlab code used to design the non optimized blade(39)

```
function [blade_design] = Blade_Design(blade, Nbl, D, omega, air,
efficiency, a, c1, r_R, alpha_struct, toll, maxiter, l_0_max,
l_0_min, dim_text_plot, dim_lines_plot, visibility_Xfoil)
%% PRELIMINARY DESIGN OF HORIZONTAL AXIS WIND TURBINE BLADES
%

%% DATA INPUT

c2 = (1-a)*c1; %wind speed at the disk actuator (at the wind turbine) [m/s]

% The sections are equally spaced between the hub and tip
% radius, according whith the number of profiles.
r = D*0.5*linspace(r_R,1,length(blade.profiles)); %[m]

%vectors that contain a value for each section at the radius r
l_0 = linspace(l_0_max, l_0_min, length(r)); %first try chord [m]
u = omega*r; %peripheral speed [m/s]
w = sqrt(u.^2 + c2.^2); %relative wind speed [m/s]
Ma = w/(sqrt(air.gamma*air.R*air.T)); %Mach number
beta = atan(u/c2); %relative wind speed angle [rad]
beta_deg = beta*180/pi; %relative wind speed angle [deg]


%% CHORD CALCULATION

err = (toll+1); % setting err > toll to start the cycle
counter = 2;
h = r(end) - r(1); %blade length

%Matrix that contains the coefficients during the iteration. Each matrix has
%a number of row equal to the number of the blade sections and a number of
%columns equal to the max iteration number. The data of each
%iteration are saved in a different column.
Re = zeros(length(r), maxiter+1); %Reynolds number
```

```
Cl = zeros(length(r), maxiter+1); %Lift coefficient
Cd = zeros(length(r), maxiter+1); %Drag coefficient
alpha = zeros(length(r), maxiter+1); %Angle of attack [deg]
l = zeros(length(r), maxiter+1);%Chord [m]
l(:,1) = l_0; %initializes the matrix with the first try chord

while max(err)>toll && (counter-1)<=maxiter

%Calculation of the blade area (Cavalieri - Simpson equation) with the
%chord of the previous iterations
S_bl = 0;
if length(r)/2 ~= round ( length(r)/2 ) %odd number of sections
for ii = 3 : 2 : length(r)
S_bl = S_bl + ( (l(ii-2,counter-1) + l(ii,counter-1) + ...
4*l(ii-1,counter-1)) )*(r(ii)-r(ii-2))/6;
end
%even number of sections --> the last value is evaluated with the trapezes eq
for ii = 3 : 2 : (length(r) - 1)
S_bl = S_bl + ( (l(ii-2,counter-1) + l(ii,counter-1) +...
4*l(ii-1,counter-1)) )*(r(ii)-r(ii-2))/6;
end
S_bl = S_bl + ( l(end,counter-1) +...
l(end-1,counter-1) )*(r(end)-r(end-1))/2;
end

%aspect ratio
AR = h^2/S_bl;

%waitbar for the chord evaluating along the sections
wait_bar = waitbar(0, ['Wait.␣Iterative␣cycle␣number␣n.
' num2str(counter-1) '␣in␣progress...']);

for section = 1:length(r) %cycle on the sections

%Reynolds number
Re(section, counter) = air.rho*w(section)*l(section,counter-1)/air.mu;

%******* FIRST CYCLE ********

%angle of attack in which Drag and Lift are evaluated
alpha_input = alpha_struct.start:alpha_struct.cycle_1:alpha_struct.finish;

%Recalling XFoil_launcher to evaluate Lift and Drag
data_profile = XFoil_launcher(Re(section, counter), Ma(section), ...
