



ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)  
GRADO EN INGENIERÍA ELECTROMECÁNICA  
Especialidad Mecánica

# DESIGN OF A TWO BLADED WIND TURBINE

Autor: Carlos Ignacio Laiz Quereda  
Director: Luis Manuel Mochón Castro

Madrid

Julio 2018



## **AUTORIZACIÓN PARA LA DIGITALIZACIÓN, DEPÓSITO Y DIVULGACIÓN EN RED DE PROYECTOS FIN DE GRADO, FIN DE MÁSTER, TESINAS O MEMORIAS DE BACHILLERATO**

### **1º. Declaración de la autoría y acreditación de la misma.**

El autor D.Carlos Ignacio Laiz Quereda

DECLARA ser el titular de los derechos de propiedad intelectual de la obra: "*Design of a two Bladed Wind Turbine*" que ésta es una obra original, y que ostenta la condición de autor en el sentido que otorga la Ley de Propiedad Intelectual.

**2º. Objeto y fines de la cesión.** Con el fin de dar la máxima difusión a la obra citada a través del Repositorio institucional de la Universidad, el autor CEDE a la Universidad Pontificia Comillas, de forma gratuita y no exclusiva, por el máximo plazo legal y con ámbito universal, los derechos de digitalización, de archivo, de reproducción, de distribución y de comunicación pública, incluido el derecho de puesta a disposición electrónica, tal y como se describen en la Ley de Propiedad Intelectual. El derecho de transformación se cede a los únicos efectos de lo dispuesto en la letra a) del apartado siguiente.

### **3º. Condiciones de la cesión y acceso**

Sin perjuicio de la titularidad de la obra, que sigue correspondiendo a su autor, la cesión de derechos contemplada en esta licencia habilita para:

- a) Transformarla con el fin de adaptarla a cualquier tecnología que permita incorporarla a internet y hacerla accesible; incorporar metadatos para realizar el registro de la obra e incorporar "marcas de agua" o cualquier otro sistema de seguridad o de protección.
- b) Reproducirla en un soporte digital para su incorporación a una base de datos electrónica, incluyendo el derecho de reproducir y almacenar la obra en servidores, a los efectos de garantizar su seguridad, conservación y preservar el formato.
- c) Comunicarla, por defecto, a través de un archivo institucional abierto, accesible de modo libre y gratuito a través de internet.
- d) Cualquier otra forma de acceso (restringido, embargado, cerrado) deberá solicitarse expresamente y obedecer a causas justificadas.
- e) Asignar por defecto a estos trabajos una licencia Creative Commons.
- f) Asignar por defecto a estos trabajos un HANDLE (URL *persistente*).

### **4º. Derechos del autor.**

El autor, en tanto que titular de una obra tiene derecho a:

- a) Que la Universidad identifique claramente su nombre como autor de la misma
- b) Comunicar y dar publicidad a la obra en la versión que ceda y en otras posteriores a través de cualquier medio.
- c) Solicitar la retirada de la obra del repositorio por causa justificada.
- d) Recibir notificación fehaciente de cualquier reclamación que puedan formular terceras personas en relación con la obra y, en particular, de reclamaciones relativas a los derechos de propiedad intelectual sobre ella.

### **5º. Deberes del autor.**

El autor se compromete a:

- a) Garantizar que el compromiso que adquiere mediante el presente escrito no infringe ningún derecho de terceros, ya sean de propiedad industrial, intelectual o cualquier otro.
- b) Garantizar que el contenido de las obras no atenta contra los derechos al honor, a la intimidad y a la imagen de terceros.
- c) Asumir toda reclamación o responsabilidad, incluyendo las indemnizaciones por daños, que pudieran ejercitarse contra la Universidad por terceros que vieran infringidos sus derechos e intereses a causa de la cesión.
- d) Asumir la responsabilidad en el caso de que las instituciones fueran condenadas por infracción de derechos derivada de las obras objeto de la cesión.

### **6º. Fines y funcionamiento del Repositorio Institucional.**

La obra se pondrá a disposición de los usuarios para que hagan de ella un uso justo y respetuoso con los derechos del autor, según lo permitido por la legislación aplicable, y con fines de estudio, investigación, o cualquier otro fin lícito. Con dicha finalidad, la Universidad asume los siguientes deberes y se reserva las siguientes facultades:

- La Universidad informará a los usuarios del archivo sobre los usos permitidos, y no garantiza ni asume responsabilidad alguna por otras formas en que los usuarios hagan un uso posterior de las obras no conforme con la legislación vigente. El uso posterior, más allá de la copia privada, requerirá que se cite la fuente y se reconozca la autoría, que no se obtenga beneficio comercial, y que no se realicen obras derivadas.
- La Universidad no revisará el contenido de las obras, que en todo caso permanecerá bajo la responsabilidad exclusiva del autor y no estará obligada a ejercitar acciones legales en nombre del autor en el supuesto de infracciones a derechos de propiedad intelectual derivados del depósito y archivo de las obras. El autor renuncia a cualquier reclamación frente a la Universidad por las formas no ajustadas a la legislación vigente en que los usuarios hagan uso de las obras.
- La Universidad adoptará las medidas necesarias para la preservación de la obra en un futuro.
- La Universidad se reserva la facultad de retirar la obra, previa notificación al autor, en supuestos suficientemente justificados, o en caso de reclamaciones de terceros.

Madrid, a 23 de Julio de 2018

**ACEPTA**

*Ignacio* *Lara Quereda*  
Fdo.....

Motivos para solicitar el acceso restringido, cerrado o embargado del trabajo en el Repositorio Institucional:

Declaro, bajo mi responsabilidad, que el Proyecto presentado con el título "**Desing of a two Bladed Wind Turbine**"

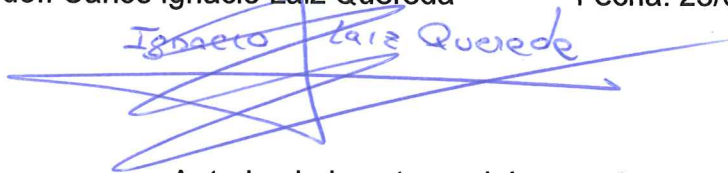
en la ETS de Ingeniería - ICAI de la Universidad Pontificia Comillas en el curso académico 2017/2018 es de mi autoría, original e inédito y

no ha sido presentado con anterioridad a otros efectos. El Proyecto no es plagio de otro, ni total ni parcialmente y la información que ha sido tomada

de otros documentos está debidamente referenciada.

