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Addis Ababa Institute of Technology School of Graduate Center of Energy Technology

Design And Development of Three Small Generators Operated Micro Wind Turbine

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A thesis submitted to the school of graduate studies of Addis Ababa University Institute of Technology in partial fulfillment for the degree of Masters of Science in Energy of Technology

Addis Ababa, Ethiopia

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CERTIFICATION

I, the undersigned, certify that I read and hear by recommend for the acceptance by Addis Ababa University institute of Technology, center of Energy Technology a thesis entitled Design And development of Three Small Generator operated Micro Wind Turbine. This certificate used as a partial fulfillment of the requirement for the design of Masters of Science in Energy Technology.

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DECLARATION

I, Tekalegn Amanuel, I declare that this thesis is the result of my own work and that all source or material used for this thesis have been duly acknowledged. This thesis is submitted in partial fulfillment of the requirement for Masters Degree in Energy Technology at Addis Ababa University and to be made available at the university's Library under the role of the Library. I confidently declare that this thesis has not been submitted to any other institutions anywhere for the award of any academic degree, diploma, or certificate.

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Abstract

World is struggling to mitigate climate change due to uses of fossil fuel for energy generation and also searching substitution for fossil fuel in energy sector. Wind energy is one of the lowest environmental impact forms of clean energy available today. In order to convert wind in to energy many technologies are used up to know from small off grid to large wind farm wind turbine.

However, it's difficult to find cost effective and durable Micro wind turbine for off grid use to generate electricity in rural part of Ethiopia which is in dark for a long period of time.

This study aims to Design And develop Three Small Generators operated Micro Wind Turbine with production capacity of $2.4KW$*, to off-grid use for rural part of Ethiopia with durability and low cost relatively to current Micro wind turbine.*

Polyvinyl chloride (PVC) is used to manufacture the small wind turbine blade and Three small generator are driven by direct coupled external ring gear with turbine axle. PVC blade is manufactured with best twist angle through the radius of blade for better direct wind contact to get better energy extraction from low wind speed.

This Three Small Generators operated Micro Wind Turbine development costs took up to 28,885 ETB.

At the end of this research is done and commercialized the electricity demand can decrease in off grid users, the electricity coverage can cover rural (remote) area of Ethiopia around 30 Percent of the rural population which is in need of electricity.

Key words: - PVC, Electricity, Ring gear , Three-small generators, Micro wind turbine.

Nomenclature

KWH	Kilo Watt Per Hour
PVC	Polyvenile Chloride

Greek Symbols

Symbol	**Description**	**Unit**
θ	Angular displacement	rad
α	Angle of Attach	rad/sec
ρ	Density of dry air	Kg/m^3
γ	pitch angle	θ
λ_D	Tip speed ratio	
ω	Angular velocity	θ

Roman Symbols

Symbol	**Description**	**Unit**
A	Area of rotor	m^2
a	Induction factor	
$a^{'}$	Tangential Induction factor	
B	Number of Blade	
C	Chord length of Airfoil	m
C_D	Drag coefficients	
C_l	Lift coefficients	
C_p	power coefficient	
d_T	Differential Torque	N/m
k	Wei-bull shape parameter	
$m^{'}$	Mass flow rate	Kgs

l	chord in each section	m
M_a	Mach Number	
V	Voltage	V
P	Pressure	Pa
P_{eR}	Rated electrical power	Watt
P_N	Normalized average power	Watt
p_e	Energy production	J
R	Circle radius	m
R_e	Reynolds Number	
T	Thrust	Kgm
u_t	Tangential velocity	m/s
V	velocity of the wind	m/s
V_1	Velocity of wind at position 1	m/s
v_R	Rated Wind speed	m/s
v_c	Cut in Wind speed	m/s
v_F	furling wind speed	m/s
V_{ref}	Reference wind velocity	m/s
w	Relative Wind speed	m/s
Z_{ref}	Reference height	m

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1. Introduction

1.1. Introduction

Wind energy is one of the most abundant form of renewable and clean energy been targeted for centuries. Its predicted that human beings have been using wind energy in their daily work for about 4,000 years. There are many study's and technologies applied to convert wind into useful form of energy for many applications. Ethiopia has a population of More than 100 million, from More than 100 millions 75 percent are rural people, the electricity coverage of Ethiopia is about 42 percent which is almost urban population, but rural and remote population are still lives without electricity which means lives in dark age. Direct drive small wind turbine is effective off grid wind energy generation machine for most remote and rural part of many country's coverings electricity demand for lot of population which is lives in need of electricity.[1] like Ethiopian rural population. Small scale wind turbine is more efficient type for small residents, local villages, excluded from grid electricity supplying area. And also, it must be simple for maintenance, assembling and it must be portable because it is small scale, this research meets this criteria correctly. This research is mainly to satisfy the rural population energy demand by designing and developing Three Small Generator operated Micro Wind Turbine for off grid usage with low cost, and with local materials for designing wind turbine blade like PVC and also low-cost material for the rest of wind turbine components like standard rectangular hollow bar and circular hollow bar. Designing of blade for Three Small Generator operated Micro Wind Turbine done by using blade element moment theory for better wind harvesting, through differential radius of blade, and the rest of body part of Three Small Generator operated Micro Wind Turbine was built from steel, by welding. gears and bearings are selected by according, i.e. fitting, life expectence, wear resistance, and material availability. Spur gear and ball bearing used for Three Small Generator operated Micro Wind Turbine.

1.2. Problem statement

In Ethiopia remote and rural population suffering from different problems, from them lack of clean drinking water, lack of medical centers this is because of lack of electricity for electricity operated appliance and additionally also suffering from indoor pollution from using of gasoline and kerosene for lighting purpose. Only 2.8 million households are connected to the main grid, the rest which about 97.2 million to be off grid areas by Ethiopian electric corporation. This remote and rural areas that are claimed to be off grid areas contains woman's, children s and elders peoples in need of clean drinking water, medical cares and related issues. However, due to this electricity problems woman's, children s and elders has to walk 10 to 20 kilometers to get clean drinking water, medical care's additionally they have to go 10 to 20 kilometers to get kerosene or gasoline for lighting which causes indoor pollution and brings diseases like cancer and eye problems from smoke to the feature country taking young generation.

1.3. Objectives

1.3.1. General objective

The main aim of this research is to design and develop Three small generators operated micro wind turbine.

1.3.2. Specific objective

- Designing turbine blade from law weighted material specifically from Polyvinyl chloride (PVC) to decrease weight on structure and wind speed.
- Design of supporting frames with stable and law weighted strengthen steels.
- Selecting of large outside ring gear which couples directly with turbine blade axis's which decreases torque, generators and bearings with respect to RPM and expected life time.
- Assembling
- Testing prototype

1.4. Scope of study

This study focuses on designing and developing multi-small generator operated direct drive small wind turbine with partially local materials like bamboo and common materials like steel. Modeling and simulation using solid work 2019 and finally developing prototype which generates 2.4Kw inside of compass (Addis Ababa university Institute of technology).

1.5. Significance of the Study

The impact of this research is very significant on solving Energy demand problems in rural and remote area of Ethiopian by adding off grid energy production along side to solar panels. This research converts wind energy to mechanical,and mechanical to electrical energy and it is easy to use and also easy configuration of structure for placing in everywhere. It is applicable in average part of Ethiopia with average wind speed of $5.5m/s$ to $6m/s$. Therefore, the impact of this study is clearly higher in solving the power demand of off-grid system with a lower financial requirement. So, this may attract the attention of many researchers to go further in improving the efficiency Three small generator operated Direct drive wind turbine. Additionally, reducing the hard currency expended for the purchasing of material will reduce for same desired maximum power output compared to hydro and Pv system.

2. Literature Review

2.1. Wind Energy

Wind energy is one of the most important energy resources on earth. It is generated by the unequal heat of the planet surface by the sun. In fact, 2 per cent of the energy coming from the sun is converted into wind energy. That is about 50 to 100 times more than the energy converted into biomass by plants. Several scientific analyses have proven wind energy as a huge and well distributed resource throughout the five continents. The European Environment Agency on its technical reports measuring the European wind Source. [2] estimates that this Source will reach 70.000TWh by 2020 and 75.000TWh by 2030, Remaining of 12.200TWh will be economy Based outstanding Source of wind energy by 2020. This amount of energy is enough to supply three times the electricity consumption predicted for this year (2020). The same study also evaluates the scenario in 2030 when the economy Based outstanding Source, increases to 200TWh, seven times the electricity consumption predicted for this year (2030). Today electricity from wind provides a substantial share of total electricity production in only a handful of Member States see Figure (2.1).but its importance is increasing. One of the reasons for this increment is the reliability of this energy resource, which has been proven from the experience in Denmark. In this country 24 percent of the total energy production in2010 was wind-based and the Danish government has planned to increase this percentage to 50 by 2030. Following Denmark, the countries with the highest penetration of wind power in electricity consumption are: Portugal(14.8) percent, Spain(14.4) percent and Ireland (10.1) percent. The wind has been used to power sailing ships for many centuries. Many countries has their Globalization and industrial revolution to their skill in harnessing wind. The New World was Sailed by wind operated vessels. As such, wind was almost the one only means of power for ships until Watt invented the steam engine in the 18th Century [4]. On land, wind turbines date back many centuries. It has been written that the Babylonian dynasty Hammurabi, Decided to apply wind turbines for agriculture in the 17th century B.C. [4] Legends of Alexandria, who lived in the third century B.C., Explained a simple structured horizontal axis wind turbine having four blades which was used to blow an organ [4]. These early machines were Unimaginably and very unstable, mechanically inefficiency, but they Applied this for their many works very well for so many centuries. They were manufactured from locally available means by low rated labor. Maintaining it was most probably a problem which made to keep many workers at work. Their size was probably measured by the means available. A need for more power was met by building more wind turbines rather than larger ones [2]. The earliest recorded English wind turbine is dated at 1191. The first corn-grinding wind turbine was built in Holland in 1439. There were a number of technological developments through the centuries, and by 1600 the most common wind turbine was the tower mill. The word mill refers to the operation of grinding or milling grain. This work was so commonly used that all, wind turbines were somehow called windmills, even though they literally pumped water or used for some other function [4]. Denmark was the first country to use the wind for generation

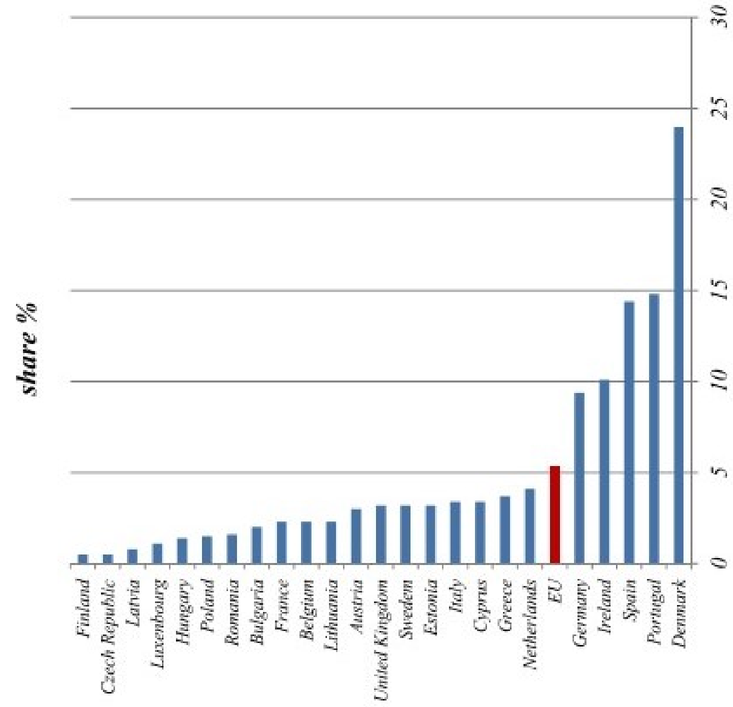


Figure 2.1.: Wind share of total electricity consumption in 2018 by country [3]

of electricity. The Danes were effectively applied a 11.5 R wind turbine in 1890 to produce electricity. By 1910, several hundreds of units with producing electricity of 5 to 25 kW were in Application in Denmark. [4]

2.2. Current Trends of wind Energy

Owing to our commitment to reduce G H G emissions and provide adequate energy to the developing world, efforts are being made to supplement our energy base with renewable sources. Several countries have already formulated policy frame- works to ensure that renewable s play an impressive role in the future energy scenario. For example, the European Union targets to meet 22 per cent of their demand from renewable s by 2010. Wind, being the commercially viable and economically competitive renewable source, is going to be the major player in meeting this target. [5] Wind is the world's Very fast growing energy means today and it has been staying that way for many consecutive years for the last five years. The world wind Energy capacity has changed to, by a factor of 4.2 for the last 5 years . The total World wide planted capacity is 39434 MW in 2004. Over all planted capacity in different countries of world is shown in Figure (2.2). Over 73 percent of the World wide Plantation are mostly in Europe. Germany is the European Third, After by Spain and Denmark. The five countries, leading in wind energy generation are listed in Table (2.1). With the increasing thrust on renewable s and reducing cost of wind generated electricity, the growth of wind energy will continue in the years to come. According to European Wind Energy Association (EWE A), wind with its expected 230, 000 MW installation, can supply 12 percent of the global energy demand by 2010 . [6] This indicates a market worth around 25 billion Euros. The Planted capacity may got to a level of 1.2 million MW by 2020.

Table 2.1.: Global leaders in wind energy generation

Country's	Installed capacity in MW
Germany	14609
USA	6352
Spain	6202
Denmark	3115
India	2120

[6]

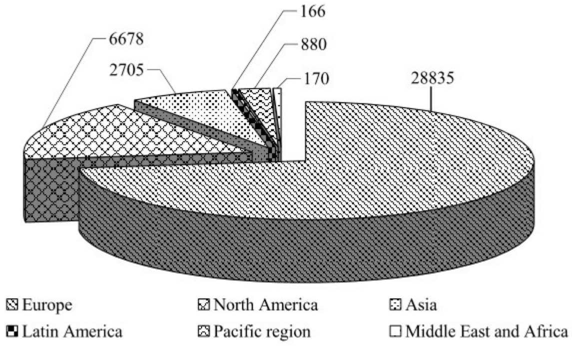


Figure 2.2.: Installed Wind energy capacity (MW) in different regions

[6]

2.3. Basics of wind energy conversion

Energy available in wind is basically the kinetic energy of large masses of air moving over the earth's surface.Blades of the wind turbine receive this kinetic energy, which is then transformed to mechanical or electrical forms of energy, depending on the end use.

How wind Energy Formed

All renewable energy (except tidal and geothermal power), and even the energy in fossil fuels, all are originated from the sun. The sun radiates $100,000,000,000,000$ KWh of solar energy to the earth per hour. In other words, the earth absorbs 10 to the $18th$ power of watts of power. About 1 to 2 per cent of the energy comes from the sun is Changed into wind energy. That is about 50 to 100 times more than the energy Changed into biomass, by all Flora on earth. [7]

(1) Temperature Differences, Drives Air Circulation

The places around the equator, at 0^0 latitude are getting more sun radiation than the Remaining part of the globe. these hot areas are indicated in the warm colors, red, orange and yellow in this infrared picture of sea surface temperatures In Figure (2.3). (taken from

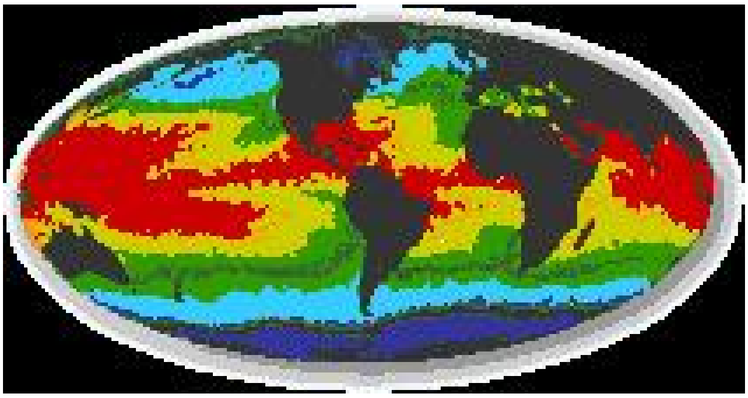


Figure 2.3.: Temperature Differences Drive Air Circulation
[4]

a NASA satellite, $NOAA - 7inJuly1984$).

Hot air is lighter than cold air and will rise into the sky until it reaches approximately $10km(6miles)$ altitude and will spread to the North and the South. If the globe didn't rotate, the air would naturally Get at the North Pole and the South Pole, sank down, and get back to the equator.

(2) The Coriolis Force

Since the globe is in orbital system and rotating, any motion linear or rotational on the Northern hemisphere is return to the right, if we see at it from our own point of position on the ground. (In the southern hemisphere it is resemble to the exact left). This causing of bending effect is called as the Coriolis force. (The name is given after French brilliant mathematician "Gustave Gaspard Coriolis 1792-1843").

The Coriolis force is a a force that can be seen in our daily bases. For example; Highway tracks wear out faster on one side than the other.Most River beds are drill deeper on one side than the other. (If you ask Which side it depends on which hemisphere we are in at: In the Northern hemisphere moving or flying objects are turn towards the right). In the Northern hemisphere the wind are tries to rotate counterclockwise (as we seen in above) as it gets to a low pressure area.As such as in northern hemisphere In the Southern hemisphere the wind rotates clockwise, about low pressure areas. See Figure (2.4) below

2.3.1. Power in wind

As we know that A wind turbine gets its power input by converting the kinetic energy of the wind into a torque (turning force) Applied on the rotor blades. Density of the air is the crucial for amount of energy which transfer to wind turbine blade, and also depends on the turbine blade area, and the wind Velocity.

Density of Air

The kinetic energy of a moving body is directly proportional to the mass (or weight). The kinetic energy in the wind are directly proportional to the air density, i.e. its mass

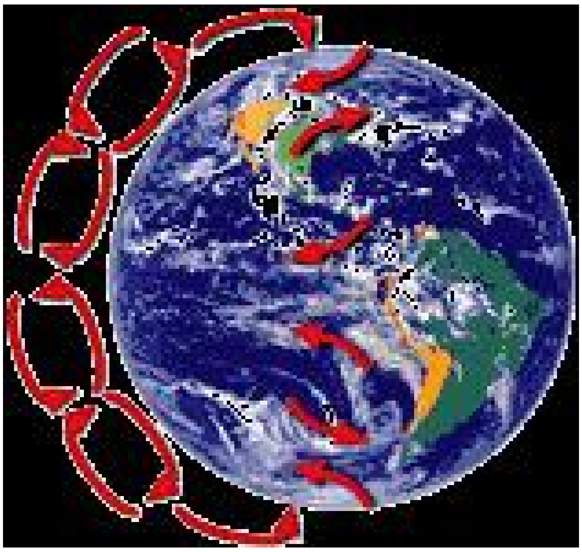


Figure 2.4.: Coriolis force
[4]

divided by unit of volume. which means exactly, if the air is heavier the energy we get from wind turbine is getting more.

At steady state atmospheric pressure and at 15^0 Celsius the air weight is constant 1.225 kilograms per cubic meter, but if humidity increases density decreases they are inversely proportional. As we know particles less denser when the expand, as such air become denser at cold state and vise versa. As i said above the particles density depends on temperature, which means when we go to high altitudes, the air pressure getting lower, and the air density becoming less.

Rotor Area

The amount of energy we get from wind depends on the rotor area because area is where wind contacts and the increase in wind contact the more we get the torque. Since the rotor area increases by power of 2 rotor diameter, a turbine with two times as large can get $2^2 = 2 \times 2 =$ multiplied by four as much energy.