alpha_input, [blade.folder '/' char(blade.profiles(section))],
visibility_Xfoil);

Cl_Cd_ratio = data_profile.CL ./ data_profile.CD; % Lift / Drag ratio
```

```
%finding the angle of attack that provides the best (max) Cl / Cd ratio
alpha_opt = data_profile.Alpha(Cl_Cd_ratio==max(Cl_Cd_ratio));

%******* SECOND CYCLE ********

%angle of attack nearby the best solution found with the first cycle
alpha_input = (alpha_opt-alpha_struct.cycle_1):alpha_struct.cycle_2:
(alpha_opt+alpha_struct.cycle_1);

%Recalling XFoil_launcher to evaluate Lift and Drag
data_profile = XFoil_launcher(Re(section, counter), Ma(section), ...
alpha_input, [blade.folder '/' char(blade.profiles(section))],
 visibility_Xfoil);

Cl_Cd_ratio = data_profile.CL ./ data_profile.CD; % Lift / Drag ratio

index = find(Cl_Cd_ratio==max(Cl_Cd_ratio));
Cl(section, counter) = data_profile.CL(index);
cd_2D = data_profile.CD(index);
alpha(section, counter) = data_profile.Alpha(index);
Cd(section, counter) = cd_2D + (Cl(section,counter)^2)/(pi*AR);
%Cd with 3D correction

%chord evaluation [m]
l(section,counter) = (pi*r(section)/Nbl)*(c2^2/w(section)^2)*(8*a/(1-a))*
1/(Cl(section,counter)*sin(beta(section))+Cd(section, counter)...
*cos(beta(section)));

waitbar(section/length(r),wait_bar); %waitbar update
end
close(wait_bar); %close the waitbar

%calculate the max error (the max chord increment)
err = max(abs(l(:,counter)-l(:,counter-1)));
if (counter-1) == maxiter
warning('Reach␣the␣max␣number␣of␣iterations')
end
counter = counter+1;
end

counter = counter - 1; %set the counter on the final blade designed

%% FOLDERS AND FILES FOR DATA SAVING

%if the folder doesn't␣exist␣the␣software␣will␣create␣it.
if␣exist('Report Design',␣'dir')~=7
mkdir('Report Design');
```

```
end

%current␣data␣and␣time
report.data␣=␣clock;
if␣report.data(2)<10
report.month␣=␣['0'␣num2str(report.data(2))];
else
report.month␣=␣num2str(report.data(2));
end
if␣report.data(3)<10
report.day␣=␣['0'␣num2str(report.data(3))];
else
report.day␣=␣num2str(report.data(3));
end
if␣report.data(4)<10
report.hours␣=␣['0'␣num2str(report.data(4))];
else
report.hours␣=␣num2str(report.data(4));
end
if␣report.data(5)<10
report.min␣=␣['0'␣num2str(report.data(5))];
else
report.min␣=␣num2str(report.data(5));
end
if␣report.data(6)<10
report.sec␣=␣['0'␣num2str(floor(report.data(6)))];
else
report.sec␣=␣num2str(floor(report.data(6)));
end

%Design␣report␣folder
report.folder␣=␣['Report Design/'␣num2str(report.data(1))
␣'-'␣report.month␣'-'report.day␣' '␣report.hours␣'-'...