Fdo.: Carlos Ignacio Laiz Querada

Fecha: 23/07/2017



Autorizada la entrega del proyecto

EL DIRECTOR DEL PROYECTO



Fdo.: Luis Manuel Mochón Castro

Fecha: 23/07/2017



ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)  
GRADO EN INGENIERÍA ELECTROMECÁNICA  
Especialidad Mecánica

# DESIGN OF A TWO BLADED WIND TURBINE

Autor: Carlos Ignacio Laiz Querada  
Director: Luis Manuel Mochón Castro

Madrid

Julio 2018

# DISEÑO DE UNA TURBINA DE VIENTO DE ROTOR BIPALA

**Autor: Laiz Quereda, Carlos Ignacio**

Directores: Mochón Castro, Luis Manuel

Entidad Colaboradora: ICAI - Universidad Pontificia Comillas y NTNU – Norwegian University of Science and Technology.

## Resumen

El objetivo de este Proyecto es diseñar, fabricar y testar una pequeña turbina de viento bipala de eje horizontal, con la meta de obtener máxima eficiencia posible en términos de eficiencia total. Consecuentemente, la eficiencia aerodinámica de la turbina  $C_p$ , la eficiencia del generador y su correspondiente acoplamiento son igualmente importantes en este proyecto. Los cálculos de este proyecto están fundamentalmente basados en buscar un compromiso entre todas las eficiencias para obtener un funcionamiento óptimo.

De esta forma, esta memoria se centrará en el diseño de una turbina de viento biapala y un generador radial trifásico, buscando el mejor acoplamiento. Sin embargo, la torre y el rotor del generador han sido suministrados por mi Universidad de destino “Norwegian University of Science and Technology” y por ello, sus diseños quedan fuera del encuadre de este proyecto.

El diseño de la turbina ha sido realizado basado en algunas condiciones y restricciones de tamaño dadas por mi Universidad de destino. El primer paso del procedimiento de diseño es la creación de un código de Matlab basado en el Blade Element Momentum (BEM) Method. Este primer diseño se importa a Ashes para comprobar el funcionamiento del modelo inicial. Después de esto, se comienza un diseño iterativo entre Ashes, Matlab, Excel e Inventor con el fin de optimizar este primer diseño.

Por otro lado, un breve análisis comparativo entre un generador axial monofásico y un generador radial trifásico se presentará a lo largo de este documento. Finalmente, el generador se diseña en base al momento producido por la turbina para su velocidad óptima de rotación. El procedimiento de diseño del generador se realiza principalmente con Excel y Ashes.

Después de la parte de diseño, se comentan los procedimientos de fabricación tanto de la turbina como del generador. Como se ha comentado anteriormente, la Universidad NTNU (Norwegian University of Science and Technology) suministró el rotor de cuatro polos del generador, y por tanto, sólo ha sido necesario fabricar el estator. Por otro lado, el rotor de la turbina, también conocido como turbina, se fabricó mediante un procedimiento de maquinado.

En este sentido, mientras el procedimiento de fabricación del generador es más manual, la fabricación de la turbina fue realizada por un procedimiento de maquinado. De esta forma, se ilustrarán todos los pasos seguidos para fabricar el mini-aerogenerado

Finalmente, se presentarán los resultados del ensayo en el túnel de viento. Para conseguir buenos resultados se realizaron dos tests diferentes. En este sentido, se realizó un ensayo del generador en el laboratorio de electricidad de la NTNU para comprobar la efectividad del generador radial trifásico. Esta parte es de las más importante del proyecto ya que el generador ha sido fabricado manualmente. Por ello, se espera que el funcionamiento real se diferencie del teórico.

Después de esto, la turbina fue llevada al túnel de viento para ensayar su funcionamiento en el punto de diseño y otros puntos. Este ensayo en el túnel de viento da la oportunidad de comprobar si los resultados teóricos concuerdan o no con los resultados reales.



# DESIGN OF A TWO BLADED WIND TURBINE

**Author: Laiz Quereda, Carlos Ignacio**

Supervisor: Mochón Castro, Luis Manuel

Colaborating organization: ICAI - Universidad Pontificia Comillas and NTNU – Norwegian University of Science and Technology

## Abstract

The aim of this project is to design, manufacture and test a small two bladed Horizontal Wind Turbine (HAWT) with the goal of achieving a high efficiency in terms of total efficiency. Consequently, the turbine mechanical efficiency  $C_p$ , the generator efficiency and its coupling are equally important in this project. The calculations of this project are mainly focus on finding a compromise of efficiencies to achieve an optimal performance.

Thus, this paper will be focus on the design of a two bladed turbine and a three phase radial generator taking into consideration their best match. However, the tower and the rotor of the generator were supplied by my destination University “*Norwegian University of Science and Technology*” and therefore their designs are out of the scope of this paper.

The turbine is designed based on some given constraints and size requirements sugested by my destination University. The procedure started from a Matlab code implementing the Blade Element Momentum (BEM) Method. This first design was imported to Ashes to check the performance of the initial modle. After this, to improve the turbine design an iterative procedure between Ashes, Matlab, Excel and Inventor was necessary.

On the other hand, a brief comparative analysis between a one phase axial generator and a three phase radial generator will be presented along this paper. Finally, the generator was designed by considering the torque produced by the turbine at its maximum performance. The generator design procedure is mainly based on Excel and Ashes.

After the design part, the manufacturing part for both the turbine and generator is commented. The NTNU (*Norwegian University of Science and Technology*) supplied me with the rotor, therefore only the stator of a four pole rotor was manufactured. On the other hand, the rotor also known as turbine will be manufactured by a milling process. To do this, it is necessary to create a 3D assembly of the final design.

In this sense, while the generator manufacturing process is more manual, the turbine manufacture is realized by a machining method. Thus, all steps to manufacture the whole wind turbine will be discussed along this paper.

Finally, the testing results in the wind tunnel are presented. To achieve accurate results two tests have been performed and both will be discussed. In this sense, a generator test was first performed in an electric laboratory to ensure the effectiveness of the three phase radial generator. As it is manufactured manually, large uncertainties may be present on the generator.

After this, the turbine was taken to the wind tunnel to test its performance. The wind tunnel gives the opportunity to check whether the design results are close to the reality or not.