Wind Speed

The wind Velocity is tremendously useful for the amount of energy we getting from a wind turbine that can converted to electrical energy: The amount energy wind caries are varies with the power of 4 ($3rd$) of the mean wind speed, e.g. if the wind speed is twice as high it contains $2^3 = 2 \times 2 \times 2 =$ eight times as much energy.see Figure (2.5) below. [7]

The wind turbine we using getting the energy from deflection of the wind, and if we multiply speed of th wind by Two, we can get twice as many deflection of wind passing the rotor every second, and each and every of those passing contains multiplied by four much energy, as we learned from the example of braking a car. the basic formula for wind energy is shown Equation (2.1) below.

$$P = \frac{1}{2}\rho A V^3 \tag{2.1}$$

where:
P= power of the wind $\frac{W}{m^2}$

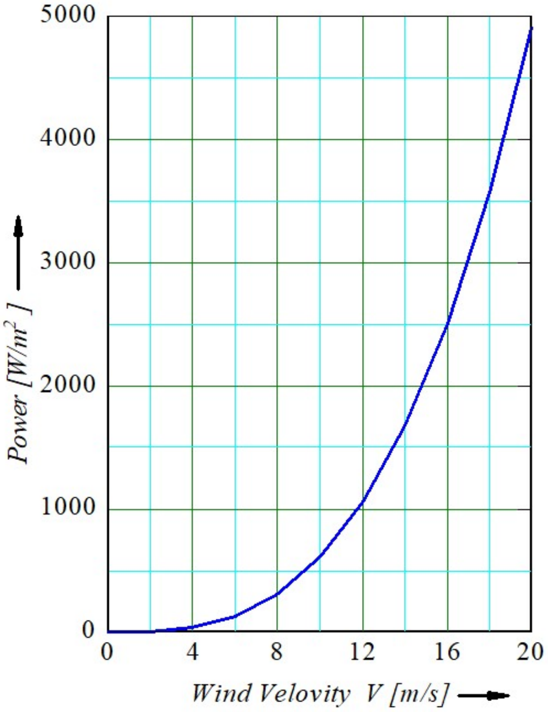


Figure 2.5.: Power Output versus of Wind Velocity
[8]

ρ = density of dry air $\frac{Kg}{m^3}$
V = velocity of the wind $\frac{m}{s}$.
A= Area of rotor in m^2

2.4. Types of Wind Turbine

A wind turbine is a modern machine that converts wind energy to electrical energy. There are different types of turbines. The most common type's are horizontal-axis wind turbine(HAWT) and vertical axis wind turbine(VAWT)

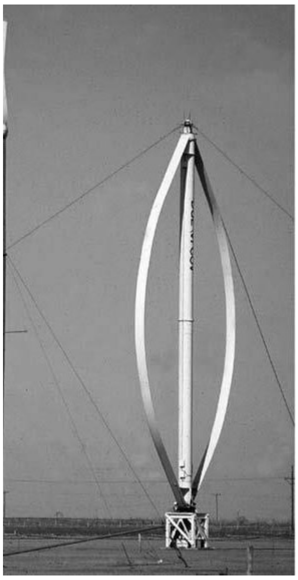
2.4.1. Horizontal Axis Wind Turbine (HAWT)

As Name implies it is parallel to ground and perpendicular to the wind speed. (HAWT) Blades are generally categorized according to the rotor Positioning (upwind or downwind of the tower), and also according to hub design (rigid or teetering), finally according to rotor control (pitch vs. stall), number of blades (usually two or three blades), and how they are aligned with the wind (free yaw or active yaw). See Figure (2.6a) Below.

2.4.2. Vertical axis wind turbine (VAWT)

That is, the axis of rotation is parallel to the blade and perpendicular to the ground (VAWT) as show in figure (2.6b) below.

(a) Horizontal Axis wind turbine in Adama I wind-farm in Ethiopia [9]



(b) Vertical axis wind turbine (VAWT) [10]

2.5. Wind turbine configuration

There are two types of configuration of wind turbine; there are Direct drive, and Gear boxed types;

2.5.1. Direct drive wind turbine

When the most complicated and crucial part of wind turbine; which is gear box removed the wind turbine can opperate direct meshing with the turbine shaft and the speed of the generator is equal to the speed of the turbine blade RPM.s[11] In this configuration the benefit is the cost of turbine is very low with respect to the gear boxed type.

2.5.2. Gear boxed Wind turbine

In gear box type the turbine is very huge and it can generate much more energy and it costs very high, and it is also has complicated designing. most of the time it used for grid power generation because of its high energy production.[11]

2.6. Wind turbine components

A general outline of the components of a wind turbine is given by the following figure (2.7) Below.

Rotor blades

Device to harvest the energy for the wind. At this part the kinetic energy of the wind is transformed into a mechanical torque.

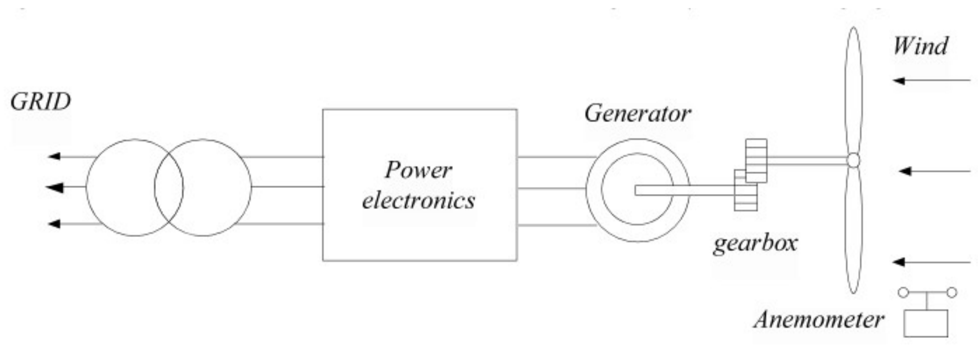


Figure 2.7.: components of wind turbine

[10]

Anemometer and wind vane

Devices for measuring wind speed and direction.

Gearbox

To convert the slowly rotating, high torque power from the wind turbine rotor to a high speed, low torque power rotation.

Electrical generator

Device to transform mechanical energy into electrical energy.

Associated power electronics

The part of the wind turbine where electric power is adapted to the frequency and the voltage amplitude of the grid.

Transformer

The turbines have their own transformer to step-up the voltage level of the wind turbine to the medium voltage line.

2.7. Aerodynamics of Wind Turbine Blades

Wind turbine power production Always considers the interaction of the rotor and wind. the wind may be considered as two kinds when you design turbine those are the combination of turbulent fluctuation and mean wind flow. Experience has shown that the major aspects of wind turbine performance (mean power produced and mean loads) are Extructed and explained by by the aerodynamic forces created by the average wind. Periodical aerodynamic forces created by wind shear, off-axis winds,blade rotation and randomly fluctuating forces stored by turbulence and dynamic effects are the means of fatigue loads are a factor in the peak load condition experienced by a wind turbine.[12]

2.7.1. One-dimensional Momentum Theory and the Betz Limit

A Easy model, generally created to attribute Betz (1926), can be used to Find the power from an ideal turbine blade, the thrust force of the wind on ideal blade, and the effect of the blade effect on the random location wind field. This Easy builtin model is based on a linear momentum theory derived over 100 years ago to estimate the efficiency of ship propellers. The analysis assumes a defined or boxed volume, in which the control volume boundaries are the body of a stream tube and two cross-sectional surface of the stream tube (see Figure (2.8)). The flow is one directional and its direction is across the ends of the stream tube surface. The turbine is Expected as a uniform 'actuator disc' which forms a discontinuity of pressure in the test tube of air flowing through it. Note: that analysis made in above are general analysis not to a specific wind turbine.

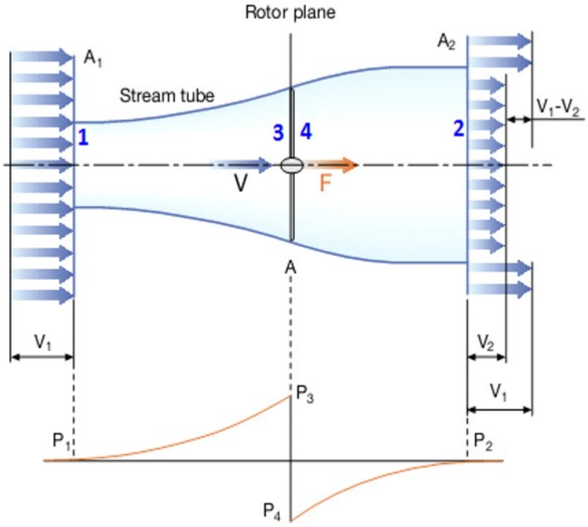


Figure 2.8.: Actuator disc model of a wind turbine; V, mean air velocity; 1, 2, 3, and 4 indicate locations

[7]

This analysis uses the following assumptions:

- homogeneous, in compressible, steady state fluid flow;
- no frictional drag;
- an infinite number of blades;
- uniform thrust through the disc or blade area;
- a not rotating wake;
- undisturbed steady static pressure is equal with steady pressure far upstream and far downstream of the blade.

Applying the conservation of linear momentum to the confined volume enclosing the overall system, one can get the net force of the contents inside the control volume. That force is equal and opposite directional to the thrust, T, which is the acting force of the wind on the wind turbine. From the conservation of linear momentum for a one-dimensional, in compressible, time-invariant flow, the thrust is equal and opposite to the rate of change of momentum of the air stream:

$$T = V_1(\rho AV)_1 - V_4(\rho AV)_4 \tag{2.2}$$

where ρ is the air density, A is the cross-sectional area, V is the air velocity, and the subscripts indicate values at numbered cross-sections in Figure (2.8) For steady state flow, where $(\rho AV)_1 = (\rho AV)_4 = m'$ is the mass flow rate. Therefore:

$$T = m'(V_1 - V_4) \tag{2.3}$$

The thrust is positive so the velocity behind the rotor,V_4, is less than the free stream velocity,V_1. No work is done on either side of the turbine rotor. 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:

$$p_1 + \frac{1}{2}\rho V_1^2 = p_2 + \frac{1}{2}\rho V_2^2 \tag{2.4}$$

In the stream tube downstream of the disc:

$$p_3 + \frac{1}{2}\rho V_3^2 = p_4 + \frac{1}{2}\rho V_4^2 \tag{2.5}$$

where the assumption made that the far upstream and far downstream pressures are equal ($p_1 = p_4$) and that the velocity across the rotor remains equal ($V_2 = V_3$).

The thrust can also be expressed as the net sum of the forces on each side of the actuator disc:

$$T = A_2(p_2 - p_3) \tag{2.6}$$

If one solves for ($p_2 and p_3$) using Equations (2.4) and (2.5) and substitutes that into Equation (2.6), one obtains:

$$T = \frac{1}{2}\rho A_2(V_1^2 - V_4^2) \tag{2.7}$$

Equating the thrust values from Equations (2.3) and (2.7) and recognizing that the mass flow rate is also$\rho A_2 V_2$, one obtains:

$$V_2 = \frac{V_1 + V_4}{2} \tag{2.8}$$

Where the wind speed at the rotor plane, using this simple model, is the difference of the upstream and downstream wind velocities. If one defines the axial induction factor, a, as the fractional decrease in wind velocity between the free stream and the rotor plane, then

$$a = \frac{V_1 + V_2}{V_1} \tag{2.9}$$

$$V_2 = V_1(1 - a) \tag{2.10}$$

and

$$V_4 = V_1(1 - 2a) \tag{2.11}$$

The quantity $V_1 a$ is often referred to as the stored velocity at the blade, in which case the velocity of the wind at the blade is a summation of the free stream velocity and the stored wind velocity. As the axial induction factor increases from 0, the wind speed behind the rotor slower and slower. If $a = \frac{1}{2}$, the wind has decreased to zero velocity behind the rotor and the simple theory is not gone work.

The power out, P, is equal to the thrust times the velocity at the disc:

$$P = \frac{1}{2}\rho A_2 (V_1^2 - V_4^2) V_2 = \frac{1}{2}\rho A_2 V_2 (V_1 + V_4)(V_1 - V_4) \tag{2.12}$$

Substituting forV_4 and V_4 from Equations (2.10) and (2.11) gives:

$$P = \frac{1}{2}\rho A V^3 4a(1 - a)^2 \tag{2.13}$$

where the control volume area at the rotor, A_2, is replaced by A, the rotor area, and the free stream velocity V_1 is replaced by$V$.

Wind turbine rotor performance is usually characterized by its power coefficient, C_p:

$$C_p = \frac{P}{\frac{1}{2}\rho A V^3} = \frac{Rotorpower}{PowerinWind} \tag{2.14}$$

The non-dimensional power coefficient represents the fraction of the power in the wind that is extracted by the rotor. From Equation (2.13), the power coexistent is:

$$C_p = 4a(1 - a)^2 \tag{2.15}$$

The maximum C_p is determined by taking the derivative of the power coefficient (Equation (2.15)) with respect to a and setting it equal to zero, yielding $a = \frac{1}{3}$. Thus:

$$C_{p,max} = \frac{16}{27} = 05926 \tag{2.16}$$

when $a = \frac{1}{3}$. For this case, the flow through the rotor co-relates to a stream tube with an upstream cross-sectional area of $\frac{2}{3}$ the disc area that enlarges to two times rotor area downstream. This outcome explains that, if an ideal blade were developed and operated such that the wind speed at the blade were $\frac{2}{3}$ of the free stream wind speed, then it would be operating at the maximum point of power production. Furthermore, given the simple laws of physics, this is as maximum power as we get.[12] and [13]

2.7.2. Airfoils and General Concepts of Aerodynamics

Airfoils are structures with special geometry that given to them. the shape of airfoil are used to produce mechanical force due to the relative motion of the airfoil and a fluid that surround the shape.Wind turbine blades use airfoils to develop mechanical power. The cross-sections of wind turbine blades have the shape of airfoils. The dimension of the blade are functions of the expected aerodynamic performance, the maximum expected rotor power, the assumed airfoil properties, and strength of the airfoil take in to considerations.[12]

Airfoil Terminology

A number of terms are used to characterize an airfoil, as shown in Figure (2.9) The mean camber line is the locus of points halfway between the upper and lower surfaces of the airfoil. The most considered points of the mean camber line are on the leading and trailing edges,of the airfoil. the chord line is expressed as the line connecting the leading and trailing edges of the airfoil, and the distance from point at edge of trialing and leading are designated as chord (c),of the airfoil. The camber is the distance between perpendicular chord line and the mean camber line. The thickness measured by the distance deference between the upper and lower surface, perpendicular to chord line. Finally, the angle of attack, α, is defined as the angle between the relative wind V_{rel} and the chord line.

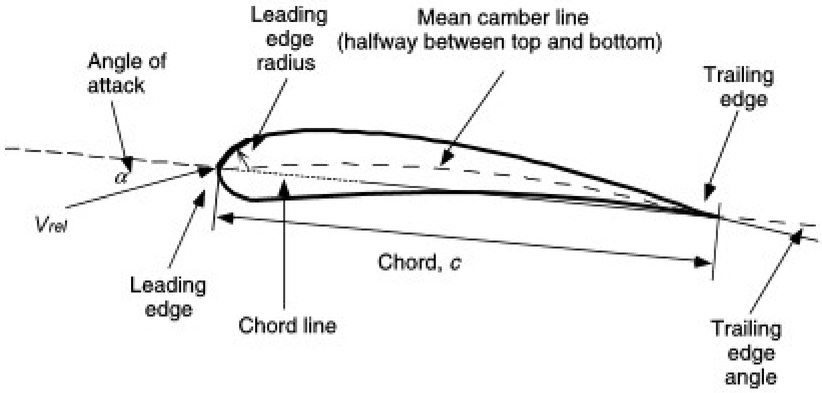


Figure 2.9.: Airfoil nomenclature
[1]

2.8. Materials for small wind turbine blade

The blades in a normally operating wind turbine rotor are continuously exposed to cyclical loads from wind and gravity. The expected lifetime for a blade is usually 20 years for large wind turbines, and less than 20 years for small wind turbines (Clausen and Wood, 2000). Based on these requirements, [7] summarized that the primary condition to be taken in to account for blade materials are high stiffness to ensure aerodynamic performance, low density to minimize mass and long-fatigue cycles. Materials used in wind turbine technology are plastics, metals, wood, composite materials, this are the main materials from the rest.[14] and [2]

2.8.1. Metal

Steel is a common, relatively inexpensive material used extensively in industry, however, it is difficult to manufacture into a complex twisted shape, and the fatigue life of steel is very poor compared to fiberglass composites (Burton et al., 2001). While steel was used for wind turbines blades before the 1950s, it is essentially no longer used [12]. Another metal that has been considered for wind turbine blades is weldable aluminum. However, its fatigue strength at 10^7 cycles is only $17MPa$ compared with fiberglass $140MPa$ and carbon fiber $350MPa$ [15]

2.8.2. Glass and carbon fiber composites

Fiber glass materials usually have laminate structure with different fibers orientations in the reinforcing glass layers. Various glass fibers orientations result in anisotropy of the material properties in the plane parallel to the laminates. E-glass materials are most common used glass type in turbine technology . These types of glasses have good combinations both mechanical, chemical and physical properties. Furthermore, E-glass more economic based and very good price and availability. E-glass fibers are usually exist in three principal types including, continue glass fiber, chopped glass fiber and unidirectional glass fiber. The types of E-glass fiber which is used in this study is unidirectional (UD) E-glass type. UD fiber type has a good mechanical properties as compared to other fiber types and most of the time it uses in the fabrication of wind turbine blade structures.[2]

2.8.3. PVC

Polyvinyl chloride is a thermoplastics material which consists of PVC resin compounded with varying proportions of stabilizers, lubricants, fillers, pigments, plasticizes and processing aids.To obtain specific group of properties, for different purposes,Different compounds of these ingredients developed, but each parts of the compounds developed are mostly PVC resin Organic chemistry categorizes PVC (vinyl chloride) as a polymer, which means chained molecules, of vinyl chloride. The PVC compounds with no plasticizers and less compounding ingredients have good short-term and long-term strengths. This mentioned PVC type is known as PVC-U or UPVC. Other resins or by adding modifiers (such as ABS, CPE or acrylics) to UPVC we can improve impact resistance of UPVC. These mentioned compounds are called as modified PVC (PVC-M).With wide range of properties, Flexible or plasticized PVC compounds can also be produced by the addition of plasticizers. Other types of PVC are called CPVC (PVC-C) (chlorinated PVC), which has a higher chlorine content and oriented PVC (PVC-O) which is PVC-U where the molecules are aligned preferentially in a particular direction..[16] and [17]

2.9. Design principles and failure mechanisms

2.9.1. Design principles

Current available wind turbine blades are most of not all optimized with respect to structural strength.so as that said, big differences can be expected in the safety analysis of many types of failures.The safety condition basis for different failure modes in current blade design,including material,buckling of the structure and strength of the structure have been separated even though both related to the structural properties of materials. This is in order to evaluate the difference in unimplemented capacity. Figure 1.7 evaluates that material strength enjoys a very large safety basics in modern wind turbine blades . This postulate is based on experimental work $5-10in$ which panels from three blade manufacturers were tested in compression. Even though the test specimens were made similar to the load-carrying laminate in a typical wind turbine blade , the material properties are not fully representative of those in real wind turbine blades as the specimens were produced in a laboratory under different conditions . Strains measured in the panel tests, with small defects, were in the range of $20000-25000\mu s$, which is a factor of $4-5$ times higher than those measured in full-scale tests. For panels with large embedded defects the strain levels were in the range of $10-15000\mu S$, which is a factor of $2-3$ times higher than those obtained in the full-scale tests.[18]

2.10. Rated wind speed and Power

It is convenient to define a model for Pe that can be used in discussing any wind system. The simplest model would use a straight line to describe the variation in output power between cut-in and rated wind speeds.

We must remember, of course, that other monotonic functions will fit the observed data nearly as good as a straight line, or perhaps even better for some machines, and may yield more accurate energy estimates or more convenient analytic results. a closed form expression for energy production can be obtained if p_e is assumed to vary as v^k between cut-in and rated wind speeds, where k is the Wei bull shape parameter. Numerical integration is required if P_e is assumed to vary as v, or in a linear fashion. Therefore, from designing simple model it is appropriate to make design-es complicated for better performance and better competition of the product we make.. We therefore define the following equations for the electrical power output of a model wind turbine;

$$p_e = 0 \rightarrow (v < v_c) p_e = a + bv^k \rightarrow (v_c \leq v \leq v_r) p_e = p_{eR} \rightarrow (v_r < v \leq v_F) p_e = 0 \rightarrow (v > v_F) \tag{2.17}$$

In the above shown expression, P_{eR} is the rated electrical power, v_c as cut-in wind speed, v_R as rated wind speed, v_F is the furling wind speed, and k is constant as wei-bull shape parameter.is an old sailing term which refers to the process of rolling up the canvas sails in anticipation of high winds. Furling it therefore is used to refer to the wind speed at which the turbine is shut down to prevent structural damage. This condition normally occurs only a few hours during the year, and therefore does not have a large influence on energy production.