␣report.min␣'-'␣report.sec␣' - '␣blade.name];
mkdir(report.folder);␣%create␣the␣folder

%creating␣the␣text␣file
report.file_name␣=␣[report.folder␣'/Design data.txt'];
report.fileID␣=␣fopen(report.file_name,␣'w');

fprintf(report.fileID,␣'PRELIMINARY DESIGN OF A HORIZONTAL
 WIND TURBINE BLADES\r\n\r\n');
fprintf(report.fileID,␣'Author: Oboe Daniele, Marinoni Andrea
and Mastrandrea Sabino\r\n');
fprintf(report.fileID,␣'Software release: 1.0\r\n\r\n');
fprintf(report.fileID,␣'Blade: %s \r\n\r\n',␣blade.name);
fprintf(report.fileID,␣'Data: %d-%s-%s \r\n',␣report.data(1),
␣report.month,␣report.day);
```

```
fprintf(report.fileID,␣'Time: %s:%s:%s \r\n\r\n',
report.hours,␣report.min,␣report.sec);
fprintf(report.fileID,␣'Analysis data: \r\n');
fprintf(report.fileID,␣'   Rotor diameter: D = %.2f m \r\n',␣D);
fprintf(report.fileID,␣'   Induction factor: a = %.4f \r\n',␣a);
fprintf(report.fileID,␣'   Tip-speed ratio = %.2f \r\n',
␣(omega*r(end)/c1));
fprintf(report.fileID,␣'   r/R ratio = %.2f \r\n',␣r_R);
fprintf(report.fileID,␣'   Undisturbed wind speed:
c1 = %.2f m/s \r\n',␣c1);
fprintf(report.fileID,␣'   Speed rotation: omega = %.4f rad/s \r\n',␣omega);
fprintf(report.fileID,␣'   Tollerance on the chord increment:
 %.7f m\r\n',␣toll);
fprintf(report.fileID,␣'   Alpha start: %.2f \r\n',␣alpha_struct.start);
fprintf(report.fileID,␣'   Alpha finish: %.2f \r\n',␣alpha_struct.finish);
fprintf(report.fileID,␣'   Alpha first cycle: %.2f \r\n',
␣alpha_struct.cycle_1);
fprintf(report.fileID,␣'   Alpha second cycle: %.2f \r\n\r\n',
alpha_struct.cycle_2);


%%␣FIGURES␣PLOT

fig␣=␣figure;
for␣ii=1:length(r)
plot(1:counter,␣l(ii,␣1:counter),␣'LineWidth',␣dim_lines_plot);
hold␣on
grid␣on
end
title('CHORD CONVERGENCE')
xlabel('Iterations')
ylabel('l [m]')
ax␣=␣gca;
ax.FontSize␣=␣dim_text_plot;
%figure␣save
saveas(fig,␣[report.folder␣'/Chord convergence.jpg'],␣'jpg');
saveas(fig,␣[report.folder␣'/Chord convergence.fig'],␣'fig');

fig␣=␣figure;
plot(r,␣l(:,counter),'b-o',␣'LineWidth',␣dim_lines_plot);
grid␣on
title('CHORD')
xlabel('r [m]')
ylabel('l [m]')
ax␣=␣gca;
ax.FontSize␣=␣dim_text_plot;
%figure␣save
saveas(fig,␣[report.folder␣'/Corda.jpg'],␣'jpg');
```

```
saveas(fig,␣[report.folder␣'/Corda.fig'],␣'fig');

fig␣=␣figure;
plot(r,␣alpha(:,counter),'b–o',␣'LineWidth',␣dim_lines_plot);
grid␣on
title('ANGLE OF ATTACK')
xlabel('r [m]')
ylabel('\alpha [deg]')
ax␣=␣gca;
ax.FontSize␣=␣dim_text_plot;
%figure␣save
saveas(fig,␣[report.folder␣'/Angle of attack.jpg'],␣'jpg');
saveas(fig,␣[report.folder␣'/Angle of attack.fig'],␣'fig');

fig␣=␣figure;
subplot(311)
plot(r,␣Cl(:,counter),'b–o',␣'LineWidth',␣dim_lines_plot);
grid␣on
title('LIFT')
xlabel('r [m]')
ylabel('CL')
ax␣=␣gca;
ax.FontSize␣=␣dim_text_plot;

subplot(312)