*This work goes for all my loved ones, my mother Pilar, my uncle Jesús, my friends and my father who rests in heaven. Thanks for who I am.*

## Acknowledgments

Firstly, I would like to thank **Norwegian University of Science and Technology (NTNU)**, specially to Professor **Ole Gunnar** and Professor **Trond Leiv Tofte-vaag** and Teacher Assistant **Tara Berg** for their interest, help and attachment to me and my Project. Without you, this project would have never been possible. Moreover, I would like to thank to my home University **Universidad Pontificia de Comillas ICAI-ICADE** for its education and values. Without any doubt, these four years have been the best of my life and some how it has been because of the opportunity to develop myself personal and academically in an atmosphere as the one of ICAI. Last but not least I would like to thank to my professor and Project Director **Luis Manuel Mochón** for his support, education, attachment and devotion. It has been a real pleasure to share with you courses like **Fluid Mechanics** and **Heat Transfer**. You are a great professor but a better person. Thank you for everything.

# Contents

<b>1. Introduction</b> .....	1
1.1 Objective .....	2
1.2 Motivation.....	3
1.3 Wind power industry in the global energy situation .....	5
1.4 Project Structure .....	8
<b>2. State of the art</b> .....	9
2.1 Historical Viewpoint.....	10
2.2 Wind turbines fundamentals .....	11
2.2.1 Definition of a Wind Turbine .....	11
2.2.2 Types of Wind Turbines .....	12
2.3 Wind characteristics and resource estimation .....	14
2.4 New technologies and modern wind turbines .....	15
2.4.1 Offshore wind turbines.....	15
2.4.2 Small wind .....	17
<b>3. Turbine design</b> .....	19
3.1 Summary .....	20
3.2 Blade design restrictions.....	21
3.3 Wind turbines and aerodynamic theory fundamentals .....	21
3.3.1 Airfoil theory.....	21
3.3.2 Airfoil and blade parameters.....	23
3.3.3 Twisting the blade to maintain a constant angle of attack .....	24
3.3.4 Energy and Power output.....	25
3.3.5 Characteristics parameters in wind turbines design .....	26
3.3.6 Betz's limit .....	30
3.3.7 Actuator disc approach.....	30
3.3.8 Axial Induction Factor .....	31
3.3.9 Expressing Power and power coefficient with respect to $a$ .....	33
3.3.10 Demonstration of the Betz limit.....	34
3.3.11 Expressing the thrust coefficient with respect to $a$ .....	36
3.3.12 Demonstration of the maximum thrust coefficient .....	36
3.3.13 Rotatory disc Theory.....	37
3.3.14 Rotational induction factor .....	37

3.3.15 The rotor disk wake model.....	38
3.3.16 Blade element momentum theory.....	39
3.3.17 Blade Element Momentum (BEM) Method.....	41
<b>3.4 Blade design .....</b>	<b>43</b>
3.4.1 Blade design Method.....	43
3.4.2 Design under Matlab .....	44
3.4.2.1 Introduction.....	44
3.4.2.2 Initial design.....	45
3.4.2.3 The algorithm .....	47
3.4.2.4 Matlab Results.....	48
3.4.2.5 Conclusion .....	51
3.4.3 Design under Ashes and Excel.....	52
3.4.3.1 Introduction.....	52
3.4.3.2 Introduction of the pre-design into Ashes.....	53
3.4.3.3 Iteration process with Ashes and Excel .....	55
3.4.3.4 Conclusion .....	59
3.4.4 Design under Inventor .....	60
3.4.4.1 Introduction.....	60
3.4.4.2 Importing the blade into Autodesk Inventor.....	60
3.4.4.3 Modelling process and results.....	61
<b>3.5 Generator design .....</b>	<b>64</b>
3.5.1 Introduction.....	64
3.5.2 Theory Fundamentals.....	65
3.5.3 Comparison of Axial generator and Radial Generator in terms of efficiency .....	66
3.5.4 Design under Excel .....	68
3.5.5 Selection of the wire.....	69
3.5.6 Excel calculations and results .....	70
3.5.7 Ashes validation.....	72
<b>4. Turbine making .....</b>	<b>73</b>
4.1 Rotor milling.....	74
4.1.1 CNC programming: SprutCAM.....	74
4.1.2 Milling process.....	76
4.1.3 Final result and polishing process .....	77
4.2 Generator manufacture .....	78
4.2.1 Coils creation .....	78

4.2.2 Generator assembly .....	80
<b>5. Testing and Results</b> .....	<b>81</b>
5.1 Generator test.....	82
5.2 Wind tunnel test .....	85
<b>6. Conclusions</b> .....	<b>89</b>
<b>References</b> .....	<b>92</b>
<b>Appendixes</b> .....	<b>95</b>
Appendix A: Matlab Code based on BEM method .....	96
Appendix B: Matlab Code function adisk.....	101
Appendix C: Generator test Results.....	102
Appendix D: Wind tunnel test.....	103
Appendix E: Generator design Excel Sheet .....	1034

## List of tables

<b>Table 1-</b> Matlab Rotor characteristics .....	48
<b>Table 2-</b> Aerodynamic parameters used to run the Matlab algorithm .....	49
<b>Table 3-</b> Blade geometry from BEM and Matlab. TSR= 6.5 .....	49
<b>Table 4-</b> Modifications Excel table to maintain a smooth blade profile at every iteration. These illustrated results are from the final design .....	58
<b>Table 5-</b> Different possible designs for one phase Axial generator .....	66
<b>Table 6-</b> Different possible designs for three phase Radial generator .....	66
<b>Table 7-</b> Three phase Radial generator designs with small wire .....	69
<b>Table 8-</b> Three phase Radial generator designs with big wire .....	69
<b>Table 9-</b> Final Three phase Radial generator design .....	70
<b>Table 10-</b> Generator test data for the design rotational speed .....	82
<b>Table 11-</b> Generator comparison between simulated and tested needed load resistance to achieve the turbine torque .....	84
<b>Table 12-</b> Test of turbine blade only .....	86
<b>Table 13-</b> Summary table of output wind tunnel test .....	86
<b>Table 14-</b> Generator test results (NTNU, 2017) .....	102
<b>Table 15-</b> Wind tunnel test (NTNU, 2017) .....	103
<b>Table 16-</b> Generator design Excel Sheet User Input (NTNU, 2017) .....	104
<b>Table 17-</b> Generator design Excel sheet Ashes Output (NTNU, 2017) .....	104