The coefficients a and b are given by;

$$a = \frac{p_{eR} v_c^k}{v_c^k - v_R^k} \tag{2.18}$$

$$b = \frac{p_{eR}}{v_R^k - v_c^k} \tag{2.19}$$

Rayleigh distribution is a special case of the Wei-bull distribution with $k = 2$ and is often considered as sufficiently accurate for analysis of wind power systems. This value of k should be used if the wind statistics at a given site are not well known.[4]

A plot of P_e versus v is shown in Figure (2.10), for $k = 2$. Pe varies as v_k between the cut-in and rated wind speeds. It is then assumed to be a constant value between the rated and furling wind speeds. At the furling wind speed v_F the turbine is shut down to protect it from high winds.

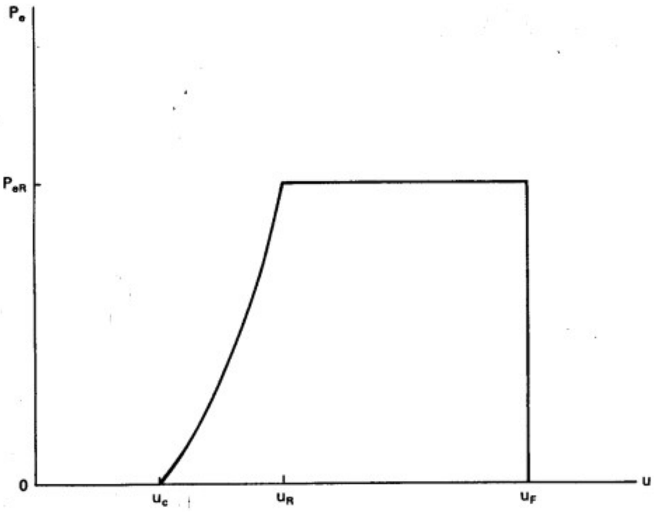


Figure 2.10.: Model wind turbine output with respect to wind speed. [8]

2.11. Energy Production and Capacity Factor

We have seen that the electrical power output of a wind turbine is a function of the wind speed, the turbine angular velocity, and the efficiencies of each component in the drive train. It is also a function of the type of turbine,the inertia of the system,and the gustiness of the wind. We now want to combine the variation in output power with wind speed with the variation in wind speed at a site to find the average power Pe,ave that would be expected from a given turbine at a given site. The average power output of a turbine is a very useful parameter of a wind energy system because it determines the overall energy production and overall income. It is a much better indicator of economics than the rated power, which can easily be chosen at too large a value.

The average power output from a wind turbine is the power produced at each wind speed times the fraction of the time that wind speed is experienced, integrated over all possible wind speeds.[4]

In integral form, this is;

$$p_{e,ave} = \int_0^\infty p_e f(v) dv \tag{2.20}$$

where $f(u)$ is a probability density function of wind speeds. We shall use the Weibull distribution.

$$f(v) = \frac{k}{c}(\frac{v}{c})^{k-1} \exp[(\frac{v}{c})^k] \tag{2.21}$$

Substituting Equation(2.17) and (2.21) into Equation (2.20) yields

$$p_{e,ave} = \int_{v_c}^{v_R} (a + bv^k) f(v) dv + p_{eR} \int_{v_R}^{v_F} f(v) dv \tag{2.22}$$

When we substitute the limits of integration into Equation (2.22), and reduce to the minimum number of terms, the result is;

$$p_{e,ave} = p_{eR}\{ \frac{\exp[-(\frac{v_c}{c})^k] - \exp[-(\frac{v_R}{c})^k]}{(\frac{v_R}{c})^k - (\frac{v_c}{c})^k} - \exp[-(\frac{v_F}{c})^k] \} \tag{2.23}$$

We can gain some insight into this design step by normalizing Equation (2.23). We first observe that the quantity inside the brackets of Eq. 30 is called the $capacityfactor\ CF$. Also called the $plantfactor$, it is an important design item in addition to the average power.

Finally we gate;

$$p_{e,ave} = p_{eR}(CF) = \eta \frac{1}{2} \rho A v_R^3 (CF) \tag{2.24}$$

When choosing rated wind speed we should not depend on the rated total efficiency, density of the air, or area of turbine rotor, because this mentioned quantity can be normalized. Also, since the capacity factor is expressed entirely in normalized wind speeds, it is convenient to do likewise in normalizing Equation (2.24) by dividing the expression by c^3 to get the term $(v_R/c)^3$. We therefore define a normalized average power P_N as;[4]

$$p_N = \frac{p_{e,ave}}{\eta_0 (\frac{\rho}{2}) A c^3} = (CF)(\frac{v_R}{c})^3 \tag{2.25}$$

2.12. Previous Works

According to Design Considerations of a Transverse Flux Machine for Direct-Drive Wind Turbine Applications paper done by Tausif Husain and his associates,direct drive wind turbine avoid disadvantage associated with gearing configuration, direct drive wind turbine designed with transverse flux, according to [19] direct drive wind turbine is optimized with transverse flux machine and they developed prototype which is more out put with less disadvantage from gear boxed type. The main consideration to design and develop small direct drive wind turbine is start up torque, startup torque is the amount of force needed to rotate first round of blade which is very useful for any designer because the design must be work on low wind speed and should work anywhere as i mentioned to be operate in low wind speed, which we can get anywhere according to paper Experimental investigation of drive train resistance applied to small wind turbines, done by Jouberson L.R. Moreira and associates, [20] Startup torque reduction is key for small direct drive wind turbine. Direct drive wind turbine is always reliable for off grid uses according to wind turbine manufacturer and it is cost effective, to transportation and maintenance it is very easy and handy, according to [11] this website direct drive wind turbine designing is very tricky because it has no yaw mechanism and it needs perfection. Wind speed required for small wind turbine to operate at optimum is average wind speed of $6.5m/s$ which is no get everywhere around the globe because of wind speed fluctuation, and small direct drive wind turbine should be designed with law torque and low rpm generator.[21] Structure of wind turbine is very important for better load distribution and maintenance, on the article done bye Sethuraman, Latha and Fingersh, Lee J and Dykes, Katherine and Hayes, Austin they focused on structural part of direct drive small wind turbine, blade structure, generator structure specially because according to this paper, its very essential part of wind turbine if it can be modified and can be driven by small amount of torque it can be operate at low wind speed, and can be operate average part of the globe.[22] Direct drive wind turbine can also be grid grid used according to the paper done by Mohamed Abbes,Jamel Belhadj , Afef Ben Abdelghani Bennani, by using a three-level grid side converter (GSC) direct drive wind turbine can also be used as grid type, this is new concept and it is promising because direct drive is need much more RPM to produce more energy, but that is can be solved by using (GSC) to step up and convert it to grid, and cover more places, which needs energy.[23] According to the paper Design study of coated conductor direct drive wind turbine generator for small scale demonstration, coated conductor generator is promisingly good output for Mega watt stage direct drive wind turbine on this paper designed generator has high flux and can generate more power in low rpm but it needed more torque, to start.[24]

3. Materials and Methodology

3.1. Methodology

Graphical representation of methodology is expressed in detail below.

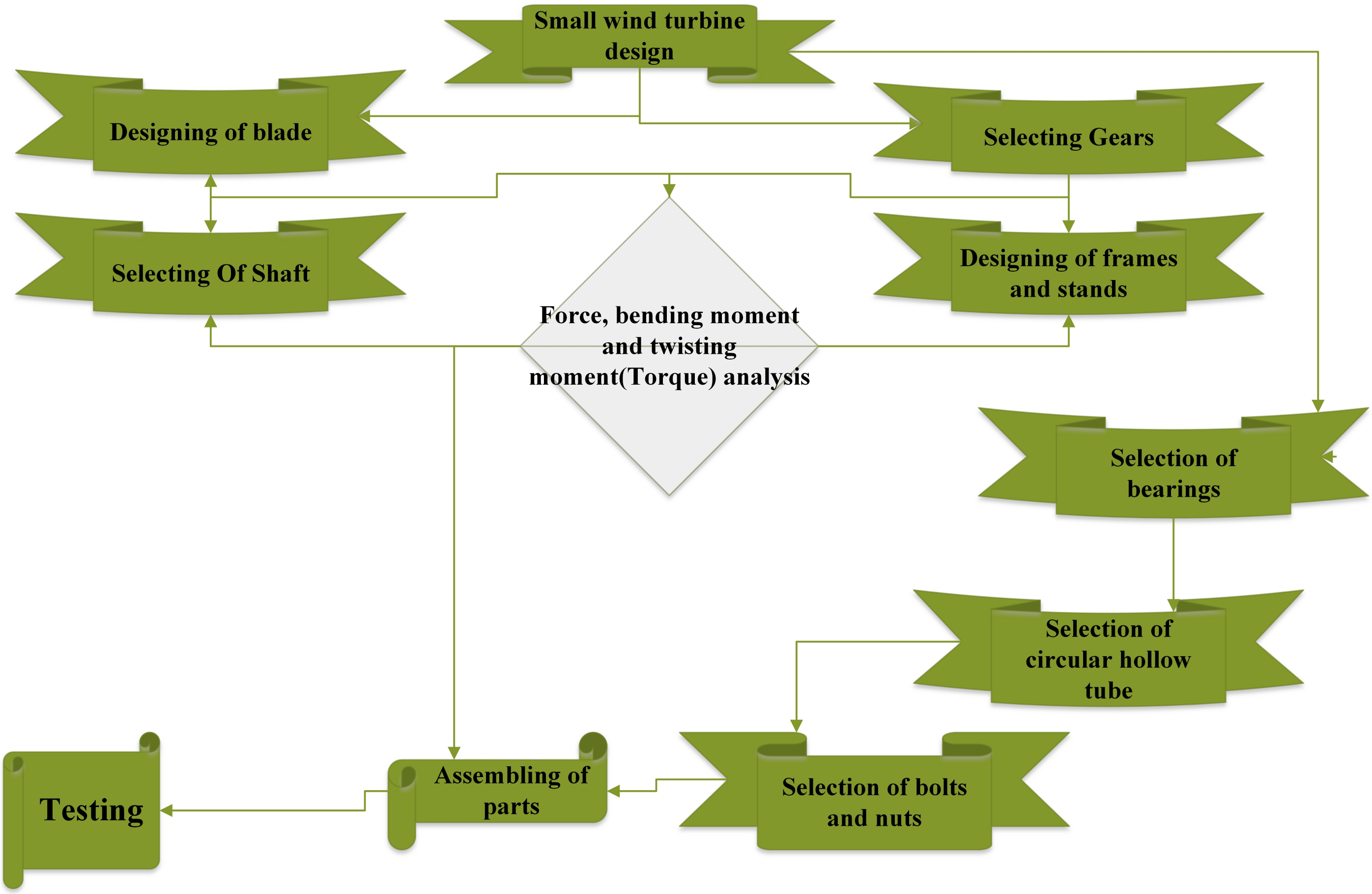


Figure 3.1.: Methodology

3.1.1. Detail on methodology

Wind blade (rotor) design: -

In this task the followings are performed in detail one by one.

- Rotor sizing
- Choice of the numbers of blade.
- Choice of blade profile and materials.
- Determination of blade chord.
- Choice of pitch angle
- Load calculation:
  - Blade loads.
  - Rotor loads.
  - Cods and standards.
  - Design loads.

Designing of frames: -

Designing of frame on the basis of the following terms;

- Material selection based on the load types subjected to,
- Load calculation:
  - Axial loads
  - Tangential loads
  - Bending moments
  - Twisting moments (Torque)

3.1.2. Materials used for the research.

Materials used for research are shown in table below in Table 3.1

Table 3.1.: Materials used for research

No	Material List	Name	Types	Specification		Mechanical Properties	
					Condition	Braille Hardiness	Minimal Tensile Strength N/mm2
1	Blade	PVC	Plastic	plastisized		20	51.675 Mpa
2	Gears	Steel	Metal	Maliable cast iron 0.5 carbon	Hardened and tempered	122	600 Mpa
3	Bearings	Steel	Metal	High carbon chromium steel	Heat treated	62-65 HRC	400-520 Mpa
4	Shaft	Steel	Metal	Carbon steel grade 40C8	Heat treated	150-180	560-670Mpa
5	RHS and Circular hollow bars	Steel	Metal	Carbon steel grade 48C8	Heat treated	130-140	610-700Mpa
6	Frames	Steel	Metal	Carbon steel grade 40C8	Heat treated	130-140	560-670Mpa
7	Bolts and Nuts	Steel	Metal	Carbon steel grade 48C8	Heat treated	160-180	610-700Mpa

3.2. Introduction

Polyvinyl chloride is a thermoplastics material which consists of PVC resin compounded with varying proportions of stabilizers, lubricants, fillers, pigments, plasticizes and processing aids.To obtain specific group of properties, for different purposes,Different compounds of these ingredients developed, but each parts of the compounds developed are mostly PVC resin Organic chemistry categorizes PVC (vinyl chloride) as a polymer, which means chained molecules, of vinyl chloride.

3.2.1. Different Types of Polyvinyl Chloride

The PVC compounds with no plasticizers and less compounding ingredients have good short-term and long-term strengths. This mentioned PVC type is known as PVC-U or UPVC. Other resins or by adding modifiers (such as ABS, CPE or acrylics) to UPVC we can improve impact resistance of UPVC. These mentioned compounds are called as modified PVC (PVC-M).With wide range of properties, Flexible or plasticized PVC compounds can also be produced by the addition of plasticizers. Other types of PVC are called CPVC (PVC-C) (chlorinated PVC), which has a higher chlorine content and oriented PVC (PVC-O) which is PVC-U where the molecules are aligned preferentially in a particular direction.

PVC-U (unplasticized)

is type of PVC is rigid and also very hard and with ultimate tensile stress at 20°C approximately 52 MPa, good resistance to many chemicals.In real life temperature is dependent on environmental conditions. It is operable, temperature of 60 degree centigrade.

PVC-M (modified)

in this type toughness is improved regarding to impact load, and it is rigid. mechanical properties such as tensile, elastic modulus etc.are less than PVC-U. These properties can be varied with respect to used modifier.

PVC (plasticized)

rigidity is less; but improved impact resistance and good mold-ability and can be easily extruded has ;low chemical resistances and low temperature resistance,ultimate tensile strength is very low respect others.

PVC-C (chlorinated)

almost the same to PVC-U in their properties but it has a higher temperature resistance, it can be operable up to 95°C. It has a th same ultimate stress at 20°C and its ultimate tensile stress of around 15 MPa at 80 degree centigrade

3.2.2. Why PVC

Choosing PVC for a lot of reasons from them due to their mechanical properties, physical properties, availability, durability, and environmental friendly.

3.2.3. Properties of PVC

Typical Properties of PVC

PVC is the most widely used member of the vinyl family. It is most commonly used in pipe and fittings. PVC offers very good resistance of corrosion and weather. It has very high weight to strength ratio and is a good thermal and also good electrical insulator. according to flammability tests PVC is also self-extinguishing per UL . PVC may be used to temperatures of (60°C) or 140°F and is vastly available in rods, sheets and tubing. PVC can be machined welded, cemented, bent and shaped readily. `https://www.ipolymer.com`

Table 3.2.: Typical Properties of PVC

TYPICAL PROPERTIES of PVC		
ASTM or UL test	Property	PVC
PHYSICAL		
D792	Density (lb/in^3) (g/cm^3)	0.051 1.41
D570	Water Absorption, 24 hrs	
Mechanical		
D638	Tensile Strength (psi)	7,500
D638	Tensile Modulus (psi)	411,000
D638	Tensile Elongation at Break	
D790	Flexural Strength (psi)	12,800
D790	Flexural Modulus (psi)	481,000
D785	Hardness	115 (Rockwell R)
D256	IZOD Notched Impact (ft-lb/in)	1

3.2.4. Mechanical Properties

For PVC, like other thermoplastics materials, the stress /strain response is dependent on both time and temperature. When we apply a constant static load to a plastics material, it has complex resultant strain behavior. The immediate elastic response is when load is removed,it fully recovered very moment. In addition while load applied until rupture occurs it has very slow deformation. This is phenomena is called creep. It gradually restores its original dimension when load removed The rate of creep and recovery is also influenced by temperature. At higher temperatures, creep rates tend to increase. Because of this type of response, plastics are known as visco elastic materials.`https://www.vinidex.com.au/technical-resources/material-properties/pvc-properties/` The detailed properties are shown in Table below 3.3.

Table 3.3.: Mechanical properties of PVC

Property	**Value**	**Conditins & Remarks**
Ultimate tensile strength	52 MPa	AS 1175 Tensometer at constant strain rate cf: PE 30
Elongation at break	50 – 80%	AS 1175 Tensometer at constant strain rate cf: PE 600-900
Short term creep rupture	44 MPa	Constant load 1 hour value cf: PE 14, ABS 25
Long term creep rupture	28 MPa	Constant load extrapolated 50 year value cf: PE 8-12
Elastic tensile modulus	3.0 – 3.3 GPa	1% strain at 100 seconds cf: PE 0.9-1.2
Elastic flexural modulus	2.7 – 3.0 GPa	1% strain at 100 seconds cf: PE 0.7-0.9
Long term creep modulus	0.9 – 1.2 GPa	Constant load extrapolated 50 year secant value cf: PE 0.2 – 0.3
Shear modulus	1.0 GPa	1% strain at 100 seconds G=E/2/(1+µ) cf: PE 0.2
Bulk modulus	4.7 GPa	1% strain at 100 seconds K=E/3/(1-2µ) cf: PE 2.0

3.2.5. physical properties

physical properties of PVC is shown table below in detail data is teken from website called `https://www.vinidex.com.au/technical-resources/material-properties/pvc-properties/` general purpose plastics are; PVC, PE, PP and PS. The features of the particular plastic are determined by its chemical composition and type of molecular structure (molecular formation: crystalline/amorphous structure) PVC has an amorphous structure with polar chlorine atoms in the molecular structure. the amorphous molecular structure and chlorine atoms are inseparably related. apparently plastics resume very resembles in the relation of daily use, in terms of performance PVC has completely different functions and features, With respect to olefin plastics which has only hydrogen and carbon atoms inside their molecular structures. Common feature among substances containing halogens is their Chemical stability from them chlorine and fluorine are mostly used. resins PVC contains this mentioned substances, which more than that possess durability, fire retarding properties,chemical resistance and oil resistance.

Fire retarding properties

PVC has Naturally very high fire retarding properties because of its chlorine content, even if fire retardants are not added in to it. For example, PVC has 455°C of ignition temperature, and since it has not ignite easily, so the material has far less fire hazard risk. moreover, the released heat from burning of PVC is considerably lower with respect to those for PP and PE. PVC therefore even while burning PVC contributes much less to spreading fire to nearby materials, PVC is very suitable for safety reasons in products close to people's daily lives.

Durability

Under normal conditions of use, the factor most strongly influencing the durability of a material is resistance to oxidation by atmospheric oxygen. PVC,where the chlorine atom is bound to every other carbon chain molecular structure, is high oxidative reactions resistant, and can maintains its efficiency for a long time. Other general purpose plastics with structures made up only of carbon and hydrogen are more susceptible to deterioration by oxidation in extended use conditions (such as, for example, through repeated recycling). Measurements on underground 35 year-old PVC pipes taken by the Japan PVC Pipe & Fittings Association showed no deterioration and the same strength as new pipes. Researchers in Germany (60 Jahre Erfahrungen mit Rohrleitungen aus Weichmachfreiem PVC, 1995, KRV) Pipes buried in soil dug-ed up after 60 years and tested for fitting and life expense showed, it is perfectly fitted and it can effective for net 50 years to use anything. Almost there is no deterioration or degradation was seen upon restore of three types of automobile exterior parts (using flexible PVC products plasticizers) cars after from about 13 years of use and upon compering physical properties with new products. Due to the heat time for thermal decomposition is Getting Shorter and shorter, in history the re-converting process, and by adding stabilizers it can be brought back to the original products. Through re-converting,in fact Recovered products can recycled into the same products, regardless of whether they are automobile parts or pipes. The physical properties of product recovered are the same as the original manufactured product from virgin resin or first produced, from resin in first place and also as good as first produced to use.