plot(r,␣Cd(:,counter),'b–o',␣'LineWidth',␣dim_lines_plot);
grid␣on
title('DRAG')
xlabel('r [m]')
ylabel('CD')
ax␣=␣gca;
ax.FontSize␣=␣dim_text_plot;

subplot(313)
plot(r,␣Cl(:,counter)./Cd(:,counter),'b–o',␣'LineWidth',␣dim_lines_plot);
grid␣on
title('Cl / Cd ratio')
xlabel('r [m]')
ylabel('CL/CD')
ax␣=␣gca;
ax.FontSize␣=␣dim_text_plot;
%figure␣save
saveas(fig,␣[report.folder␣'/Drag and Lift.jpg'],␣'jpg');
saveas(fig,␣[report.folder␣'/Drag and Lift.fig'],␣'fig');

%%␣FIGURE:␣PROFILES␣WITH␣PITCH␣ANGLE

fig␣=␣figure;
```

```
title('PROFILES WITH PITCH ANGLE')

pitch_angle␣=␣zeros(1,length(blade.profiles));

for␣jj␣=␣1:length(blade.profiles)

%data␣input␣from␣the␣profiles
coordinates_profile␣=␣load([blade.folder␣'/'␣char(blade.profiles(section))]);
x_profile␣=␣coordinates_profile(:,1);
y_profile␣=␣coordinates_profile(:,2);

%index␣of␣the␣min␣value␣of␣x␣profiles
index_x_min␣=␣find(x_profile␣==␣min(x_profile));

%coordinate␣traslation␣in␣order␣to␣create␣a␣coincidence␣between␣the
%center␣of␣the␣profile␣and␣the␣y␣axis
x_profile␣=␣x_profile*l(jj,counter)␣-␣0.5*l(jj,counter);
y_profile␣=␣y_profile*l(jj,counter);

%pitching␣angle␣of␣the␣section␣jj
pitch_angle(jj)␣=␣beta_deg(jj)+␣alpha(jj,counter);

%section␣rotation
for␣ii=1:length(x_profile)
sol␣=␣[cosd(90-pitch_angle(jj))␣-sind(90-pitch_angle(jj));␣...
sind(90-pitch_angle(jj))␣cosd(90-pitch_angle(jj))]␣*␣...
[x_profile(ii);␣y_profile(ii)];
x_profile(ii)␣=␣sol(1);
y_profile(ii)␣=␣sol(2);
end

line_plot(jj)␣=␣plot(x_profile,␣y_profile,␣'LineWidth',␣2);
legend_text␣=␣char(blade.profiles(jj));
legend_line{jj}␣=␣legend_text(1:end-4);
axis␣equal
grid␣on
hold␣on
%plot␣of␣the␣chord␣profile
plot([x_profile(index_x_min)␣x_profile(1)],
␣[y_profile(index_x_min)␣y_profile(1)],␣'k--',␣'LineWidth',␣1.2)
ax␣=␣gca;
ax.FontSize␣=␣11;
hold␣on
end

legend(line_plot,␣legend_line);
%figure␣save
saveas(fig,␣[report.folder␣'/Profiles with pitch angle.jpg'],␣'jpg');
```

```
saveas(fig,␣[report.folder␣'/Profiles with pitch angle.fig'],␣'fig');

%%␣PLOT␣3D
fig␣=␣figure;
title('3D BLADE')

for␣jj␣=␣1:length(blade.profiles)
%data␣input␣from␣the␣profiles
coordinates_profile␣=␣load([blade.folder␣'/'␣char(blade.profiles(section))]);
x_profile␣=␣coordinates_profile(:,1);
y_profile␣=␣coordinates_profile(:,2);

%coordinate␣traslation␣in␣order␣to␣create␣a␣coincidence␣between␣the
%center␣of␣the␣profile␣and␣the␣y␣axis,␣with␣reshaping␣of␣the␣profile
%based␣on␣the␣chord␣dimension
x_profile␣=␣x_profile*l(jj,counter)␣-␣0.5*l(jj,counter);
y_profile␣=␣y_profile*l(jj,counter);

%pitching␣angle␣of␣the␣section␣jj
pitch_angle(jj)␣=␣beta_deg(jj)+␣alpha(jj,counter);

%section␣rotation
for␣ii=1:length(x_profile)
sol␣=␣[cosd(90-pitch_angle(jj))␣-sind(90-pitch_angle(jj));␣...
sind(90-pitch_angle(jj))␣cosd(90-pitch_angle(jj))]␣*␣...