# List of Figures

<b>Figure 1-</b> Two bladed HAWT (Dreamstime) .....	12
<b>Figure 2-</b> Three bladed HAWT (Gamesa).....	12
<b>Figure 3-</b> VAWT in Netherlands (WePower).....	13
<b>Figure 4-</b> VAWT in Denmark (WePower).....	13
<b>Figure 5-</b> Hywind floating farm model (Statoil, Hywind, 2018).....	16
<b>Figure 6-</b> Example of a horizontal two bladed small wind turbine (Bornay, 2018).....	17
<b>Figure 7-</b> Definition of chord line and angle of attack (Frøyd & Kjetil Haugset) .....	22
<b>Figure 8-</b> Airflow behaviour around the blade (Frøyd & Kjetil Haugset).....	22
<b>Figure 9-</b> Differences between chord length and chord line (quora, 2018).....	23
<b>Figure 10-</b> Twisting the blade to maintain an optimal angle of attack along the blade .....	25
<b>Figure 11-</b> Thrust and foundation momentum (NTNU, 2017) .....	27
<b>Figure 12-</b> Velocity rate of change along the turbine (Dixon & Hall) .....	31
<b>Figure 13-</b> Axial induction velocity at the actuator disc.....	32
<b>Figure 14-</b> Wind velocity changes through the turbine. Velocity triangles (NTNU, 2017).....	38
<b>Figure 15-</b> Illustration of rotor disc wake model (NTNU, 2017) .....	38
<b>Figure 16-</b> Illustration of the turbine blade elements (Haugset & Frøyd).....	39
<b>Figure 17-</b> Decomposition of lift and drag forces along the horizontal and vertical axis (Frøyd & Kjetil Haugset).....	40
<b>Figure 18-</b> Blade design procedure Algorithm. ....	43
<b>Figure 19-</b> BEM Algorithm. Blade optimization. (Haugset & Frøyd) .....	47
<b>Figure 20-</b> Aerodynamic parameters in a blade section of the final model.....	52
<b>Figure 21-</b> Ashes wind velocity triangles .....	53
<b>Figure 22-</b> Text file example to enter the blade profile into Ashes.....	53
<b>Figure 23-</b> Ashes simulation example.....	54
<b>Figure 24-</b> Ashes and Excel iteration algorithm to compute the final design .....	55
<b>Figure 25-</b> Illustration of the Excel used to maintain a smooth profile at every iteration.....	57
<b>Figure 26-</b> Blade geometry in Step file format exported into Inventor .....	60
<b>Figure 27-</b> Final 3D drawing created by Inventor. Blade extrusion and turbine assembly .....	61
<b>Figure 28-</b> Minimum thickness correction procedure.....	62
<b>Figure 29-</b> Blade tip extrusion to create a smoother profile .....	63
<b>Figure 30-</b> Roundness procedure to ensure a good manufacturing process and a smoother profile .....	63
<b>Figure 31-</b> Electrical equivalent circuit for a three phase radial generator (Frøyd & Kjetil Haugset) .....	65
<b>Figure 32-</b> Generator design algorithm .....	68
<b>Figure 33-</b> Ashes generator simulation example.....	72
<b>Figure 34-</b> SprutCAM simulation for the final design before the manufacturing process.....	74
<b>Figure 35-</b> SprutCAM matrix necessary to simulate the CNC program for the final design before the manufacturing process .....	75
<b>Figure 36-</b> Milling process .....	76
<b>Figure 37-</b> Turbine after the polishing process .....	77
<b>Figure 38-</b> Turbine before the polishing process .....	77
<b>Figure 39-</b> Coils manufacture for the three phase Radial generator .....	79
<b>Figure 40-</b> Generator final design. After the assembly .....	80
<b>Figure 41-</b> Three phase radial generator test.....	84
<b>Figure 42-</b> Wind turbine assembly in the wind tunnel.....	85
<b>Figure 43-</b> Rotor assembly in the wind tunnel .....	85

# List of Graphics

<b>Graphic 1</b> - Wind power growth during the last two decades (aeolica, 2018) .....	5
<b>Graphic 2</b> - European Ranking for new installed wind power (aeolica, 2018).....	6
<b>Graphic 3</b> - Pressure behaviour through the wind turbine from far upstream to far downstream (Dixon & Hall).....	30
<b>Graphic 4</b> - Power coefficient in function of axial induction factor .....	35
<b>Graphic 5</b> - Power coefficient in function of Tip Speed ratio (TSR).....	35
<b>Graphic 6</b> - Thrust coefficient in function of axial induction factor .....	36
<b>Graphic 7</b> - Torque and Thrust forces at every blade section .....	50
<b>Graphic 8</b> - Distribution of the Chord length at every blade section .....	50
<b>Graphic 9</b> - Twist angle at every mean radius.....	50
<b>Graphic 10</b> - Power output at every mean radius.....	50
<b>Graphic 11</b> - Power coefficient of the first pre-design.....	56
<b>Graphic 12</b> - Power output of the first pre-design.....	56
<b>Graphic 13</b> - Distribution of the twist angle at the final iteration.....	58
<b>Graphic 14</b> - Distribution of the Chord length at the final iteration .....	59
<b>Graphic 15</b> - Generator Torque matching the Turbine torque. Different possibilities for the final design.....	71
<b>Graphic 16</b> - Generator efficiency for all different designs in function of Load resistance .....	71
<b>Graphic 17</b> - Generator torque at the design rotational speed for different values of tested load resistance	83
<b>Graphic 18</b> - Power Output at the design rotational speed for different values of tested load resistance ....	83

## List of equations

<b>Equation 1-</b> Lift and Drag forces.....	22
<b>Equation 2-</b> Reynolds number.....	23
<b>Equation 3-</b> Total available kinetic energy in the wind.....	25
<b>Equation 4-</b> Definition of Mass flow rate.....	25
<b>Equation 5-</b> Ideal total power output available.....	26
<b>Equation 6-</b> Total energy in KWh.....	26
<b>Equation 7-</b> Tip-Speed Ratio (TSR).....	26
<b>Equation 8-</b> Thrust force.....	27
<b>Equation 9-</b> Thrust coefficient.....	28
<b>Equation 10-</b> Lift coefficient.....	28
<b>Equation 11-</b> Drag coefficient.....	28
<b>Equation 12-</b> Power coefficient.....	29
<b>Equation 13-</b> Total power output.....	29
<b>Equation 14-</b> Power coefficient in function of the axial induction factor.....	34
<b>Equation 15-</b> Thrust coefficient in function of the axial induction factor.....	36
<b>Equation 16-</b> Decomposition of the total force in the axial and tangential direction.....	40
<b>Equation 17-</b> Axial force coefficient and rotational force coefficient.....	40
<b>Equation 18-</b> Axial and tangential components for one blade element.....	41
<b>Equation 19-</b> Axial and tangential forces components for the total number of blades per disc section.....	41
<b>Equation 20-</b> Ideal axial and rotational forces coefficients without drag.....	45
<b>Equation 21-</b> Blade Element Parameter.....	45