Oil/Chemical resistance

PVC has best acid, alkali and almost all inorganic chemicals resistance.PVC Although can swells or dissolves in and cyclic esters, aromatic hydrocarbons, ketones, PVC cn not dissolve in other organic solvents unless there is additional chemical applied. Because of this properties PVC can be used in many applications such for example,sheets used in construction, bottles,exhaust gas ducts,hoses and tubes.

Mechanical stability

PVC material is chemically stable, which shows very little structural change in molecular structure, and also Expresses changes in its mechanical strength. However, long chained polymers are visco-elastic materials, and can be deformed by continuously applying of external force, even if the force applied is much less than their yield point. This phenomena is known as creep deformation. However PVC is a visco-elastic material,but its creep deformation is much lower compared to other plastics due to limited motion molecules at their ordinary temperature, in compering to PP and PE,Their amorphous section have greater molecular motion. Study on European very early pipes of PVC – Manufactured from the 1930s to 1950s – showed characteristics of a excellent durability and service life of 50 year. More recent manufactured (latest) PVC pipes would be expected to have very long lasting durability approximately about 100 years or exceed 100 years.

Processability and mouldability

The process ability of a thermoplastic material are largely affected on its melting viscosity. PVC is not applicable for injection molding of big or huge sized products, because of its high melt viscosity comparatively. On the other hand, the visco-elastic properties of molten PVC is less affected on temperature and also more stable. Therefore, PVC is Applicable for complex shaped extrusion profiling (e.g., Household materials and car accessories), as well as production of wide sheets and films (e.g., agricultural films and PVC leather). The exterior surfaces of PVC display excellent superior embossing performance-giving it to a vast variety of surface treatments with textures ranging from surface rendering to the completely de-lustered suede. as we know PVC is an amorphous plastic with no phase transition, molded PVC products has high dimensional accuracy. PVC also exhibits excellent secondarily, fabrication, welding process-ability in bending , high-frequency bonding, as well as on-site work ability and vacuum forming. Processes only feasible with PVC and very good qualities of PVC paste resin processing are screen printing, coating and slush molding. These mentioned processing methods are most of the time used in undercoating, flooring,automobile sealants and wall covering.

Other properties making PVC versatile

PVC has good element, polar groups (chlorine), and is amorphous, because of that it, mixes effectively with various other substances. Physical properties that required for end products (e.g.,elasticity, flexibility,prevention of microbial growth, impact resistance,fire retarding anti-fouling, anti-mist.) can be freely designed through formulation with plasticizers and various coloring agents, modifiers and additives . PVC is the only multi-purpose plastic that allows wide, free and seamless adjustment of the expected physical properties of products such as elasticity, flexibility, and impact resistance, by adding plasticizers, modifiers and additives. Hence the physical properties of end products are adjustable through compounding with additives, only a little types of resin are expected to cover all applications (rigid and flexible plastic,fiber, rubber, paint and adhesive). This controlability is also extremely beneficial for recycling. The polar groups in PVC contribute to ease of coloring, printing and adhesion. PVC products do not require pre-treatment, which enables a wide variety of designs. PVC is used in many more decorative applications taking full advantage of its superior print-ability, adhesion properties and weather-ability. Patterns such as metallic tones, wood grain and marble are possible outcomes. Familiar examples include wall coverings and flooring's, housing materials, furniture, home electric appliances, or signboards and ads on airplanes, trains, buses and trams. The rest Physical properties of PVC are show in table below 3.4

Table 3.4.: Physical properties of PVC

Property	**Value**	**Conditins & Remarks**
Molecular weight (resin)	140000	cf: K57 PVC 70,000
Relative density	1.42 – 1.48	cf: PE 0.95 – 0.96, GRP 1.4 – 2.1, CI 7.2, Clay 1.8 – 2.6
Water absorption	0.0012	23^0C, 24 hours cf: AC 18 – 20% AS1711
Hardness	80	Shore D Durometer, Brinell 15, Rockwell R 114, cf: PE Shore D 60
Impact strength – 20°C	20 $\frac{KJ}{m^2}$	Charpy 250 µm notch tip radius
Impact strength – 0°C	8 $\frac{KJ}{m^2}$	Charpy 250 µm notch tip radius
Coefficient of friction	0.4	PVC to PVC cf: PE 0.25, PA 0.3

4. Technical Design

4.1. Introduction

4.1.1. Wind Turbine Blade Material

The complexity of external loads on rotor blades lies in the fact that these loads cannot be adequately modeled. Building a wind turbine blade is not simple a task, however, it requires accomplishing certain benchmarks. Wind turbine blade materials need to have a strict property requirement of high stiffness, low weight, and long fatigue life. [25][4][12]

- High modulus of rigidity – to maintain optimal aerodynamic performance
- Low density – to reduce gravitational forces,
- Long-fatigue life – to reduce material failure.

4.2. PVC (Polyvinyl chloride)

4.2.1. Introduction

PVC is the most wide range applied member of the vinyl family. from various most commonly it is used in fittings and pipe. PVC has its special characters such as excellent corrosion and weather resistance. It has a high weight to strength ratio and is a good thermal and electrical and insulator. PVC is also self-extinguishing per UL flammability tests. PVC may be used to temperatures of $140F$ ($60C$) and is readily available in sheets, rods, and tubing. PVC may be cemented, welded, machined, bent and shaped readily.

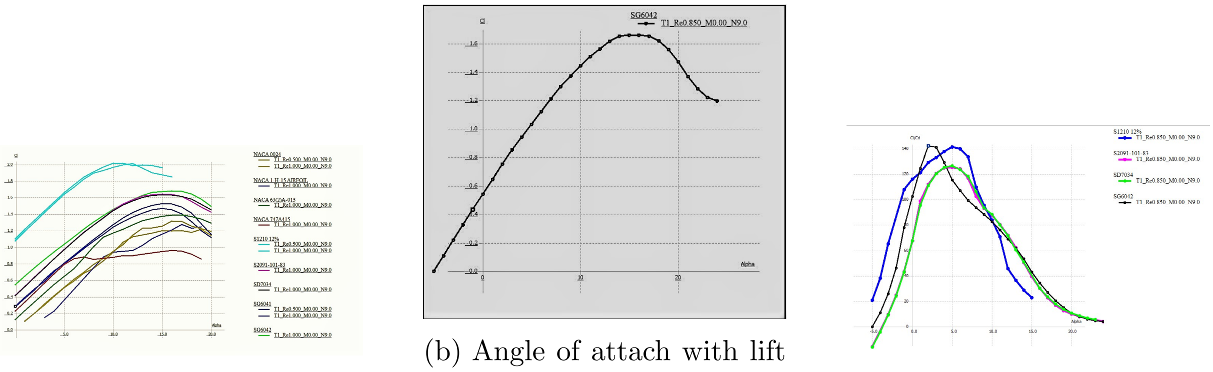
4.2.2. Choosing Best Aero-foil for the design

Thus, wind turbine thrust and power depend upon the lift and drag coefficients, C_l and C_d respectively, of the airfoils sections that comprise each blade. For a great many airfoils, these coefficients are known from wind tunnel investigations, and, at least in principle, can be used immediately for power and thrust calculations. From available and tested airfoils we choose for small wind turbine blade with the help of Q-blade software `http://q-blade.org`

From the Q blade analysis we choose the best airfoil with the respect of Glids ratio which means the largest ratio of C_d to C_l.

For selection of the lift coefficient and designing angle of attach the ratio of must be minimum.

From above polar data from Q-Blade analysis of airfoil the minimum is**0.006811** .
Corresponding lift coefficient (C_l) , drag coefficient (C_d) and angle of attach (α) are;
The chosen aero-foil from above analysis is; $SG6042$



(a) Lift with angle of attach for differentiated airfoils

(b) Angle of attach with lift ratio of airfoil SG6042 generated from Q blade

(c) Glide ratio of three different airfoils

Figure 4.1.: Criteria for Choosing Best Airfoil

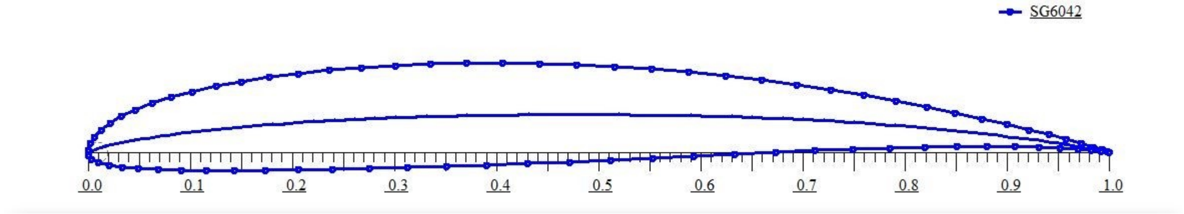


Figure 4.2.: Airfoil of SG6042

$$C_l = 0.748$$
$$C_l = 0.0051$$
$$\alpha = 2^0$$

4.2.3. Typical blade designs

The design of a wind turbine blade is a compromise between structural and aerodynamic considerations. Aerodynamic aspects usually overcome the structural aspects, the design of the outer two out of three of the blade while structural aspects considerations are more important for the design of the inner one-third of the blade. Structurally the blade is most of the time hollow with the outer geometry formed by two shells: one on the suction side and one on the pressure side. One or more structural webs are fitted to join the two shells together and to transfer shear loads.

4.2.4. State-of-the-art rotor design

Many design and simulation software's and tools have been developed for estimation of wind turbine rotor flow. They range from the very simple models, such as the Blade Element Momentum (B EM) method, requiring low computational means, to the very advanced models, such as three-dimensional Computational Fluid Dynamics (CF D) which resolves the boundary layers on the rotor and the domain several blade diameters downstream and upstream of the rotor plane, thus demanding high computational means. However, despite the fast growing and updating of computer power, using the very upgraded models to produce estimation to inform the optimization process is, even now in 2019, still rather Not effective regarding to time; these methods should therefore be considered as tools for evaluating the turbine blade design, rather than as part of the inherently iterative turbine blade design process.

4.2.5. The blade element momentum (BEM) method

The B EM method was developed in the 1930*s*, and since then other, but not very different, formulations have been developed. In what follows, the B EM method will be Explained, starting with a simplest and easy model which assumes that the Flow through the blade acts the same way at all points which makes the problem one-dimensional. Furthermore, the assumption in the one-dimensional problem is that the rotor has no losses such as friction caused by the air viscosity and no losses caused by the Flow at the tips.[26][27] The description of the simplified one-dimensional model is followed by a description of the more advanced B EM model, which uses the one-dimensional model in each annular element and also takes these types of losses into account.

4.2.6. Blade element momentum theory

Even now the Flow through a wind turbine blade is very complex because of the vortex of tip and root. and also the mutual interaction of the wind Flows between the rotor blades, it is possible to simplify the drive mechanisms in a very effective way. As shown in Figure (4.3), the blade can be divided into annular elements of differentiated width, dr. Because the theory that will be derived in this section is based on the one-dimensional momentum theory, it must be assumed that there is no interaction between surrounding elements, something says which one-dimensional Blade element momentum theory can show to be a good assumption. Also, it must be assumed that the axial and tangential velocity are uniformly distributed all over the annular element. This means that the forces are not concentrated on the blades, but are smeared out over the annular element.[26][27]

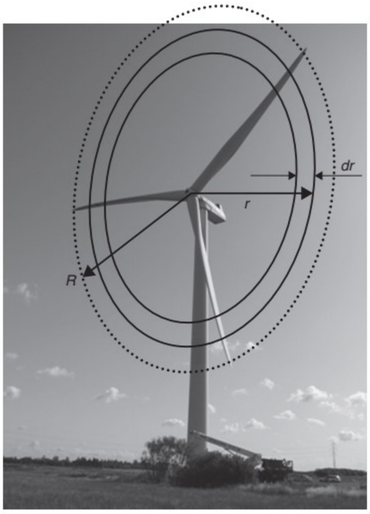


Figure 4.3.: Differential radius of blade
[28]

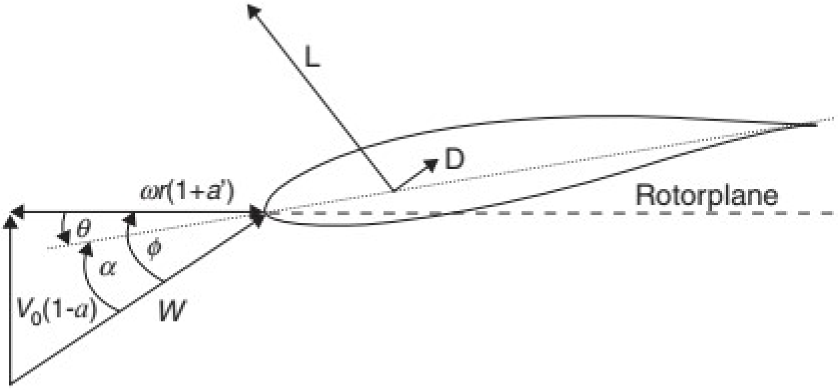


Figure 4.4.: Sketch of the division of a wind turbine rotor into annular elements. [29]

Table 4.1.: Suggested blade number, B, for different tip speed ratios, λ

Tip speed ratio(λ)	No of Blade (B)
1	8-24
2	6-12
3	3-6
4	3-4
4	1-3

Figure above 4.4 . shows a section on the rotor blade under considerations the symbols used in the Blade Element Momentum Developments. The blade section is Left open to the axial velocity (wind speed) V_0 and the tangential velocity (eigen velocity) $r\omega$. Because of the forces from the rotor on wind where the total induced velocity is parallel to the lift force but in the opposite direction. the axial velocity is reduced to $(1 - a)$, V_0 and the tangential velocity is increased to $(1 + a')$. the resulting velocity that the blade section experiences, the (relative speed), W, is the vector sum of the axial and tangential velocity. The angle from W to the rotor plane is called the inflow angle, φ. [26][30]
The blade section is in general twisted, θ, positive in an anticlockwise direction. The twist is defined as the angle from the rotor plane to the airfoil chord line, which is from the very leading edge of the airfoil to the very trailing edge of the airfoil. The angle from the relative velocity, W, to the chord line is called the angle of attack, α. [26] First, a design tip speed ratio,λ , the desired number of blades, B, the radius, R, and an airfoil with known lift and drag coefficients as a function of angle of attack is chosen.

According to the type of application, choose a tip speed ratio, l. For a water-pumping windmill, for which greater torque is needed, use $1 < l < 3$. For electrical power generation, use $4 < l < 10$. The higher speed machines use less material in the blades and have smaller gearboxes and small direct drive wind turbines.[12][15]

- **For the design tip speed ratio, I choose, λ_D=7**

The next step is finding design wind speed for this thesis; my goal is to generate power from low wind speed which we can get average part of Ethiopia. To find the mean wind speed we have to extrapolate to design height. Above the wind map of Ethiopia in $50m$

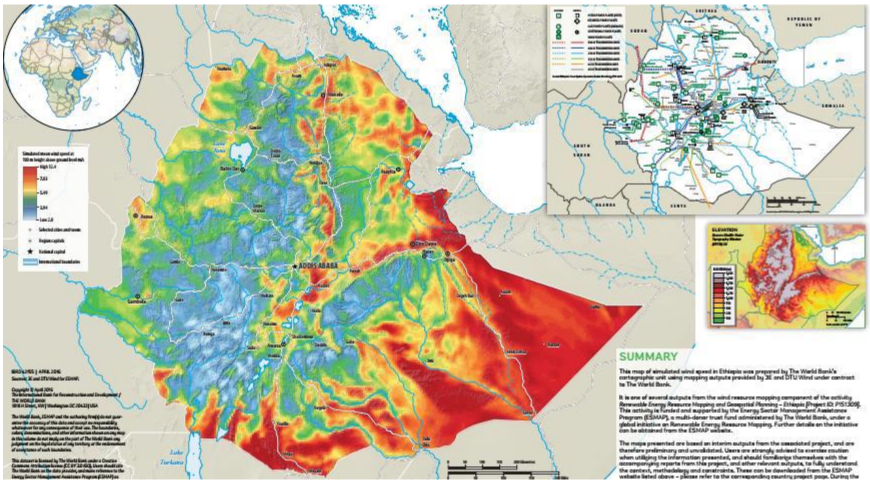


Figure 4.5.: wind map of Ethiopia in $50m$ height.
[31]

height. Figure 4.5
I wanted to design with the hub height of 10 m. so the formula for extrapolation we use Equation; (4.1)

$$V = \frac{V_{ref} ln\frac{z}{z_0}}{ln\frac{z_{ref}}{z_0}} \tag{4.1}$$

Where;

- V_{ref} Reference wind velocity at height Z_{ref}.
- Z Height above ground for desired velocity V.
- Z_0 Surface Roughness.
- Z_{ref} Reference height, i.e. the height where exact velocity (V_{ref}) found.
- V Wind velocity at height Z meter above the ground.

From above wind map of Ethiopia, the average wind speed which we can get average part of Ethiopia at height of 50 m is 8 m/s. Extrapolating to 10 m height using above formula we get wind speed of $5.48m/s \approx 5.5m/s$.

Table 4.2.: Design parameters

T.S.R(λ)	Rated wind speed(V) in m/s	N.O.B (B)	Design (C_l)	Design (C_D)	Design A.O.A (α)
7	10	3	0.7488	0.0051	2°

The next step is calculating for the rotor radius (wind turbine blade radius); Based on the sketch in Figure 4.4, the following relations can be derived, Equations;

$$\alpha = \phi - \theta_p \tag{4.2}$$

$$tan\phi = \frac{(1-a)V}{(1+a')r\omega} \Leftrightarrow \phi = arctan(\frac{(1-a)V}{(1+a')r\omega}) \tag{4.3}$$

From the principles of wing section theory, see, e.g. Abbot and Doenhoff,20 the lift and drag forces per length on each blade section, respectively, can be expressed in terms of respectively lift and drag coefficients as Equation; (4.4) and (4.5)

$$l = \frac{1}{2}(\rho \times c \times W^2 \times C_l) \tag{4.4}$$

$$D = \frac{1}{2}(\rho \times c \times W^2 \times C_D) \tag{4.5}$$

First, we have to find the cord (c);
Here, c is the chord length and and are the lift C_l andC_D drag coefficients per meter, respectively.[10][12]

$$dT = \frac{1}{2}(\rho \times c \times W^2 \times c_y \times d_r) \tag{4.6}$$

$$dQ = \frac{1}{2}(\rho \times c \times W^2 \times c_x \times rd_r) \tag{4.7}$$

Here, the force coefficients normal to the rotor plane, c_y, and parallel to the rotor plane, c_x, have been used.

$$c_y = c_l \times cos\phi + c_d \times sin\phi \tag{4.8}$$

$$c_x = c_l \times sin\phi - c_d \times cos\phi \tag{4.9}$$

To sum up the forces from the blade elements with the results from the blade element momentum theory, the response from the tangential forces must be taken into consideration. Therefore, the one-dimensional theory, described in the previous section, where the wake rotation is not part of the theory, must be extended with a rotational part reflecting the momentum in tangential direction. Furthermore, a correction for a finite number of blades will be included as shown in Equations (4.6) and (4.7)

$$dT = \frac{1}{2}\rho \times V^2 \times 4F_a(1-a) \times 2\Pi \times rd_r \tag{4.10}$$

$$dQ = \frac{1}{2}\rho \times V_0^2 \times 4F(1-a)a'\frac{\omega r}{V_0} \times r2\Pi \times rd_r \tag{4.11}$$

Here u_t is the tangential velocity caused by the wake rotation in the far wake, a' is the tangential induction factor and F is the Prandtl correction for a finite number of blades described by Equation (4.12) in.[28][26]

$$F = \frac{2}{\phi}arccose(e^f)withf = \frac{B}{2}\frac{R-r}{rsine\phi} \tag{4.12}$$

B EM theory or strip theory refers to the determination of wind turbine blade performance by combining the equations of momentum theory and blade element theory.[12]

$$\frac{C_l Bc}{4\phi r} = tan\phi sin\phi \tag{4.13}$$

which relates a, a', and based on geometrical considerations, can be used to solve for the blade shape. with $a'= 0$ and $a=1/3$.

$$tan\phi = \frac{2}{3\lambda_r} \Rightarrow \phi = tan^{-1}(\frac{2}{3\lambda_r}) \tag{4.14}$$

$$c = \frac{8\Pi r sin\varphi}{3BC_l\lambda_r} \tag{4.15}$$

From blade element theory;

$$\sigma^{'} = \frac{Bc}{2\pi r} \tag{4.16}$$

In the calculation of induction factors, a and a', accepted practice is to set C_d equal to zero (see Glauert) [28]. For airfoils with low drag coefficients, this simplification introduces negligible errors. So, when the torque equations from momentum and blade element theory are equated;

$$\frac{a'}{1-a} = \frac{\sigma^{'} C_l}{4\lambda_r \sin\varphi} \tag{4.17}$$

$$C_l = \frac{4\sin\varphi}{\sigma^{'}}(\frac{\cos\varphi - \lambda_r \sin\varphi}{\sin\varphi + \lambda_r \cos\varphi}) \tag{4.18}$$

Solving for the induction factors from above equations (4.17) and (4.18)

$$a = \frac{1}{\frac{1+4\sin^2\varphi}{\sigma^{'} C_l \cos\phi}} \tag{4.19}$$

$$a^{'} = \frac{1}{\frac{4\cos\varphi}{\sigma^{'} C_l} - 1} \tag{4.20}$$

4.2.7. Blade Element Momentum Theory for Induction Factors

The above formulation of thrust and torque for an annular blade element, Equations (4.6) and (4.7), can now be used in combination with the extended momentum theory, Equations (4.10) and (4.11). The result can be written as:

solution methods will be proposed using these equations to determine the flow conditions and forces at each blade section. The first one uses the measured airfoil characteristics and the B EM equations to solve directly for C_l and a. This method can be solved numerically, but it also lends itself to a graphical solution that clearly shows the flow conditions at the blade and the existence of multiple solutions. The second solution is an iterative numerical approach that is most easily extended for flow conditions with large axial induction factors.