[x_profile(ii);␣y_profile(ii)];
x_profile(ii)␣=␣sol(1);
y_profile(ii)␣=␣sol(2);
end

line_plot(jj)␣=␣plot3(x_profile,␣y_profile,
(r(jj)*ones(length(x_profile),1)),␣'LineWidth',␣2);
axis␣equal
hold␣on
legend_text␣=␣char(blade.profiles(jj));
legend_line{jj}␣=␣legend_text(1:end-4);

ax␣=␣gca;
ax.FontSize␣=␣11;
hold␣on
end

legend(line_plot,␣legend_line)
%figure␣save
saveas(fig,␣[report.folder␣'/3D blade.jpg'],␣'jpg');
saveas(fig,␣[report.folder␣'/3D blade.fig'],␣'fig');

%%␣WIND␣TURBINE␣POWER
```

```
%power␣with␣trapezes␣integral
[P_trap,␣P_ideal,␣Cp_trap,␣P_sup_trap]␣=␣Power_trapezes(r,␣l(:,counter),
beta,␣c1,␣w,␣Cl(:,counter),␣Cd(:,counter),␣air,␣omega,␣Nbl,␣efficiency,
␣report,␣dim_text_plot);

%power␣with␣Cavalieri-Simpson␣integral
[P_cs,␣P_ideal,␣Cp_cs]␣=␣Power_cs(r,␣l(:,counter),␣beta,␣c1,␣w,
Cl(:,counter),␣Cd(:,counter),␣air,␣omega,␣Nbl,␣efficiency,
report,␣dim_text_plot,␣true);

%%␣OUTPUT␣PROFILES␣IN␣THE␣REPORT␣FILE

fprintf(report.fileID,␣'Profiles of the blade used\r\n');