# List of symbols

## Symbols

### Latin symbols

$A$	rotor sweep area, [m <sup>2</sup> ]
$a$	axial induction factor, [-]
$a'$	rotational induction factor, [-]
$a_c$	critical axial induction factor, [-]
$AR$	aspect ratio of the blade, [-]
$B_{EP}$	Blade element parameter, [-]
$C_a$	axial force coefficient, [-]
$C_D$	drag coefficient, [-]
$C_L$	lift coefficient, [-]
$C_P$	power coefficient, ratio of efficiency, [-]
$C_r$	rotational force coefficient, [-]
$C_T$	thrust coefficient, [-]
$dX$	value of $X$ on one blade element
$E$	energy, [J]
$F$	Prandtl's tip loss factor, [-]
$f$	exponential integer in the tip loss factor
$F_D$	drag force, [N]
$F_L$	lift force, [N]
$K$	factor in Glauert's correction factor, [-]
$k_M$	Non-dimensional moment coefficient [-]
$k_V$	Non-dimensional wind speed coefficient [-]
$L_C$	chord length, [m]
$m$	mass, [kg]
$M$	torque force, [N]
$P$	power, [W]
$p$	pressure, [Pa]
$r$	radius of a location of the blade [m]
$R$	radius of the tip of the blade, [m]
$Re$	Reynolds number, [-]
$t$	time, [s]
$T$	thrust force, [N]
$U$	rotational speed of the blade, [m/s]
$V$	wind speed, [m/s]
$W$	resultant wind speed, [m/s]
$Z$	number of blades on the turbine, [-]

### Greek symbols

$\alpha$	angle of attack, [deg]
$\beta$	angle of attack, [deg]
$\Delta$	difference over a distance
$\theta$	twist angle, [deg]
$\lambda$	tip speed ratio, [-]
$\lambda_r$	speed ratio at radius $r$ , [-]
$\rho$	density, [kg/m <sup>3</sup> ]
$\sigma$	solidity of the blade, [-]
$\nu$	cinematic viscosity, [kg·m <sup>2</sup> ]
$\varphi$	flow angle, [deg]
$\omega$	rotational speed [rad/s]
$MP$	Matching point
$tot$	total
$\dot{m}$	time derivative of $m$
1	far upstream of the turbine
2	at the turbine
2-	just before the sweep area
2+	right after the sweep area
3	far downstream of the turbine

1

# Introduction

## 1.1 Objective

The main objective of this project is to design a small two bladed wind turbine optimizing the total efficiency. This paper is focus on the turbine and stator generator designs. Consequently, I had tried to compromise both turbine and generator efficiencies by optimizing its matching.

More specifically, my personal goal in this project is to create an optimal turbine design with a total efficiency around 40%, value not too far away from industrial turbines. Thus, I decided to optimize as much as possible the turbine to later optimize the generator design.

Moreover, the NTNU offered me the opportunity to test my design in its wind tunnel. This opportunity gave me the chance to apply for first time in my life my personal engineering knowledges to a real project.

In this sense, all data simulations were contrasted by the real wind tunnel data. Thus, this made me learn that theory often moves away from reality.

In summary, my main goal in this project is to produce a wind turbine with a total efficiency of 40% by designing and manufacturing the turbine rotor and a three phase generator stator. Secondly, my personal goal is to learn the more I can about wind turbines and enjoy the experience of carrying out sucessfully my first real engineering project.

## 1.2 Motivation

Since the last century, we have try to reduce our dependency on fossil fuels by exploring and investigating other energy sources. This change of tendency was mainly due to economic and to lesser extents to social reasons. Especially the 80s was the time for the society to concern about the new arising term known nowadays as Global Warming. Global warming is the most recent type of climate change. It is true that our planet has suffered from climate changes since the beginning. However, our social and industrial evolution based on CO2 emissions and fossil fuels are producing this change to happen faster than ever.

Indeed, this rapid rise in greenhouse gases is a problem because it is changing the climate faster than some living things may be able to adapt. Also, a new and more unpredictable climate poses unique challenges to all life. (Geographic, s.f.)

Because of this, the renewable energies have started to experience a market growth. However, the fossil fuels continued to govern the energy market and it was not until this century when renewable energies experience a great boom.

This boom has been boosted by the concerns of the society and governments in environmental issues. Since this century, global warming is globally known to be one of the biggest challenges we need to face in our modern history.

This awareness for the sake of our planet is making the governments, the society and most of multinational companies to invest in energy sustainability and renewable energies. What is more, some governments are not only investing in these new sources but penalizing fossil fuels and its derivatives.

For instance, some cities as Madrid, London or Oslo are currently penalizing the use of combustion engine cars by increasing their taxes or not allowing them to go into the city centre. Moreover, all multinational companies are usually controlled by governments which are regulating the limits of contamination for their industrial processes. These policies, which are necessary but not always good implemented, have had also an impact in our society.

All this reasons are leading to our society and industry to invest more in sustainability and renewable energies. This investments increase have led to new technologies, researches, projects and ideas to develop. In this sense, the strongest arguments imposed by the fossil fuels defenders have been weakened by the increase of renewable energy performances up to incredible efficiencies.

Moreover, this evolution in the energy market is questioning other old arguments by making wind power to be competitive in prize with other energy sources like nuclear power and thermal power which were used to be known as the cheapest sources.

In conclusion, our society and industry are currently evolving to a more environmentally friendly version. Wind power is currently a great alternative to finish with massive fossil fuel energy processes. Nowadays, wind industry is investing incredible amounts of money to explore new projects such as offshore wind turbines and small wind.

This evolution is opening to us a new working industry which will not only give us the opportunity to work in great projects but to help our society and our planet.

In this sense, my motivation for this project is take part in this change. Since I started my Bachelor I have been really interested in renewable energies but it was not until this year when I discover my passion for Wind Energy. Therefore, my interest for this project is to start my education in wind turbines field by learning to design a small two bladed wind turbine.