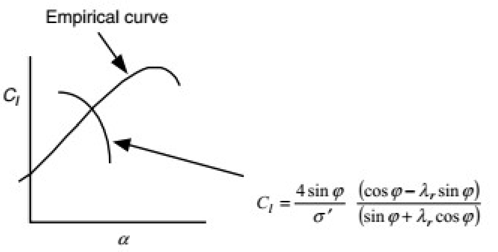


Figure 4.6.: Angle of attack cl and induction factor graphical solution method. [3]

Method 1 – Solving for C_l and α

Since $\varphi = \alpha + \Theta_p$, for a given blade geometry and operating conditions, there are two unknowns in Equation (4.18), C_l and α at each section. In order to find these values, one can use the empirical C_l V_s α curve for the chosen airfoil. One then finds the C_l and α from the empirical data that satisfy Equation (4.18). This can be done either numerically or graphically as shown in Figure 4.6. Once C_l and α have been found,a and a' can be determined from any two of Equations (4.19) and (4.20). It should be verified that the axial induction factor at the intersection point of the curves is less than 0.5 to ensure that the result is valid. [12]

Method 2 – Iterative Solution for a and a'

Another equivalent solution method starts with guesses for a and a', from which Flow conditions and new induction factors are calculated. Specifically:

1. Guess values of a and a'.
2. Calculate the angle of the relative wind from Equation (4.3).
3. Calculate the angle of attack from Equation (4.2) and then C_l and C_d.
4. Update a and a' from Equations (4.19) and (4.20).

The process is then repeated until the newly calculated induction factors are within some acceptable tolerance of the previous ones. [12]
From above two methods i choose the second which is iterative way of finding for this method i choose the software **mat lab** which used for several things in engineering one of its purpose is for iterative optimization. the code uses the following inputs;

1. c_1 = undisturbed wind speed [m/s]
2. c_2 = wind speed at the wind turbine [m/s]
3. w = relative wind speed [m/s]
4. u = blade peripheral speed [m/s]
5. ω = rotational speed [rad/s]
6. a = induction factor

7. l= chord in each section [m]
8. r = radial coordinate (distance between the axis of rotation and the blade section) [m]
9. R_e = Reynolds number
10. M_a = Mach number
11. C_l = Lift coefficient
12. C_d = Drag coefficient
13. γ = pitch angle: angle between the chord and the undisturbed wind speed direction [deg]
14. α = angle of attack: angle between the chord and the relative wind speed direction on the profile [deg]
15. β = relative angle: angle between the relative wind speed and the undisturbed wind speed directions [deg]

The above inputs uses the following geometry in figure (4.7) below;

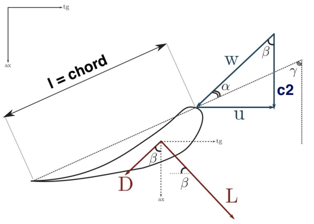


Figure 4.7.: Airfoil geometry of the calculation
[3]

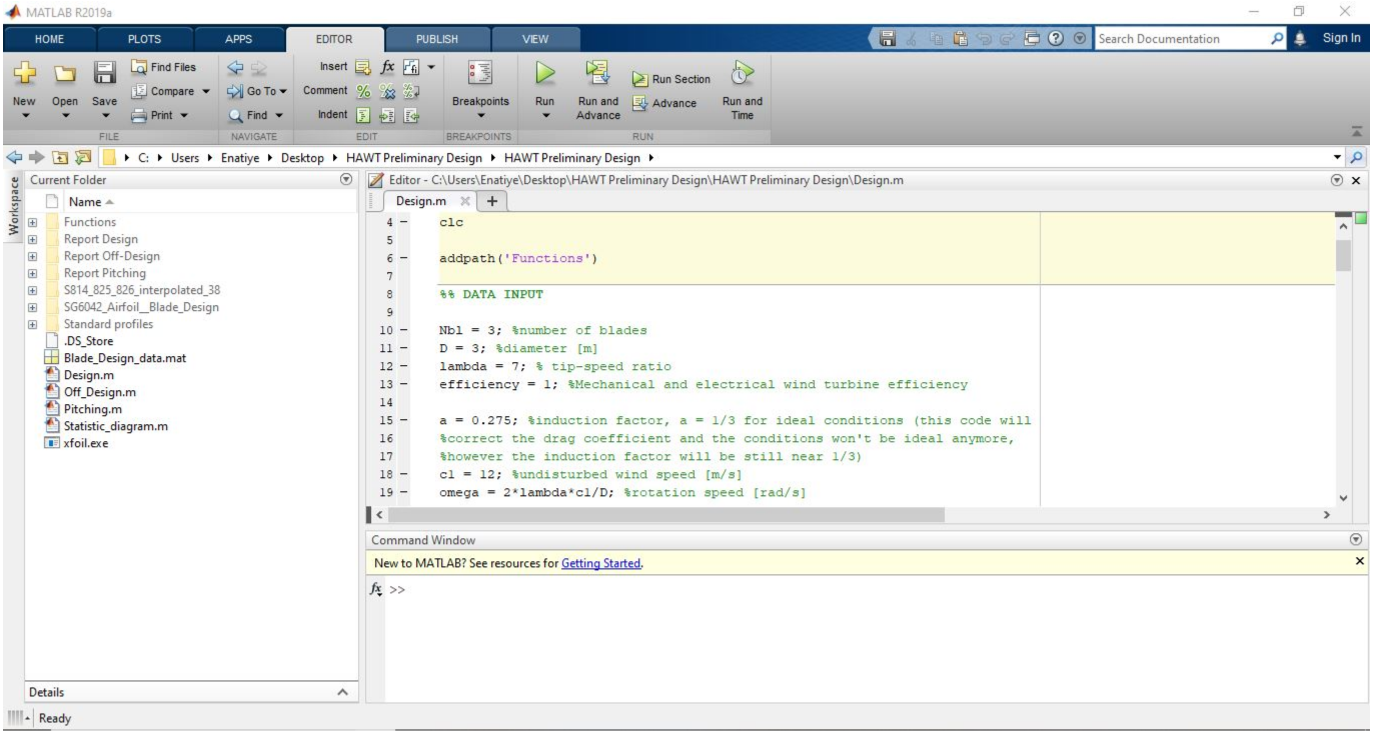
Using the equation from (4.3) to (4.20) , and finally writing mat-lab code to iterate the induction factor and also chord distribution to angle of attach, lift and drag coefficient to differential radius.

4.3. Input parameters

Table 4.3.: Input variables for the Matlab code

Input parameters	Values
Rated wind speed	10 m/s
Tip speed ratio (λ_D)	7
Chord distribution (c)	0.179-0.042
angle of attach starting and end (α)	$-10^{0} to 20^{0}$
Number of blade (B)	3
Blade diameter (D)	$3m$

Matlab code layout



```
clc

addpath('Functions')

%% DATA INPUT

Nbl = 3; %number of blades
D = 3; %diameter [m]
lambda = 7; % tip-speed ratio
efficiency = 1; %Mechanical and electrical wind turbine efficiency

a = 0.275; %induction factor, a = 1/3 for ideal conditions (this code will
%correct the drag coefficient and the conditions won't be ideal anymore,
%however the induction factor will be still near 1/3)
cl = 12; %undisturbed wind speed [m/s]
omega = 2*lambda*cl/D; %rotation speed [rad/s]
```

New to MATLAB? See resources for Getting Started.

```
>>
```

Figure 4.8.: Matlab code folder layout
[32]

After Editing and Rewriting Matlab code Written by Oboe Daniele, Marinoni Andrea, Mastrandrea Sabino,[32] see Matlab code in Appendix (B.2) and substituting the input parameters in above Table (4.3) and running Matlab code and the output from the code is;

Angle of attack with cord distribution

In the figure (4.9) below shows the relationship between angle of attack (α) and chord (c) distribution and it is evenly distributed which means the angle of attack increases from root to tip of the blade radius.

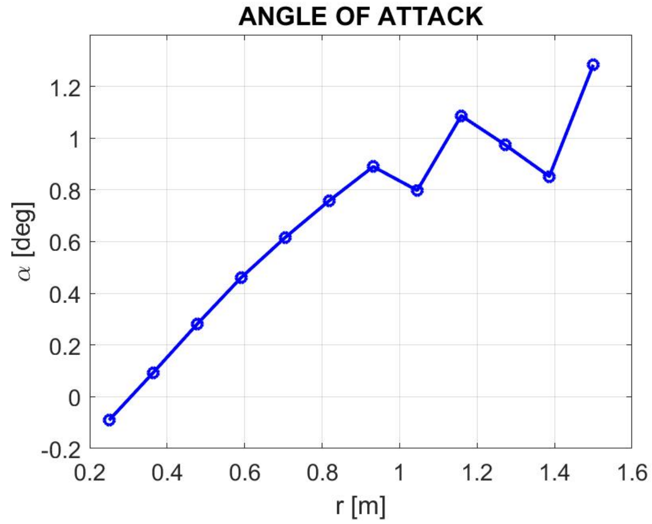


Figure 4.9.: Relationship between Angle of attach with chord

Chord distribution through Blade radius (c)

Chord distribution calculation is core design parameter in blade design, assuming woke rotation is the best way of wind turbine design and in the Figure (4.10) below shows the chord distribution through the blade radius from hub to tip.

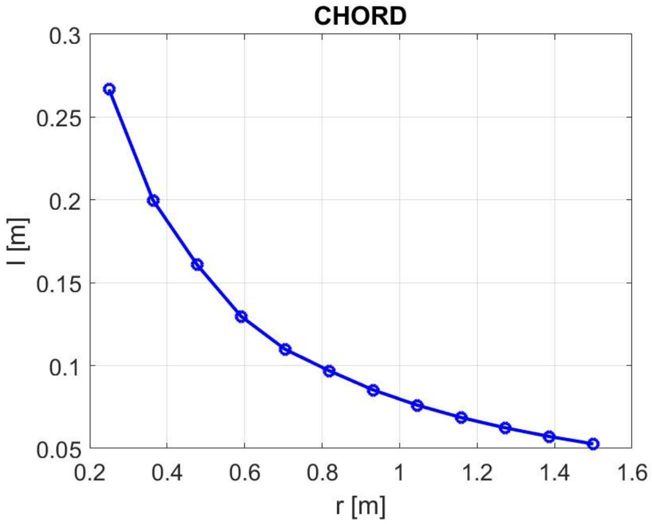


Figure 4.10.: Chord distribution from hub to tip

Lift (C_l), Drag (C_d) and Glid-ratio ($\frac{C_l}{C_d}$) Through Blade length

Lift, drag and Glid ratio of the blade are basic parameters for wind turbine design and in Figure (4.11) below shows the relationship between Lift C_l through the blade length, Drag C_d through the blade length and Glid-ration $\frac{C_l}{C_d}$ through the blade length.

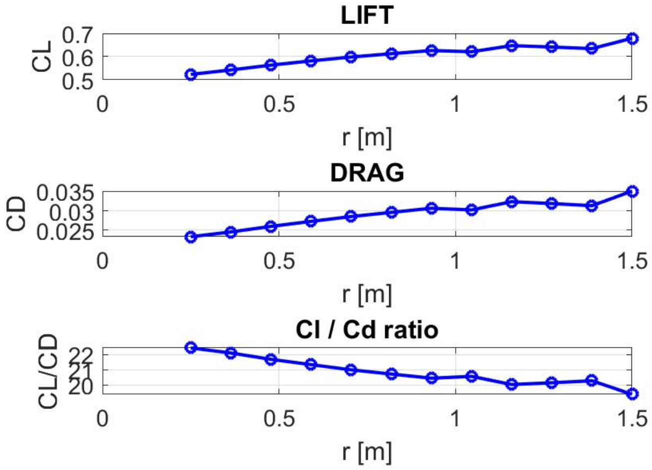


Figure 4.11.: Lift , Drag and Glid-ratio Through Blade length

Induction factor through the blade length

When we assuming wake rotation and recalling Betz-limit that the power in wind can't change totally or (100^{0}_{0}) to usable energy in our case to electrical energy which means there is difference between input wind and wind far from the turbine this difference will be explained by induction factor. In Figure (4.12) below shows the induction factor from hub to tip of the blade.

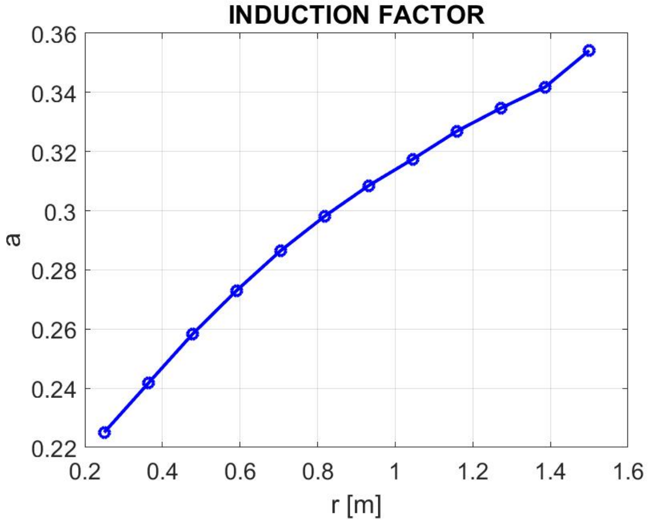


Figure 4.12.: Induction factor (a) from hub to tip

Airfoil Profiles with Twist angle

The twist in blade is for better energy production very useful for that purpose modern wind turbines are designed with twist angles in the Figure (4.13) below shows twist angle of blade through the length of designed blade.

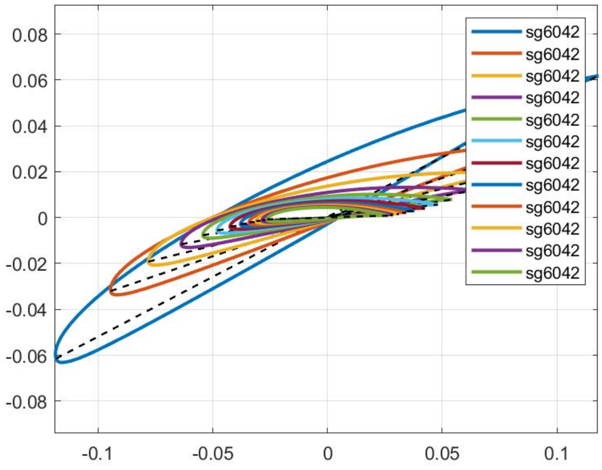
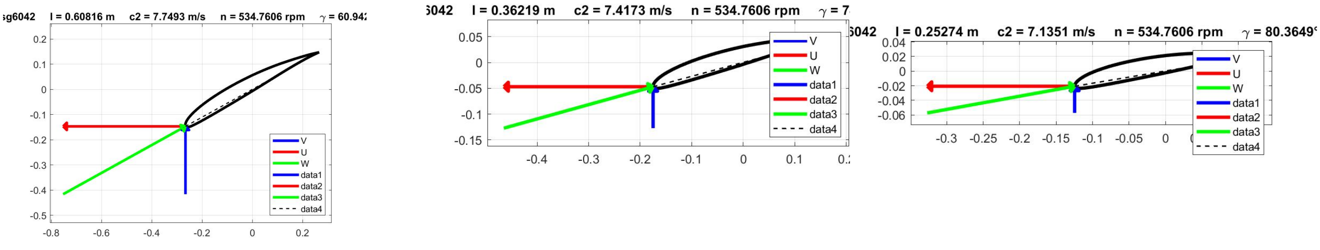


Figure 4.13.: Profiles with Twist angle

Velocity Tingle in different position of the Differential blade length

Position of incoming wind speed and direction of resultant velocity in differential length of blade shows how wind contacts with blade profile in different section of blade, in the Figure (4.14) blow shows the velocity vectors.



(a) Velocity triangle ($R = 0.25m$)

(b) Velocity triangle (R=0.40455 m)

(c) Velocity triangle (R=0.70455 m)

Figure 4.14.: Velocity Triangle at different position of Blade

3D Blade Geometry from Matlab code and Edited by Q-Blade software

After 15 iteration using above all analysis from Figure (4.9) to Figure (4.14) Matlab code constructed 3D blade geometry show in Figure (4.15a) below and adding circular foil in beginning of the blade using Q-Blade final Designed blades are look like in the Figure (4.15b) Below.

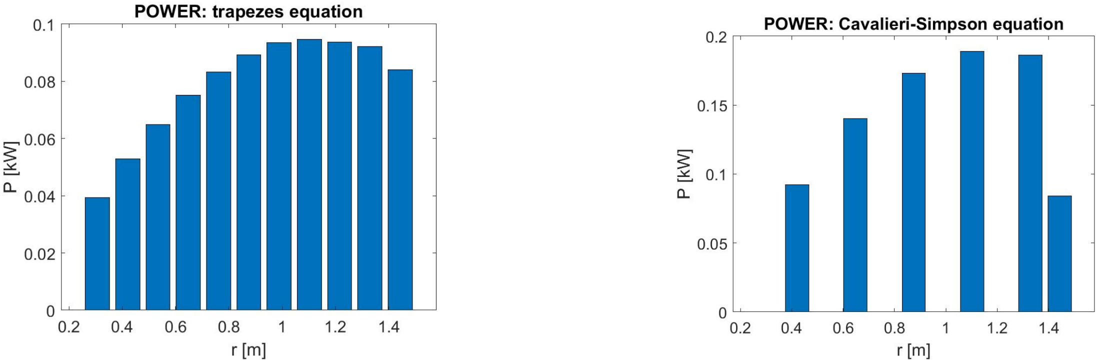
(a) 3D Blade Generated from Matlab

(b) 3D Blade Generated using Q-Blade

Figure 4.15.: Final Blade Designed

Power Output from Matlab code

1. Power from trapezes Equation shown in Figure (4.16a) below.
2. Power from Cavaliers Simpson Equation shown in Figure (4.16b) below.



(a) Power from trapezes Equation

(b) Power from Cavaliers Simpson Equation

Figure 4.16.: Power Output from Matlab code

4.4. Structural design

4.5. General

The integrity of the load-carrying components of the wind turbine structure shall be verified and an acceptable safety level shall be ascertained. The ultimate and fatigue strength of structural members shall be verified by calculations and/or tests to demonstrate the structural integrity of a wind turbine with the appropriate safety level.

The structural analysis shall be based on ISO 2394.According to [14] Calculations shall be performed using appropriate methods. Descriptions of the calculation methods shall be provided in the design documentation. The descriptions shall include evidence of the validity of the calculation methods or references to suitable verification studies. The load level in any test for strength verification shall correspond with the safety factors appropriate for the characteristic loads according to 7.6.