fprintf(report.fileID,␣'section    -    profile\r\n');
for␣ii=1:length(blade.profiles)
section␣=␣char(blade.profiles(ii));
fprintf(report.fileID,␣'   %d    -    %s \r\n',␣ii,␣section(1:end-4));
end

%%␣CLOSING␣REPORT␣FILE␣and␣saving␣analisys␣data

fclose(report.fileID);␣%closes␣the␣report

%deleting␣some␣unnecessary␣variables
clear␣fig␣ax␣wait_bar␣line_plot␣legend_line␣alpha_input␣alpha_opt␣ans␣cd_2D
clear␣coordinates_profile␣dim_lines_plot␣dim_text_plot␣h␣h_section␣ii
clear␣index␣jj␣legend_text␣section␣sol␣visibility_Xfoil
%saving␣all␣the␣variables␣in␣a␣Matlab␣file
save([report.folder␣'/Analysis_data.mat'])

%%␣SAVE␣THE␣FINAL␣BLADE␣DATA␣for␣the␣off-design␣and␣the␣pitching␣test

blade_design.l␣=␣l(:,counter);␣%chord␣for␣each␣section␣[m]
blade_design.Nbl␣=␣Nbl;␣%number␣of␣blades
blade_design.gamma␣=␣alpha(:,counter)␣+␣beta_deg'; %pitch angle [deg]
blade_design.r = r; %radial coordinate (distance from the axis of rotation)
blade_design.folder = blade.folder; %folder with the profiles
blade_design.profiles = blade.profiles; %blade profiles