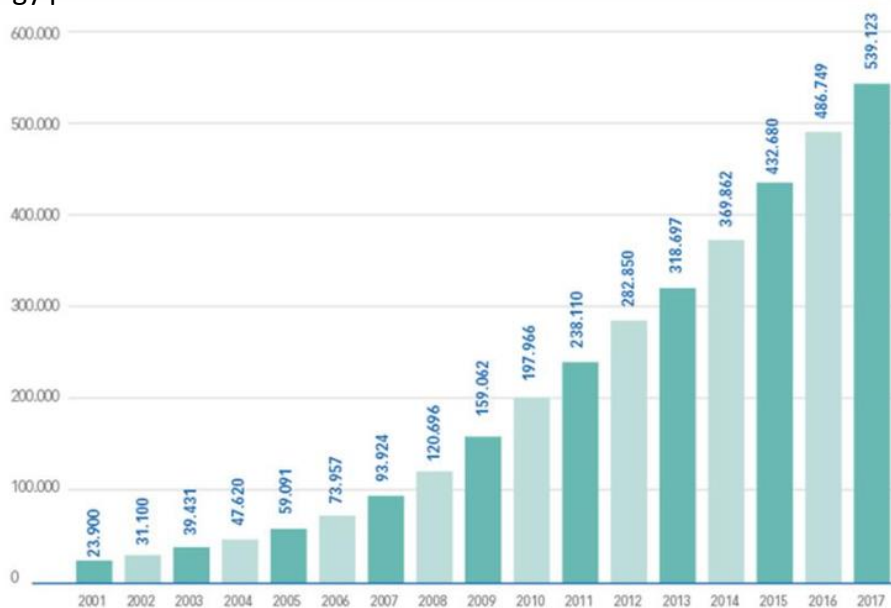


## 1.3 Wind power industry in the global energy situation

For the last two centuries, the global population has grown from 1000 to 7300 million people approximately. This add to the constant growth of the industry and economic possibilities of the population have promote an increase in the energy consumption.

In this sense, it is foreseen that the world will consume 30% more energy in 2040. This increase is similar as adding another country like India or China in the current global energy consumption market. These circumstances added to the Global Warming led the United Nations to sign in 2016 the Pact of Paris. The aim of this pact is to reduce emissions of greenhouse gases that cause global warming and limit the Global Warming down to 2 degrees.

Because all of this, the European Union (EU) has stated that at least the 30% of the energy production should come from renewable energies in 2030. This added to the existing growth in the renewable energy market has empower the solar and especially the wind power industry during the las two decades. The aim of the UE during the following years is to improve the global sustainability and clean energy production.



**Graphic 1** - Wind power growth during the last two decades (*aeolica*, 2018)

Likewise, other countries like China have taken similar policies. For instance, China is the country that have invest more in wind energy up to the point of producing 145.100 MW. In other words, during the last year in this Asian country, more wind energy (30,500 MW) was launched than in the 25-year history of wind energy in Spain (23,025 MW) (Elcacho, 2016).

Thus, these investments in the renewable energy market and especially in the wind power industry are promoting great advances in this technology. For instance, during the last two decades companies are starting to go offshore in their projects.

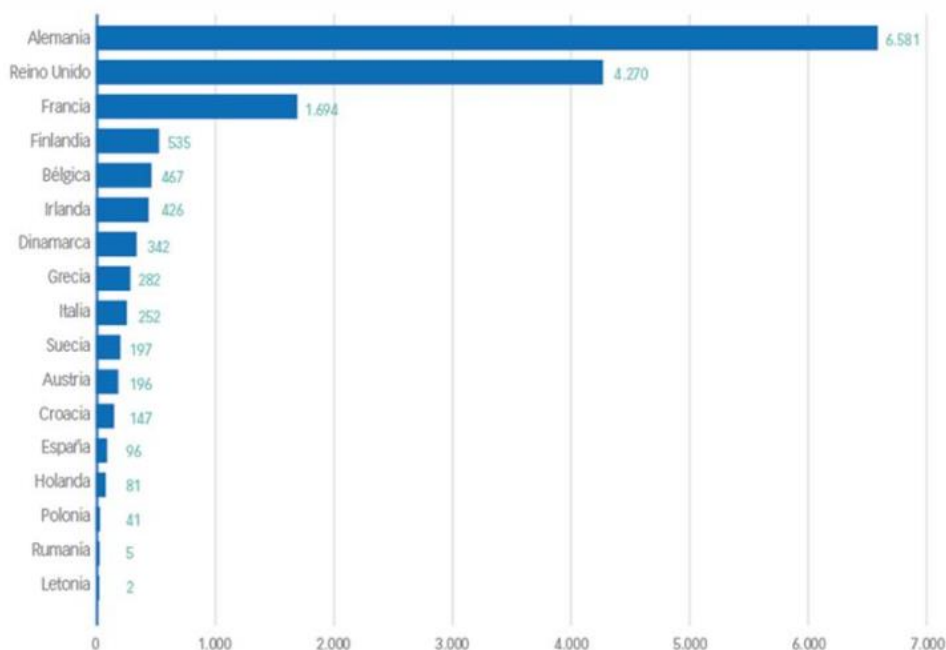
Wind turbines are becoming bigger and more efficient. Although, it has been always known that wind resource is better in the ocean than onshore, years ago the companies did not have enough technology to install and maintain offshore wind farms. However, the majority of the companies are currently working to develop systems to cheap and improve the offshore technology.

This change of trend in society and politics have led some companies to evolve from a business based on the production and marketing of oil to being leading companies in the renewable energy sector. For instance, a great example of this tendency change is the Norwegian company Statoil which has recently change its name to Equinor. Statoil is a Norwegian petrol company that has been investing during the last decades in renewable energies. Indeed, they are the creators of a new offshore technology used in offshore floating wind farms.

The aim of this pilot floating project “Hywind” in Scotland is to enable future projects to go to deeper waters. *“Offshore wind already has a strong foothold in Europe with 10 GW installed capacity, and a global potential to reach more than 100 GW by 2030. With fixed turbines, offshore wind is optimal for 20-50 metres water depth. With floating structures, further expansion will be enabled in new deep-water areas around the world”* (Statoil, 2018).

On the other hand, some other countries like Spain, Germany, Denmark and Netherlands are also leaders in wind power Industry. For its part, Spain counts with international companies like Acciona and Gamesa which are two of the biggest wind turbines designers in the world.

On the other hand, Germany counts with Siemens which is one of the five biggest wind turbines producers. When talking about wind turbines it is necessary to mention Denmark and Vestas. Denmark is known for their tradition in the wind power. Indeed, Denmark was with the USA pioneers in wind power study.



**Graphic 2-** European Ranking for new installed wind power (aeolica, 2018)

In conclusion, the energy market will tend to increase more and more the use of renewable energies. The three most important clean energies are Hydroelectric, wind power and solar power. However, during the last decades there has been a special interest for wind power. This global interest have made all companies to develop new technologies in wind turbines field.