4.6. Design methodology

It shall be verified that limit states are not exceeded for the wind turbine design. Model testing and prototype tests may also be used as a substitute for calculation to verify the structural design, as specified in ISO 2394.

4.7. Loads

4.7.1. Gravitational and inertial loads

Gravitational and inertial loads are static and dynamic loads that result from gravity, vibration, rotation and seismic activity.

4.7.2. Aerodynamic loads

Aerodynamic loads are static and dynamic loads that are caused by the airflow and its interaction with the stationary and moving parts of wind turbines.

The airflow is dependent upon the average wind speed and turbulence across the rotor plane, the rotational speed of the rotor, the density of the air, and the aerodynamic shapes of the wind turbine components and their interactive effects, including aero-elastic effects.

4.8. Stationary Blade Loading

4.8.1. Lift and drag coefficients

Maximum blade loading's are in the out-of-plane direction and occur when the wind direction is either approximately normal to the blade, giving maximum drag, or at an angle of between 128 and 168 to the plane of the blade when the angle of attack is such as to give maximum lift. values for lift and drag coefficients are given in Table (4.2).

4.8.2. Dynamic response

Tip displacement

Wind fluctuations at frequencies close to the first flap-wise mode blade natural frequency excite resonant blade oscillations and result in additional, inertial loading's over and above the quasi-static loads that would be experienced by a completely rigid blade. As the oscillatory motion result from unstable of the wind speed about the average value, the standard deviation of resonant tip displacement can be explained in terms of the wind Unstable intensity and the normalized power spectral density at the resonant frequency,

5. Development (Manufacturing) and Field Testing

5.1. Manufacturing of Wind Turbine Blade

Manufacturing of wind turbine blade is one of the most sophisticated processes and it was very struggling, after so many trial and flair finally we manufactured the blade but it was not perfect, manufacturing of blade from polyvinyl chloride is much harder than we thought but we manage to do it, and finally it was very satisfying and when we manufacturing Blade there are things any one who want to manufacture wind turbine blade should consider.

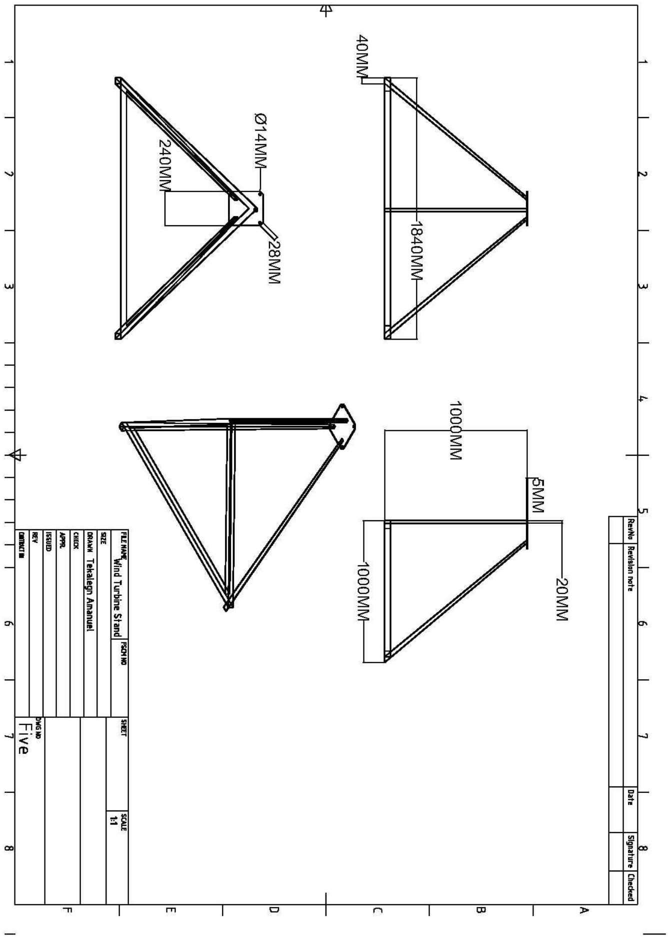
1. Length of turbine blade (Radius of blade)
2. Number of blade
3. Airfoil profile
4. Wind angle
5. Twist angle from base to tip
6. Chord length, and chord to length ratio
7. Thickness of the blade

From considering above mentioned points we manufactured blade shown in Figure 5.1below.

Figure 5.1.: Manufactured blade

5.2. Manufacturing of Frame (stands of turbine)

The frame of wind turbine blade was manufactured from steel (Carbon steel grade $40C8$). And by welding the rectangular hollow steel with the spec mentioned above the frame was built like in figure below. the dimension are set considering the length of the blade and the stability of the whole wind turbine. manufactured frame is shown in the figure 5.2b below



(a) Wind Turbine Stand Designed

(b) Manufactured Frame

5.3. Manufactured and assembled three small generators

5.3.1. Generator

Generator is a device or a machine which converts mechanical energy or rotation to electrical energy and, mine is winded generator, it is type of generator which produces electric energy from electromagnetic force and commonly used in diesel generators. is shown in figure below After manufacturing frame for the three generators i put three small generators in 120o spacing by welding them and connecting them with spur gear from blade shaft the look like this in the figure 5.4 below.

After Assembling three small generators, then i fastened with the frame like shown in figure 5.5 below.Finally assembling turbine blade was look like this in figure 5.6b below.

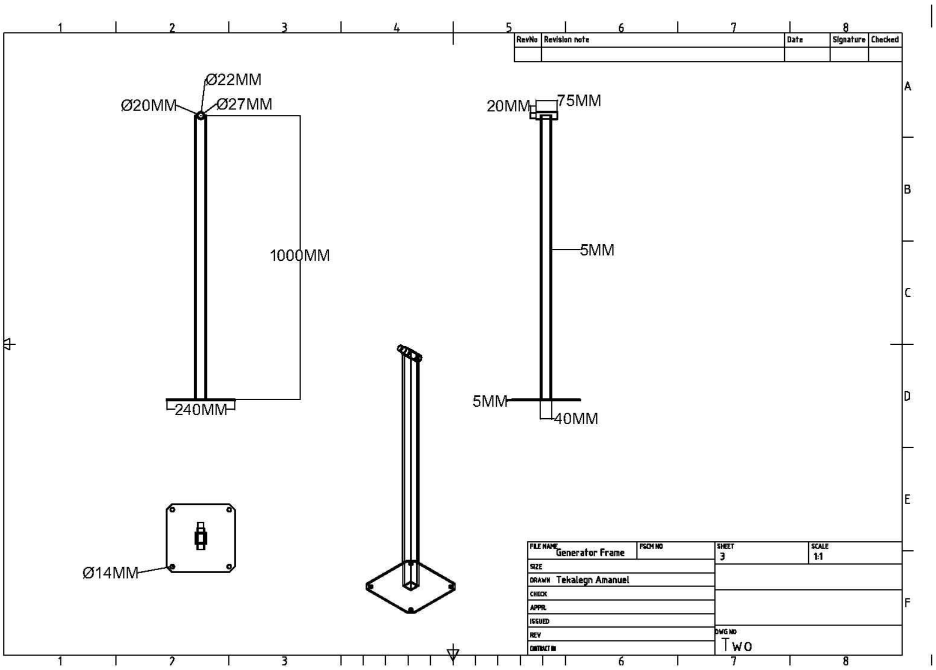


Figure 5.3.: Generator Frame

(a) left side

(b) Right side

(c) Front

Figure 5.4.: Assembled Three small generators

Figure 5.5.: Three small generators assembled with Frame

(a) Final Assembled Auto cad Design

(b) Final assembled with blade

Figure 5.6.: Final assembled generator with blade

5.4. Measuring Devices

Measuring instruments (devices) used for field tests are:

1. Multi meter
2. clamp meter
3. Anemometer
4. Taco meter

This above mentioned instruments are direct measuring instruments for voltage; AC or DC and clamp meter is as its name clamping the wire and measuring current flow through the wire clumped. Anemometer is used for measuring wind speed. pictures of the instruments are shown in figure 5.7 below.

(a) Multi meter (b) Clump meter (c) Environmental meter

Figure 5.7.: Measuring instruments(Devices)

5.5. Experiment Conducted

After assembling the hole parts taking out to AAiT space science society building terass, the result of experiments are set in table 5.1 below.

Table 5.1.: Experiment Results

Counts of experments	Wind Speed	Voltage From Design	Voltage From Experment	Current	Ex. Power
1	3 m/s	150V	130 V	3.5A	455W
2	3.6m/s	160	140V	4A	560W
3	3.94 m/s	130V	110V	4A	440W
4	5.9 m/s	210	130V	4A	520W
5	6.5 m/s	250V	200V	4A	800W
6	5.6 m/s	200V	130V	3.4A	442W
7	3.45 m/s	150V	100V	3A	300W
8	2 m/s	100V	90V	3A	270W
9	5.5 m/s	190V	140V	3.2A	448W
10	5.4 m/s	180V	170V	4.3A	730W
11	4.9 m/s	150V	140V	4A	560W
12	4.77 m/s	150V	110V	3.4A	374W
13	6.5 m/s	260V	130V	3.2A	416W
14	4.3 m/s	150V	140V	3.2A	448W
15	5.31 m/s	180V	100V	3.2A	320W
16	3.4 m/s	130V	110V	3.1A	341W
17	4.3 m/s	140V	110V	3.1A	341W
18	4.1 m/s	150V	120V	3.1A	372W
19	6.36 m/s	260V	160V	4A	640W
20	5.6 m/s	250V	180V	4A	720W

The above experiments are taken with in two weeks of times from 1:00Pm to 11:30Pm, when wind fluctuation very high and low to consider wind fluctuation. as shown in table above the power is measured from each generators which means the total power is the summation of three. which is maximum is $800W$ multiply by 3 equal to $2.4KW$, and minimum of $270W$ multiply 3 which is $810W$. The above power output shows as that the experiments are done and the output is satisfyingly good.

6. Conclusion and Recommendation

6.1. Conclusion

Following the mathematical model developed by different authors as a guidance a, mathematical model was developed for this study. For rural and remote part of Ethiopia electrical application, the design of $3KW$ power output the modeling methodology was presented with momentum equation, Blade element moment equation and energy equation. MATLAB software is used to obtain the solution of the model developed, from the output of Matlab code and Mathematical model, wind turbine blade is designed and manufactured,The rest of Structure is designed and manufactured according to mechanical design. Solid Work-2019 and Auto-cad 2020 is used for geometrical modeling of the development. The experiment is conducted from manufactured Three small generator operated direct drive wind turbine placed in AAiT Science society building Top, by setting up materials like, Multi meter, Clump meter, and Anemometer. Following the result from the experiment conducted the following conclusion are drawn.

- Because of low PVC weight, turbine can rotate with low wind speed specifically with wind speed of 5.5 to 6.5m/s.
- Due to PVC pre-made Shape, making Twist angle for better wind harness was quite promising.
- The designed blade is more effective after first rotation, after first rotation blade can rotate for 5 seconds with same RPM even wind speed is dropping because of light weight and best twist angle.
- After Rated wind speed achieved Turbine works perfectly and generates designed power output.
- The experimental data and simulated data collected has a similarities and variation throughout, the variation is a result of fluctuation of the wind in test site.
- The designed Wind turbine generates 2.4 KW energy at rated wind speed and above.

6.2. Recommendation

In the future, in order to increase the efficiency of Three small generator operated direct drive wind turbine the following basic recommendation are made

1. For better wind harness, the yaw mechanism can added and can increase wind contact area.
2. Break system is main component of wind turbine and for the future work, the life expectense can be increase when break system applied.

3. PVC can be molded, for better airfoil shape, molding can increase the efficiency of the turbine Blade.
4. Finally Wind Generators are replaceable and if efficient generators applied power out put can increase and by reducing RPM can generate more power with less win speed.