blade_design.name = blade.name; %blade name (label)
blade_design.omega = omega; %rotational speed [rad/s]
blade_design.AR = AR; %Aspect Ratio
blade_design.S = S_bl; %Blade area [m^2]
blade_design.efficiency = efficiency; %Mechanical and electrical wind
turbine efficiency
blade_design.a_design = a; %Designed induction factor

save([report.folder '/Blade_Design_data.mat'], 'blade_design')
```

Appendix C

Drawing for preparation of the bamboo for blade manufacturing

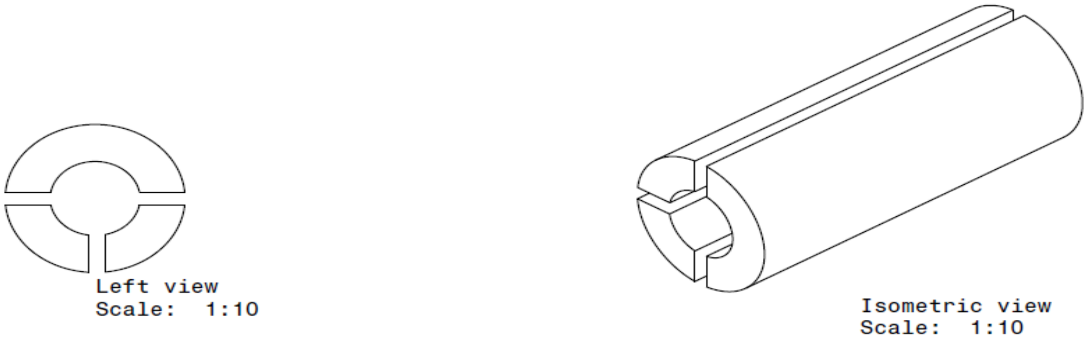

Figure C.1: Cutting the bamboo to form a plate

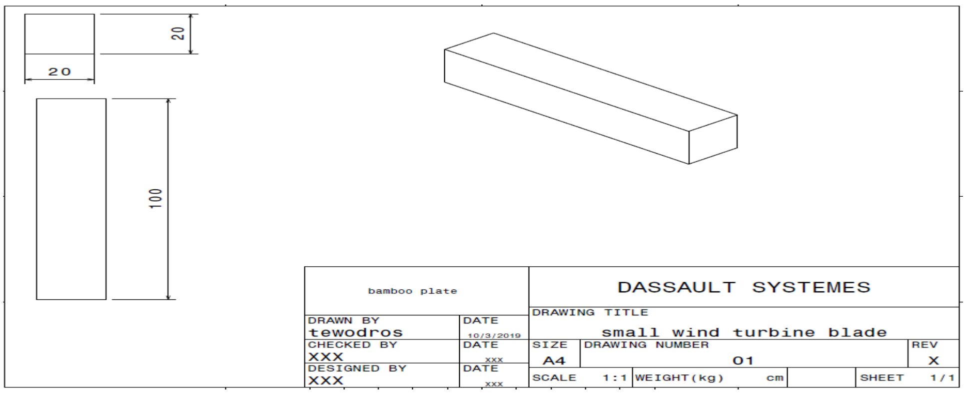

Figure C.2: A bamboo plate prepared for further processing

Drawing and pictures of the designed blade

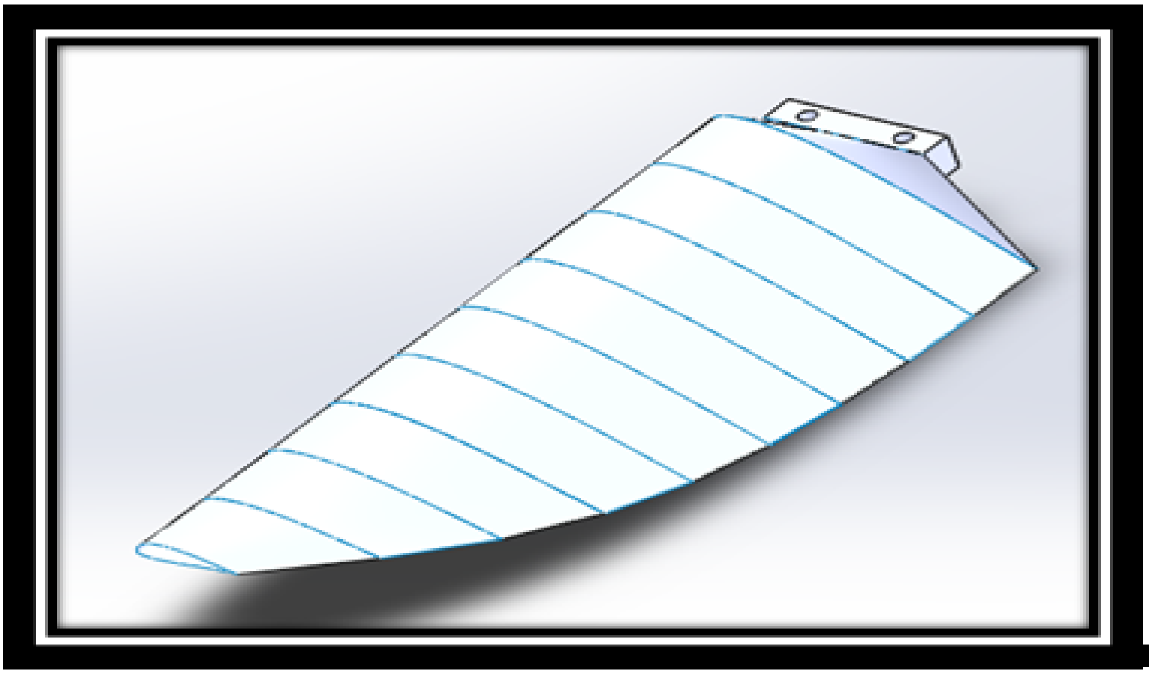

Figure C.3: The final designed wind turbine blade for manufacturing by solid work

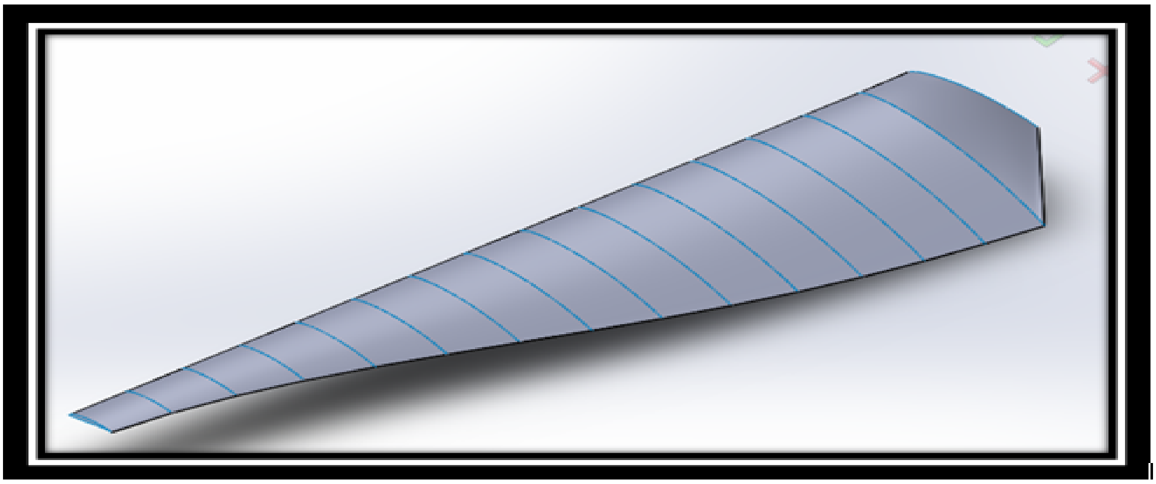

Figure C.4: The first designed blade which have 0.846m blade length

Figure C.5: Partial assembly of the designed wind turbine