We are facing a slow social and industrial change that still has a long way to go. Our power industry is evolving to an industry focus on sustainability and renewable energies with wind power industry like the relay of non-renewable energies and fossil fuels.

## 1.4 Project Structure

The paper is structured as following:

- First of all, the state of art of wind turbines will be briefly discussed. In this section, the history of wind turbines from their origins up to the modern wind turbines will be commented.
- In the next space, it will be analysed not only the design of a two bladed HAWT but the main theory fundamentals behind the design procedures are presented along the paper. Moreover, all steps up to the final design will be extensively illustrated.
- Then, this paper makes mention to the manufacture procedure for both generator and rotor. Both manufacturing procedures will be explained and commented.
- In the next section, an analysis of the test results is presented for both generator and the whole turbine. First, it will be presented the generator test and then the wind tunnel test.
- Finally, a global conclusion is presented. Along this conclusion, a comparison between theoretical and tested data will be discussed.

2

State of art

## 2.1 Historical Viewpoint

The extraction of mechanical power from the wind is not a new art. For three thousand years, the human being has been using the wind for their daily lives. Beginning with sailing ships, the wind power was extended to the early windmills to grind the grain. Windmills are known to be one of the ancient's machines of the history. They are believed to have originated in Persia during the seventh century. Then by the twelfth century, their use had spread across Europe. (Dixon & Hall)

However, industry was and is dominated by fossil fuels and petrol extraction. Even so, this tendency is something that has started to change for the last four decades. In this sense, our society and specially our industry are evolving to be more environmentally friendly.

The first studies in wind energy were carried out by **Charles F. Brush** (1849-1929) who created the first wind turbine for power generation. This first wind turbine was composed by a **17 m** diameter rotor with **144** wool blades. Moreover, this American entrepreneur established the **Brush Electric Company** in 1890, which would merge with others in the origin of **General Electric** in 1891.

Secondly, when talking about wind energy is necessary to mention the German physicist **Albert Betz** (1885-1968). In his stage of director of the aerodynamic institute in Göttingen, he formulated the law Betz, that established the maximum value that can be used the kinetic energy of the wind, 59,3%. His theory on the formation of wings can still be used for the construction of wind turbines.

On the other hand, another pioneer in this field was the Danish **Poul la Cour** (1846- 1908) who is considered the father of the modern wind energy. He established the first wind energy academy from which the first specialized engineers emerged.

The production of his first modern wind turbines was between the 1930s and 1940s. However, after the Second World War, their development were stopped due to the low prize of fossil fuels during these years. It was not until the big recession in the petrol market around 1970s when they retake their study.

During these years, the oil market recession led to a change of tendency in the energy policy. In this sense, the interest in alternative energies grew and led to the creation of research programs and grants. Since this moment, the wind industry started to receive large investments.

Moreover, during the 1980s there were movements against nuclear energy that empowered the use of renewable energies. During this decade and the next one, there were great advances in wind energy technologies that started to make them competitive compared to other non-renewable energies. In 2001, it was founded the **World Wind Energy Association** based in Bonn, Germany. Since its creation, the aim of this association has been to promote this source of energy. During this century, the wind energy market has experienced a huge boost, especially the offshore technologies.

“It is interesting to note that the global wind power capacity is now still doubling every 3 years. The biggest regional contributors to this installed growth in wind power are the Peoples Republic of China. According to the GWEC, the development of wind energy in China in terms of scale is absolutely unparalleled in the world. By the end of 2010, the installed wind power capacity had reached 41.8 GW. Up to May 2009, 80 countries around the world contributed to the generation of wind power on a commercial scale. Predicting the growth of wind power generation is far from reliable. At the end of 2011, the total worldwide wind power capacity had reached 237 GW” (Dixon & Hall)

These changes in energy policies and the constant population growth, place the wind energy as one of the best positioned alternatives to take over the energy market. In this sense, a great growth is expected in the wind energy market.

Because of this, the big international companies like **Siemens, Gamesa, Vestas, Norges, Statoil** and **Enercon** among others are currently empowering their offshore projects. Offshore turbines experience a better wind source and can be bigger than onshore turbines. This change of workplace allow the manufacturers to produce taller and bigger turbines which is summarized in a higher energy production.

## 2.2 Wind turbines fundamentals

### 2.2.1 Definition of a Wind Turbine

A **wind turbine** is a device that converts kinetic energy from the wind into electricity (Acciona, s.f.). This device is mainly composed by a Rotor and a Generator. While the Rotor (also known as Turbine) converts the wind kinetic energy into mechanical rotation of the blades, the generator converts this mechanical energy of the turbine into electricity. This term must be not confused with **windmill** which is a machine used to convert wind power to mechanical power. (Dixon & Hall)

Although, great advances have been done in aerodynamics and wind energy during the last decades, the efficiency of wind turbines comes limited by a theoretical limit called the Betz limit (Dixon & Hall). In other words, wind turbines are not able to extract all the kinetic energy from the wind. For a wind turbine to achieve a 100% efficiency, the wind should be completely stopped by the turbine which is physically impossible. This is shown by the **actuator disc theory** and the **Betz limit**.

## 2.2.2 Types of Wind Turbines

Wind turbines can be divided into two main categories: the ones that depend on aerodynamic drive to drive them, and the ones that depend on the lift force. (Dixon & Hall)

It is remarkable that turbines driven by drag force are much less efficient. This is the case of the ancient windmills designs and consequently they used to have a really low efficiency.

On the other hand, current turbines usually work by using the lift force. The rotor of this machines is designed to interact with the airflow to produce a lift force. However, they still producing a small drag force. In modern turbines, the lift usually is a hundred times bigger than the drag force.

Modern turbines can be divided also in Horizontal Axis Wind Turbines (HAWT) and Vertical Axial Wind Turbines (VAWT). HAWT are currently the most used in energy production. However, VAWT have some mention in turbulent airflow and small wind. Furthermore, they are silent and can work with winds that continuously change direction. Nevertheless, this project is focus on HAWTs and therefore VAWT's performance is out of the scope of this paper.



**Figure 1-** *Two bladed HAWT (Dreamstime)*



**Figure 2-** *Three bladed HAWT (Gamesa)*





**Figure 3-** VAWT in Netherlands (WePower)



**Figure 4-** VAWT in Denmark (WePower)

### Large HAWTs

As it was mentioned above, HAWTs are dominant in all energy market applications. The most common wind turbine is the three blade horizontal wind turbine showed in **Figure 1**. These turbines basically are compromised by a nacelle mounted on top of a high tower, containing a generator and, usually a gearbox to which the rotor is attached (Dixon & Hall).