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Appendices

A.1. Design Detail Drawing

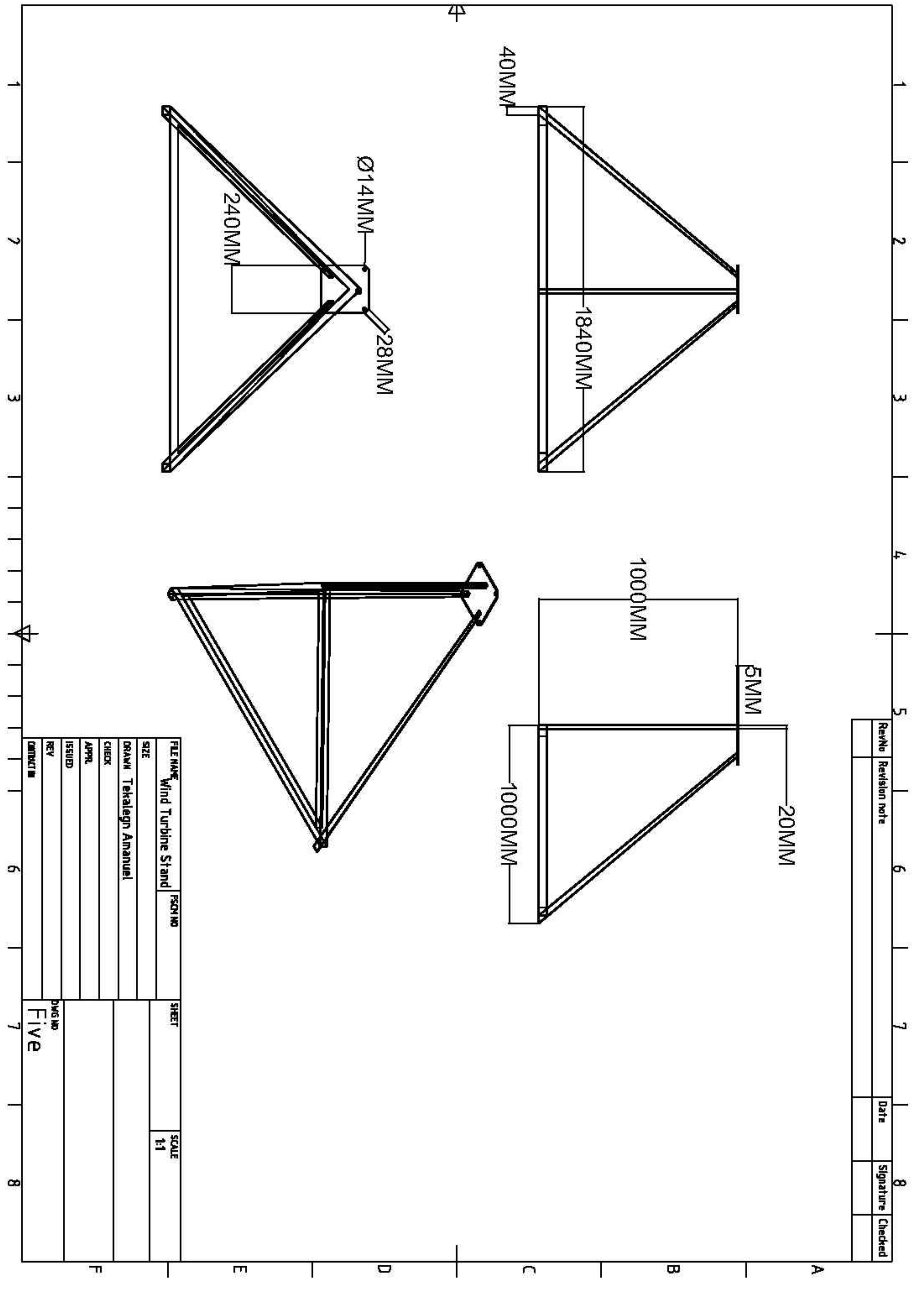

Figure .1.: Wind Turbine Stand

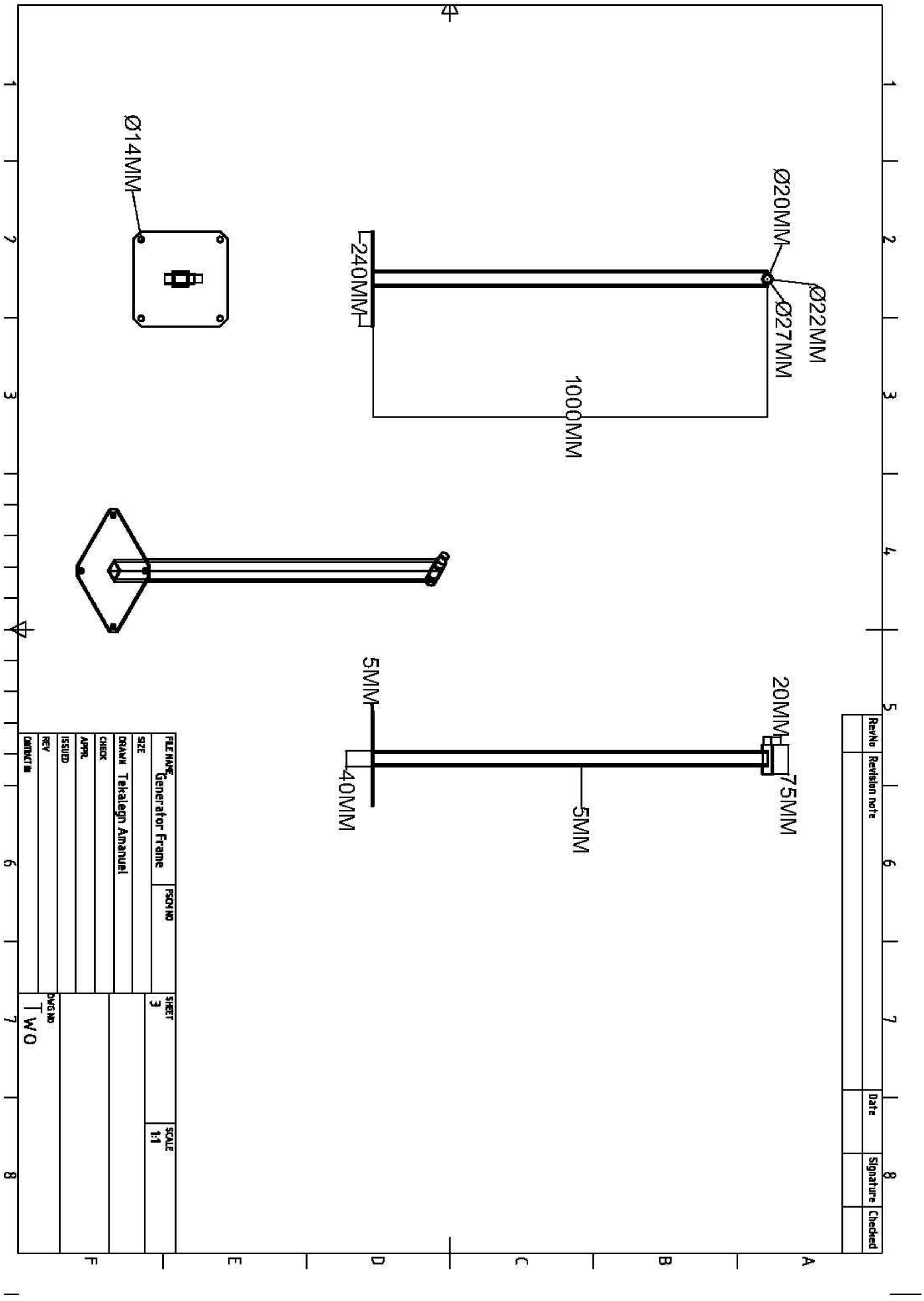

Figure .2.: Generator Frame

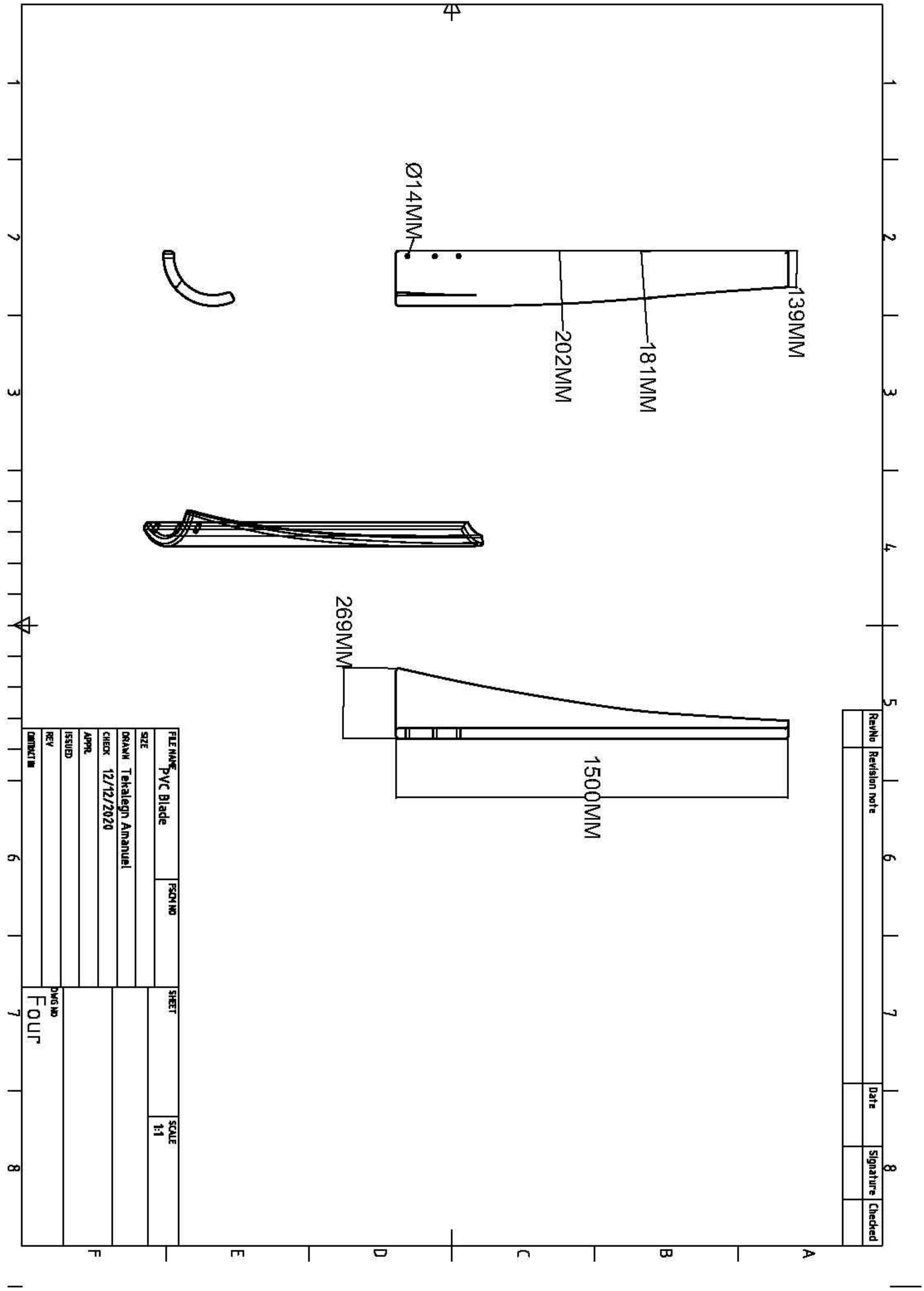

Figure .3.: PVC Blade

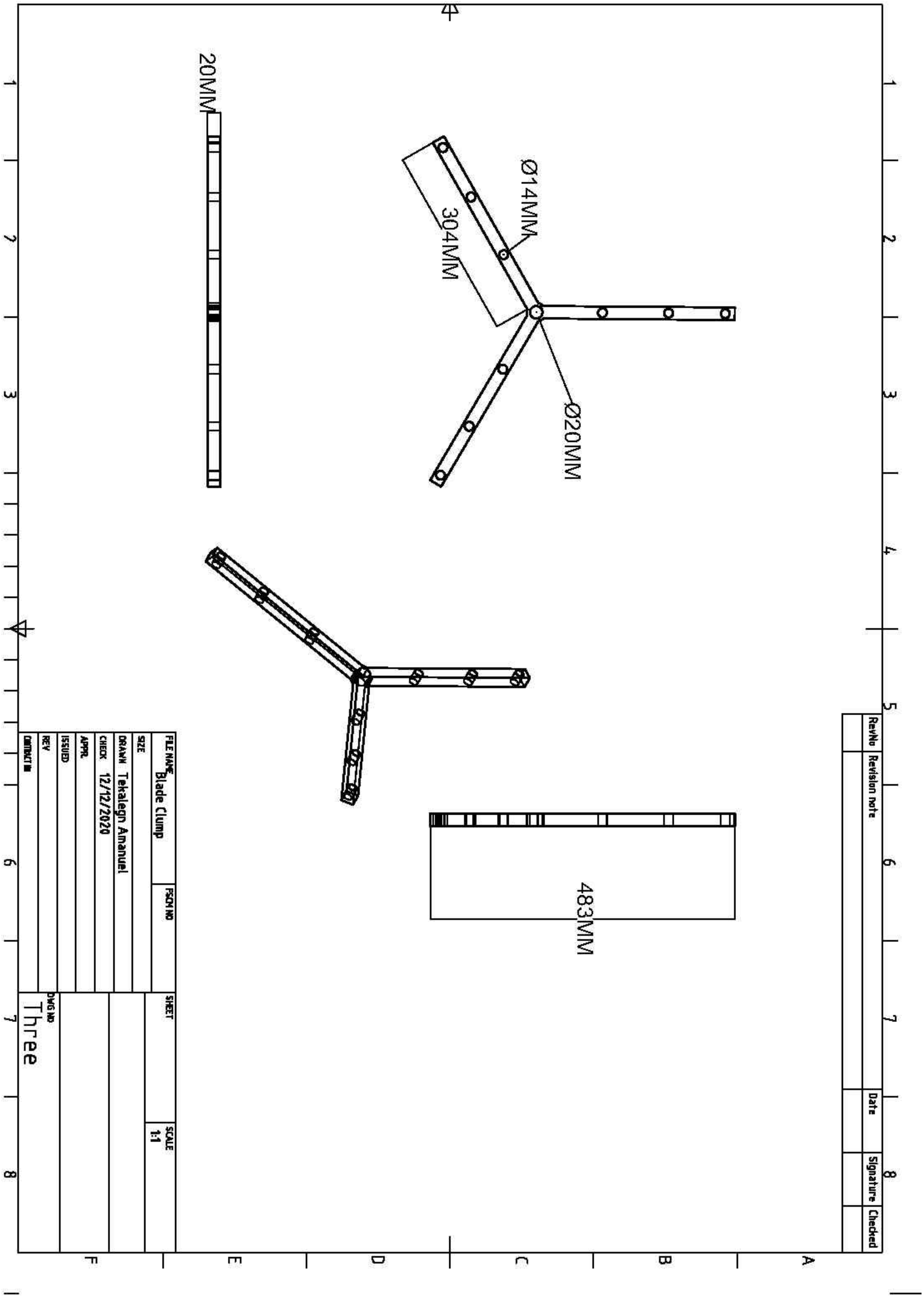

Figure .4.: Blade Support

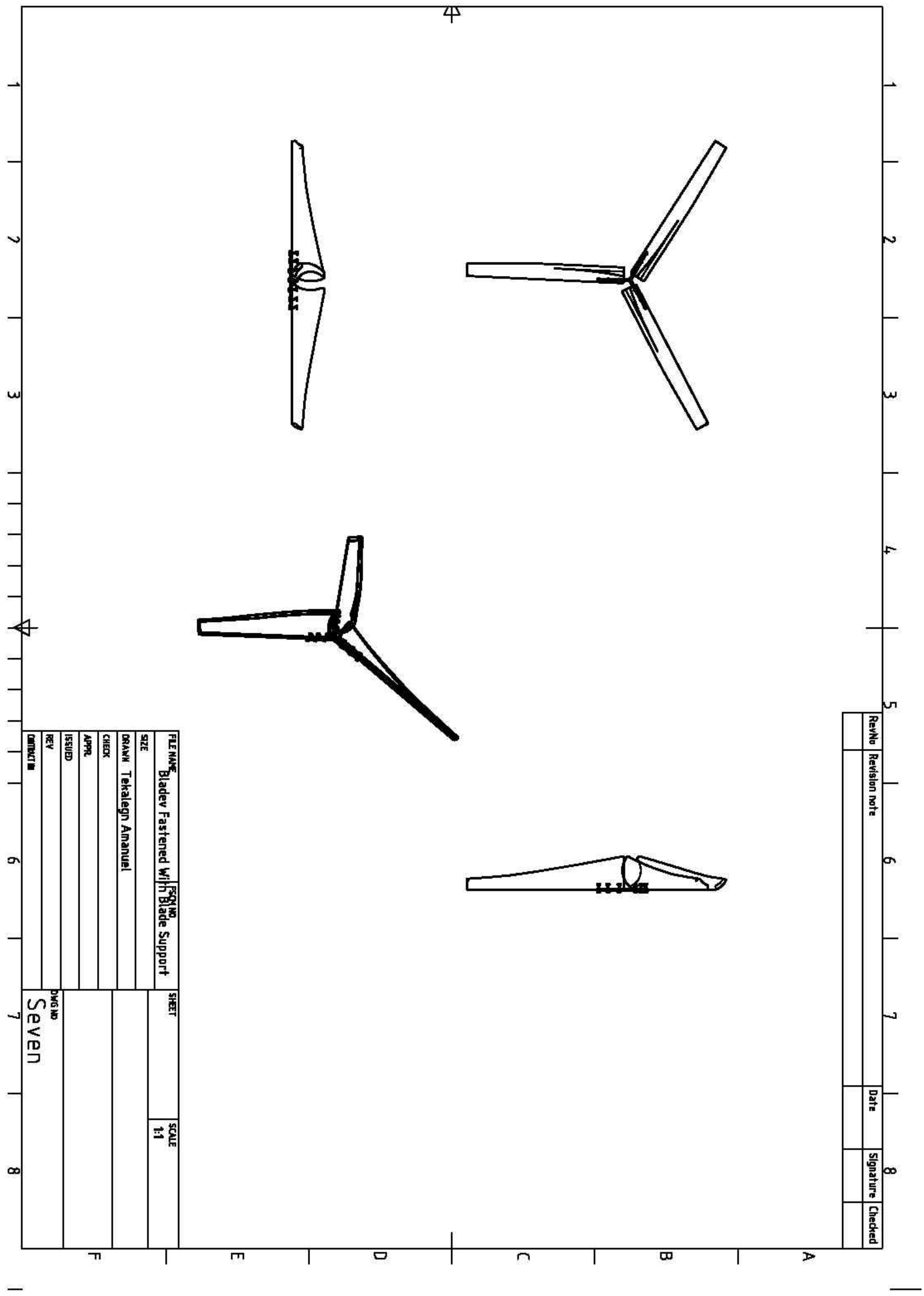

Figure .5.: Blade With Support

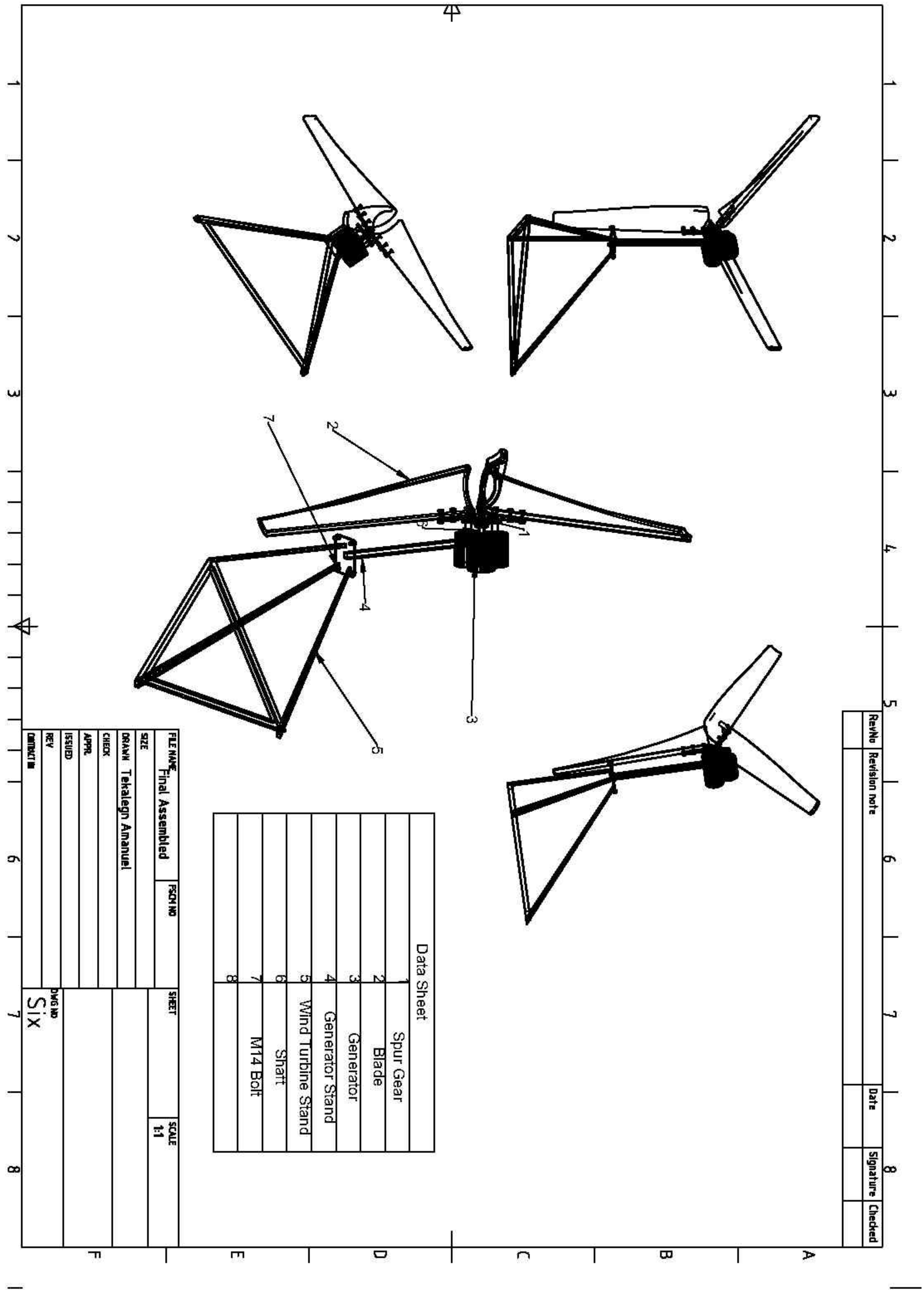

Figure .6.: Final Assembled Wind Turbine

B.2. Matlab code

Listing 1: Design code file from matlab

```

clear variables
close all
clc

addpath('Functions')

%% DATA INPUT

Nbl = 3; %number of blades
D = 3; %diameter [m]
lambda = 7; % tip-speed ratio
efficiency = 1; %Mechanical and electrical wind turbine efficiency

a = 0.275; %induction factor, a = 1/3 for ideal conditions (this code will
%correct the drag coefficient and the conditions won't be ideal anymore,
%however the induction factor will be still near 1/3)
c1 = 7; %undisturbed wind speed [m/s]
omega = 2*lambda*c1/D; %rotation speed [rad/s]

r_R = 0.16666667; %external radius / internal radius ratio (r / R)

toll = 0.005; %tollerance on the chord increase [m] (we suggest to use 0.0001 for a good result)
maxiter = 15; %number of max iterations on the chord

%Air features
air.gamma = 1.4; % gamma = Cp / Cv
air.R = 287; %gas constant
air.T = 273.15 + 15; %air temperature [K]
air.rho = 1.1162; %air density [kg/m^3]
air.mu = 1.75e-5; %air viscosity [kg * s / m]

visibility_Xfoil = false;
%false = do not show the XFoil window
%true = show the XFoil window

%angle of attack
alpha.start = 0; %start value of the angle of attack
alpha.finish = 20;  %finish value of the angle of attack
```

```
alpha.cycle_1 = 1; %step of the first cycle (we suggest to use 1 as step)
alpha.cycle_2 = 0.2; %step of the second cycle: this value must be a submultiple
        %of the first cycle step (we suggest to use one of the following
        %values: 0.1, 0.2, 0.25)

%chord dimension for the first iterative cycle
l_0_max = 0.76; %chord dimension on the first section (hub) [m]
l_0_min = 0.06; %chord dimension on the last section (tip) [m]

dim_text_plot = 14; %text dimension of the plot axis, title and legend
dim_lines_plot = 2; %plot lines thickness

%% BLADES DATABASE

% All the profiles used for the blade must be contained in the folder
% selected with the variable "blade.folder". The variable "blade.name" is a
% label with the name of the blade, you can put the name that you prefer.
% This name will be used for identify the the folder in which the results
% will be automatically saved.
% You can add a new blade adding a new line in the menu and a new case with
% the corresponding characteristics in the switch

%menu for the blade selection
blade_number = menu('SELECT THE BLADE', ...
    'Blade 1: 3 sections DU99W405LM and NACA64618',...
    'Blade 2: 4 sections NREL',...
    'Blade 3: 4 sections NREL',...
    'Blade 4: 3 sections NREL',...
    'Blade 5: 3 sections NREL',...
    'Blade 6: 10 section NREL',...
    'Blade 7: S814 S825 S826 interpolated with 38 profiles');

%Blade load
switch blade_number
    case 1 % Blade 1: 3 sections DU99W405LM and NACA64618
        blade.folder = 'Standard Profiles'; %folder that contains the profiles
```

```
        blade.name = 'Blade 1'; %name of the blade
        blade.profiles = {'DU97W300LM.dat','DU91W2250LM.dat','NACA64618.dat'}; %profiles
            % in array and linspaced fron the hub to the tip
    case 2 % Blade 2: 4 sections NREL
        blade.folder = 'Standard Profiles';
        blade.name = 'Blade 2';
        blade.profiles = {'s814.dat', 's809.dat','s810.dat'};
    case 3 % Blade 3: 4 sections NREL
        blade.folder = 'Standard Profiles';
        blade.name = 'Blade 3';
        blade.profiles = {'s814.dat', 's812.dat', 's813.dat'};
    case 4 % Blade 4: 3 sections NREL
        blade.folder = 'Standard Profiles';
        blade.name = 'Blade 4';
        blade.profiles = {'s818.dat','s816.dat','s817.dat'};
    case 5 % Blade 5: 3 sections NREL
        blade.folder = 'Standard Profiles';
        blade.name = 'Blade 5';
        blade.profiles = {'S814.dat', 'S825.dat', 'S826.dat'};
    case 6 % Blade 6: 10 sections NREL
        blade.folder = 'SG6045_Airfoil__Blade_Design';
        blade.name = 'Blade 6';
        blade.profiles = {'sg6042.dat', 'sg6042.dat', 'sg6042.dat','sg6042.dat','sg6042.dat','sg6042.dat','sg6042.dat','sg6042.dat','sg6042.dat','sg6042.dat','sg6042.dat','sg6042.dat',};
    case 7 % Blade 6: S814 S825 S826 interpolated with 38 profiles
        %This is the final blade we have designed during our project.
        blade.folder = 'S814_825_826_interpolated_38';
        blade.name = 'Final blade';
        blade.profiles = {'s814.dat','s814825_95.dat','s814825_90.dat','s814825_85.dat','s814825_80.dat','s814825_75.dat',...
            's814825_70.dat','s814825_65.dat','s814825_60.dat','s814825_55.dat','s814825_50.dat','s814825_45.dat',...
            's814825_40.dat','s814825_35.dat','s814825_30.dat','s814825_25.dat','s814825_20.dat','s814825_15.dat',...
            's814825_10.dat','s814825_5.dat','s825.dat','s825826_95.dat','s825826_90.dat','s825826_85.dat',...
```

```
            's825826_80.dat','s825826_75.dat','s825826_70.dat','s825826_65.dat','s825826_60.dat','s825826_55.dat',...
            's825826_50.dat','s825826_45.dat','s825826_40.dat','s825826_35.dat','s825826_30.dat','s825826_25.dat',...
            's825826_20.dat','s825826_15.dat','s825826_10.dat','s825826_5.dat','s826.dat'};

    otherwise
        error('The blade selected do not exist in the database')
end

%% PRE - ANALYSIS CHECKS

%check if the blase folder exist
if exist(blade.folder, 'dir')~=7
    error('Error: the blade folder selected do not exist')
end

%check if all the profiles exist inside the blade folder
for ii=1:length(blade.profiles)
    if exist([blade.folder '/' char(blade.profiles(ii))], 'file')~=2
        error(['Error: Profile ' char(blade.profile(ii)) ' is missing from the folder'])
    end
end

%% DESIGN

% Recalls the function for the preliminary blade design
[blade_design] = Blade_Design(blade, Nbl, D, omega, air, efficiency, a, c1, r_R, alpha, toll, maxiter, l_0_max, l_0_min, dim_text_plot, dim_lines_plot, visibility_Xfoil);
```

Listing 2: Off Design code file from matlab

```
%% OFF - DESIGN HORIZONTAL AXIS WIND TURBINE BLADES
%
%
% This code calculates the power produced by a wind turbine in off-design
% conditions. You have to copy in the Current Folder the Matlab file
% "Blade_Design_data.mat" created with the Design script, this file
% contains all the blade design information. You can set the off-design
% wind speed and the other variables to calculate the power produced.

clear variables
close all
clc

addpath('Functions')

disp('PRELIMINARY DESIGN OF HORIZONTAL WIND TURBINE BLADES')
disp('Off-Design')
disp(' ')

%% USER INPUT

c1 = 10; %off - design undisturbed wind speed [m/s]

%Air features
air.gamma = 1.4; % gamma = Cp / Cv
air.R = 287; %gas constant
air.T = 273.15+15; %ait temperature [K]
air.rho = 1.1162; %air density [kg/m^3]
air.mu = 1.75e-5; %air viscosity [kg * s / m]

%positions in which to plot the triangle of velocity (from the hub to the tip)
sec_plot_triangle = [1 3 5];
%this vector contains the position in which to plot the triangle of velocity.
%The number must be contained between 1 and the number of sections of the
%blade

dim_text_plot = 14; %text dimension of the plot axis, title and legend
dim_lines_plot = 2; %plot lines thickness
```

```

%parameters for the calculation of the induction factor
toll = 0.0001; %tollerance on the induction factor increment
maxiter = 30; %max number of iterations for the induction factor calculation
max_errors = 6; %max number of errors due to XFoil convergencefor each cycle

visibility_Xfoil = false;
%false = do not show the XFoil window
%true = show the XFoil window

%% AUTOMATIC INPUT

%load the data of the blade
load('Blade_Design_data.mat');

%associate the blade bata loaded to the current variables for the script
blade.folder = blade_design.folder; %folder that contains the profiles
blade.name = blade_design.name; %name of the blade
blade.profiles = blade_design.profiles; %profiles in array and linspaced
                                        %from the hub to the tip
l = blade_design.l; %chord [m]
Nbl = blade_design.Nbl; %number of blades
gamma = blade_design.gamma; %angle of design pitch [deg]
r = blade_design.r; %radius of each section fron the axis of rotation [m]
omega = blade_design.omega; %rotation speed [rad/s]
AR = blade_design.AR; %aspect ratio
S_blade = blade_design.S; %blade area [m^2]
efficiency = blade_design.efficiency; %mechanical and electrical efficiency
a_design = blade_design.a_design; %design induction factor

u = omega*r; %periferical speed [m/s]

D = 2*r(end); %wind turbine diameter [m]

%% PRE - ANALYSIS CHECKS

%check if the blase folder exist
if exist(blade.folder, 'dir')~=7
    error('Error: the blade folder selected do not exist')
end
```

```

%check if all the profiles exist inside the blade folder
for ii=1:length(blade.profiles)
    if exist([blade.folder '/' char(blade.profiles(ii))], 'file')~=2
        error(['Error: Profile ' char(blade.profiles(ii)) ' is missing from the folder'])
    end
end

if max(sec_plot_triangle) > length(blade.profiles)
    error('It is not possible plot the triangle of velocity. The number selected in "sec_prot_triangole" for the plot exceed the number of the blade sections.')
end

% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%% CALCULATE THE INDUCTION FACTOR IN EACH SECTION

%initialize the vectors. The last letter "c" means cycle
a_od_c = zeros(length(r), maxiter); %induction factor in off design conditions for each section
Re_c = zeros(length(r), maxiter); %Reynolds number
Cl_c = zeros(length(r), maxiter); %Lift coefficient
Cd_c = zeros(length(r), maxiter); %Drag coefficient
w_c = zeros(length(r), maxiter); %Realtive wind speed [m/s]
c2_c = zeros(length(r), maxiter); %wind speed at the actuator disc (at the wind turbine) [m/s]
Ma_c = zeros(length(r), maxiter); %Mach number
beta_c = zeros(length(r), maxiter); %relative wind speed angle [deg]
alpha_c = zeros(length(r), maxiter); %angle of attack [deg]

%Final values of the same variables
a_od = zeros(length(r), 1);
Re = zeros(length(r), 1);
Cl = zeros(length(r), 1);
Cd = zeros(length(r), 1);
w = zeros(length(r), 1);
```

```
Ma = zeros(length(r), 1);
beta = zeros(length(r), 1);
alpha = zeros(length(r), 1);

wait_bar = waitbar(0, 'Wait. Induction factor calculation in
   progress...');
for ii = 1:length(r) %calculate the induction factor on the
   section ii

    [a_od(ii), Re(ii), Cl(ii), Cd(ii), w(ii), Ma(ii), beta(ii
       ), alpha(ii)] = Induction_factor(toll, maxiter, l(ii),
        c1, u(ii), r(ii), air, blade, gamma(ii), ii, a_design
       , Nbl, AR, visibility_Xfoil, max_errors);

    waitbar(ii/length(r),wait_bar); %upgrade the waitbar
end
close(wait_bar)

%wind speed at the wind turbine for each section [m/s]
c2 = (1-a_od).*c1;

%% FOLDER AND FILE FOR DATA SAVING

%if the folder do not exist the software will create it.
if exist('Report Off-Design', 'dir')~=7
    mkdir('Report Off-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 Off-Design/' num2str(report.data(1)) '-' report.month '-' ...
    report.day ' ' report.hours '-' report.min '-' report.sec ' - ' blade.name];
mkdir(report.folder); %create the folder

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

fprintf(report.fileID, 'OFF-DESIGN REPORT ANALYSIS\r\n\r\n');
fprintf(report.fileID, 'Author: Oboe Daniele, Marinoni Andrea and Mastrandrea Sabino\r\n\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, '   r/R ratio = %.2f \r\n', r(1)/r(end));
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, '   Max number of iterations for the chord: %d m\r\n\r\n', maxiter);


%% WIND TURBINE POWER

beta_rad = beta * pi / 180;

%power with trapezes integral
```

```
[P_trap, P_ideal, Cp_trap, P_sup_trap] = Power_trapezes(r, l,
    beta_rad, c1, w, Cl, Cd, air, omega, Nbl, efficiency,
   report, dim_text_plot);

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

%% FIGURES

fig = figure;
plot(r, a_od, 'b-o', 'LineWidth', dim_lines_plot);
grid on
xlabel('r [m]')
ylabel('a')
title('INDUCTION FACTOR')
ax = gca;
ax.FontSize = dim_text_plot;
saveas(fig, [report.folder '/Induction factor.jpg'], 'jpg');
saveas(fig, [report.folder '/Induction factor.fig'], 'fig');

fig = figure;
plot(r, alpha,'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;
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,'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,'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./Cd,'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;
saveas(fig, [report.folder '/Lift and Drad.jpg'], 'jpg');
saveas(fig, [report.folder '/Lift and Drag.fig'], 'fig');

%% PLOT TRIANGLE OF VELOCITY

for ii=1:length(sec_plot_triangle)
    profile_plot = [blade.folder '/' char(blade.profiles((sec_plot_triangle(ii))))];
    nama_profile_plot = char(blade.profiles((sec_plot_triangle(ii))));

    [fig] = velocity_triangle(c2(sec_plot_triangle(ii)), omega, r(sec_plot_triangle(ii)),...
         l(sec_plot_triangle(ii)), gamma(sec_plot_triangle(ii)), profile_plot, nama_profile_plot);

    %figure save
    saveas(fig, [report.folder '/Velocity triangle_ R ' num2str(r(sec_plot_triangle(ii))) ' m.jpg'], 'jpg');
    saveas(fig, [report.folder '/Velocity triangle_ R ' num2str(r(sec_plot_triangle(ii))) ' m.fig'], 'fig');
end


%% PROFILES OUTPUT 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

%% END FUNCTION

```

```
fclose(report.fileID); %close the report file

%delete 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
%save all the variables on a Matlab file
save([report.folder '/Analysis_data.mat'])
```

q

B.2.1. call codes

Listing 3: Induction factor code file from matlab

```
function [a_od, Re, Cl, Cd, w, Ma, beta, alpha] = Induction_factor(toll, maxiter, l, c1, u, r, air, blade, gamma, ii, a_design, Nbl, AR, visibility_Xfoil, max_errors)
% INDUCTION FACTOR CALCULATION


%initializing the vectors. The last letter "c" stands for cycle
a_od_c = zeros(1, maxiter); %induction factor in off design conditions
Re_c = zeros(1, maxiter); %Reynolds number
Cl_c = zeros(1, maxiter); %Lift coefficient
Cd_c = zeros(1, maxiter); %Drag coefficient
w_c = zeros(1, maxiter); %Relative wind speed [m/s]
c2_c = zeros(1, maxiter); %wind speed at the disk actuator (at the wind turbine) [m/s]
Ma_c = zeros(1, maxiter); %Mach number
beta_c = zeros(1, maxiter); %relative wind speed angle [deg]
alpha_c = zeros(1, maxiter); %angle of attack [deg]

counter = 1;
err = toll + 1; %setting err > toll to start the cycle
a_od_c(1) = a_design; %setting the first induction factor

%iterative cycle to calculate the induction factor
while err>toll && counter<=maxiter
    counter = counter+1;

    %wind speed at the wind turbine [m/s]
    c2_c(counter) = (1-a_od_c(counter-1))*c1;

    error = true; %setting true to start the cycle
    counter_error = 0; %counter for the errors in Xfoil (when XFoil doesn't
                       %converge)

    while error == true

        w_c(counter) = (u^2 + c2_c(counter)^2)^0.5; %relative wind speed
        beta_c(counter) = atand(u / c2_c(counter)); %relative wind angle
```

```matlab
        alpha_c(counter) = gamma - beta_c(counter); %angle of attack

        Re_c(counter) = air.rho*w_c(counter)*l/air.mu; %Reynolds number
        Ma_c(counter) = w_c(counter)/(sqrt(air.gamma*air.R*air.T)); %Mach number

        %Recalling Xfoil to evaluate the Lift and Drag coefficients
        data_profile = XFoil_launcher(Re_c(counter), Ma_c(counter), alpha_c(counter),...
            [blade.folder '/' char(blade.profiles(ii))], visibility_Xfoil);

        if isempty(data_profile.CL)==0 %XFoil converged
            Cl_c(counter) = data_profile.CL;
            cd_2D = data_profile.CD;
            Cd_c(counter) = cd_2D + (Cl_c(counter)^2)/(pi*AR); %Cd with 3D correction
            error = false; %do not recall XFoil again for this blade section
        else %XFoil didn't converge
            error = true; %recalling XFoil again for this blade section
            %The code slightly modifies the input,trying to reach
            %convergence with a small error
            c2_c(counter) = c2_c(counter)*1.001;
            counter_error = counter_error + 1;
            disp(['WARNING: XFoil attempt n. ' num2str(counter_error) ' didn''t converge.'])
            if counter_error == max_errors
                if counter > 1
                    %setting the Drag and Lift coefficients calculated in
                    %the previous iterative cycle
                    Cl_c(counter) = Cl_c(counter-1);
                    Cd_c(counter) = Cd_c(counter-1);
                    error = false; %do not recall XFoil again for this blade section
                    warning('XFoil convergence failed. Reached the max number of errors allowed.')
                else
                    %sorry, we can't solve the problem...
                    error('XFoil convergence failed. Reached the max number of errors allowed.')
```

```
                end

            end
        end
    end

    %calculating the off - design induction factor for this cycle
    a_od_c(counter) = 1 / ( 1 + (8*pi*r*c2_c(counter)^2)/(Nbl*w_c(counter)^2*...
        ( Cl_c(counter)*sind(beta_c(counter)) + Cd_c(counter)*cosd(beta_c(counter)) )) );

    if a_od_c(counter) > 0.5
        a_od_c(counter) = 0.5;
        break;
    end

    %error on the induction factor increment
    err = abs(a_od_c(counter-1) - a_od_c(counter));

    if counter == (maxiter+1)
        warning('Reach the max number of iterations')
    end
end

%assigning the calculated values to the variables
a_od = a_od_c(counter);
Re = Re_c(counter);
Cl = Cl_c(counter);
Cd = Cd_c(counter);
w = w_c(counter);
Ma = Ma_c(counter);
beta = beta_c(counter);
alpha = alpha_c(counter);


end
```

Listing 4: Blade design code file from matlab

```
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)


%% DATA INPUT

```

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

% Vector with the radial coordinates, in which the software evaluates the chord.
% 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
    else %even number of sections --> the last value is evaluated with the trapezes equation
        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));
```

```matlab

        %******* 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, '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'); % standard jpg format
saveas(fig, [report.folder '/Chord convergence.fig'], 'fig'); % Matlab format

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([report.folder '/Analysis_data.txt'])
%% 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) [m]
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')
end
```

Listing 5: Cavaliers Simpson Equation code file from matlab

```
function [P, P_ideal, Cp] = Power_cs(r, l, beta, c1, w, Cl, Cd, air, omega, Nbl, efficiency, report, dim_text_plot, output_data)
% CAVALIERI-SIMPSON INTEGRAL TO CALCULATE THE PRODUCED POWER
%
%Disk actuator ideal power [W]
P_ideal = 0.5*pi*(r(end))^(2)*c1^3*air.rho;

%The integral of a function f(x) , calculated in the interval [a,b] with Cavalieri - Simpson method , is:
%Integral = (f(a)/3 + 4*f((b+a)/2)/3 + f(b)/3 )*(b-a)/2

if length(r)/2 ~= round( length(r)/2 ) %odd number of sections
P_section = zeros(1,length(r));
    for ii = 3 : 2 : length(r)
```

```
    h_section = r(ii) - r(ii-2);
    %power produced in the area ii [W]
    P_section(ii) = (( (l(ii)*w(ii)^2*(Cl(ii)*cos(beta(ii)) - ...
        Cd(ii)*sin(beta(ii)))*r(ii)) +...
        4*(l(ii-1)*w(ii-1)^2*(Cl(ii-1)*cos(beta(ii-1)) - ...
        Cd(ii-1)*sin(beta(ii-1)))*r(ii-1))+...
        (l(ii-2)*w(ii-2)^2*(Cl(ii-2)*cos(beta(ii-2)) - ...
        Cd(ii-2)*sin(beta(ii-2)))*r(ii-2)))*h_section / 6 ) *0.5*air.rho*omega;
    end
else %even number of sections --> the last value is evaluated with the trapezes equation
P_section = zeros(1,length(r));
    for ii = 3 : 2 : (length(r) - 1)
    h_section = r(ii) - r(ii-2);
    P_section(ii) = (( (l(ii)*w(ii)^2*(Cl(ii)*cos(beta(ii)) - ...
        Cd(ii)*sin(beta(ii)))*r(ii)) +...
        4*(l(ii-1)*w(ii-1)^2*(Cl(ii-1)*cos(beta(ii-1)) - ...
        Cd(ii-1)*sin(beta(ii-1)))*r(ii-1))+...
        (l(ii-2)*w(ii-2)^2*(Cl(ii-2)*cos(beta(ii-2)) - ...
        Cd(ii-2)*sin(beta(ii-2)))*r(ii-2)))*h_section / 6 ) *0.5*air.rho*omega;
    end
    h_section = r(end) - r(end-1);
    P_section(end) = (( (l(end)*w(end)^2*( Cl(end)*cos(beta(end)) - ...
        Cd(end)*sin(beta(end)) )*r(end)*h_section) +...
        ( l(end-1)*w(end-1)^2*( Cl(end-1)*cos(beta(end-1)) - ...
        Cd(end-1)*sin(beta(end-1)) )*r(end-1)*h_section) ) / 2 )*0.5*air.rho*omega;
end

%wind turbine power
P = sum(P_section)*Nbl*efficiency;
%Cp with Cavalieri - Simpson power
Cp = P/P_ideal;

if output_data == true

    %output results
    disp('Power with Cavalieri-Simpson equation')
    disp(['    Power = ' num2str(P/1000) ' kW'])
    disp(['    Cp = ' num2str(Cp)])

    %writing the results in the report file
```

```
    fprintf(report.fileID, 'Power with Cavalieri-Simpson equation\r\n');
    fprintf(report.fileID, '    Power = %.3f kW\r\n', P/1000);
    fprintf(report.fileID, '    Cp = %.4f \r\n\r\n', Cp);

    fig = figure;
    x_cavalieri = linspace(r(1),r(end),((length(r)*2)-1));
    x_cavalieri_index = 2:2:length(x_cavalieri);
    bar(x_cavalieri(x_cavalieri_index),P_section(2:end)/1000)
    title('POWER: Cavalieri-Simpson equation')
    xlabel('r [m]')
    ylabel('P [kW]')
    ax = gca;
    ax.FontSize = dim_text_plot;
    %saving figure
    saveas(fig, [report.folder '/Power Cavalieri Simpson.jpg'], 'jpg');
    saveas(fig, [report.folder '/Power Cavalieri Simpson.fig'], 'fig');

end

end
```

Listing 6: trapezes Equation code file from matlab

```
function [P, P_ideal, Cp, P_sup] = Power_trapezes(r, l, beta, c1, w, Cl, Cd, air, omega, Nbl, efficiency, report, dim_text_plot)
% TRAPEZES INTEGRAL TO CALCULATE THE PRODUCED POWER
%
% Note: the wind speed angle beta must be setted in radiants [rad]

%disk actuator ideal power [W]
P_ideal = 0.5*pi*(r(end))^(2)*c1^3*air.rho;

P_section = zeros(1,length(r)); %power array
Area_section = zeros(1,length(r)); %blade area between two sections array

for ii = 2:length(r)
    h_section = r(ii) - r(ii-1);

    %power produced in the area ii [W]
    P_section(ii) = (( (l(ii)*w(ii)^2*(Cl(ii)*cos(beta(ii)) - ...
        Cd(ii)*sin(beta(ii)))*r(ii)*h_section) +...
        (l(ii-1)*w(ii-1)^2*(Cl(ii-1)*cos(beta(ii-1)) - ...
```

```
        Cd(ii-1)*sin(beta(ii-1)))*r(ii-1)*h_section) ) / 2 )
           *0.5*air.rho*omega;

    %ii blade area [m^2]
    Area_section(ii) = (l(ii-1)+ l(ii))*(r(ii)-r(ii-1))/2;
end

%Wind turbine power [W]
P = sum(P_section)*Nbl*efficiency;
%Cp
Cp = P/P_ideal;
%Power per unit of area [W/m^2]
P_sup = P_section ./ Area_section;

%output results
disp(' ')
disp('Power with trapezes equation')
disp(['   Power = ' num2str(P/1000) ' kW'])
disp(['   Cp = ' num2str(Cp)])

%writing the results in the report file
fprintf(report.fileID, 'Power with trapezes equation\r\n');
fprintf(report.fileID, '   Power = %.3f kW\r\n', P/1000);
fprintf(report.fileID, '   Cp = %.4f \r\n', Cp);

fig = figure;
x_trapezes = linspace(r(1),r(end),((length(r)*2)-1));
x_trapezes_index = 2:2:length(x_trapezes);
bar(x_trapezes(x_trapezes_index),P_section(2:end)/1000)
title('POWER: trapezes equation')
xlabel('r [m]')
ylabel('P [kW]')
ax = gca;
ax.FontSize = dim_text_plot;
%figure saving
saveas(fig, [report.folder '/Power trapezes.jpg'], 'jpg');
saveas(fig, [report.folder '/Power trapezes.fig'], 'fig');

fig = figure;
x_trapezes = linspace(r(1),r(end),((length(r)*2)-1));
x_trapezes_index = 2:2:length(x_trapezes);
bar(x_trapezes(x_trapezes_index),P_sup(2:end)/1000)
title('POWER PER UNIT OF AREA')
xlabel('r [m]')
ylabel('P [kW/m^2]')
ax = gca;
ax.FontSize = dim_text_plot;
%figure saving
```

```
saveas(fig, [report.folder '/Power per unit of area.jpg'], 'jpg');
saveas(fig, [report.folder '/Power per unit of area.fig'], 'fig');

end
```

ss