Another key difference in wind turbines is the number of blades which basically depends on the purpose of the turbine. For instance, while three blade turbines are generally used in massive electricity production, two bladed turbines are generally used in small wind applications.

Two bladed turbines have in general higher Tip-speed ratios and a smaller starting torques. This makes sense, as its inertia is lower than three bladed wind turbines. However, two bladed wind turbines usually need some assistance at their start up to go up to their operation points.

On the other hand, the most important parameter when talking about electricity production is the diameter of the rotor. The bigger are the blades, the more swept area and the more power output they produce. In this sense, new designs of HAWT tends to be larger and taller. It is remarkable that the upper the rotor is located the better wind resource will experience.

## Small HAWT

These turbines were developed in the nineteenth century for agricultural tasks like pumping water. However, there has been a worldwide revival in small HAWT for provide electricity to remote homes (Dixon & Hall). Furthermore, they can be used in airports and other places where large HAWT cannot operate legally. Small HAWT are also a great tool to extract energy from poor wind resources. This tendency of small wind was develop in the early 1970s but now it has experienced a revival because of the new policies in the energy market. New small HAWTs range from 1 to 100 KW and are a perfect option for cities and remote places.

Multinationals are starting to invest a lot of money to find a compromise between fossil fuels and renewable energies where small HAWT can perfectly match their interests.

## 2.3 Wind characteristics and resource estimation

Wind energy is known for its variability both spatially and temporally. This variability depends on many factors like: season of the year, type of vegetation in the location, climatic region but especially on altitude and topography. In this sense, the wind is stronger on the mountains or in the cost rather than in valleys (Dixon & Hall).

For this reason the new designs of modern wind turbines are tending to go offshore where the wind resource is better. Furthermore, offshore the legislation is less strict in terms of size and therefore we can produce bigger turbines and improve the electricity production. Moreover, offshore wind is characterised to be higher and less turbulent than inland wind.

The main reason why cost and offshore areas have a better wind resource is the difference in heating between inland and sea. For all of this, before installing wind turbines a deep analysis of wind resource is required. This wind resource estimations comes hand to hand with statistics.

Consequently, to assess the frequency of wind speed at a location, a probability distribution is often needed. The two most common used distributions are:

- *Rayleigh distribution*
- *Weibull distribution*

While Rayleigh distribution is known to be simpler than Weibull distribution, this latter is more accurate and more widely used in industrial applications. However, wind may change from one year to the next. These changes are not well understood and statistics is the only tool we have to analyse wind resources.

The wind must be strong for a time enough to be profitable. Consequently, the wind resource is the main parameter in the decision of where to locate an Eolic farm and which type of turbine match better the local resource. However, as my turbine was tested in a wind tunnel, this analysis of wind resource is out of the scope of this project. Thus, I have designed my turbine supposing a nominal wind velocity of 10 *m/s*.

## 2.4 New technologies and modern wind turbines

### 2.4.1 Offshore wind turbines

As it has been commented above, wind power industry has experienced a great development during the last decades. Although good improvements have been on the aerodynamic of wind turbines, the big advanced that stand out are related to offshore technology.

Since this century, big wind turbines manufactures are investing and investigating offshore projects. Although, go offshore is not a new idea (some pilot projects were performed during the 1990s) it was not until the XX century when they become popular.

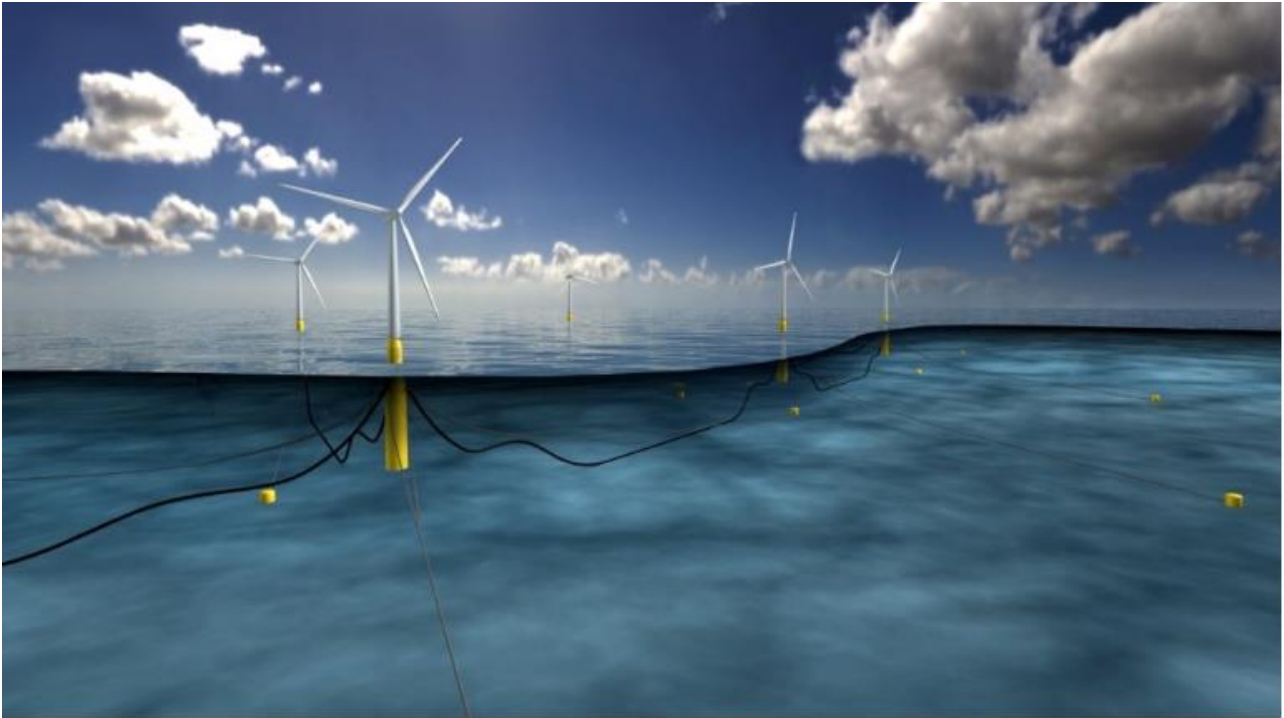
Go offshore have some advantages but also some disadvantages. In this sense, while wind turbines experienced a better performance and a better wind source, their installation and maintenance are more complex. Note that big storms and waves could be really strong in the middle of the ocean and can easily damage the turbine. Moreover, offshore turbines expects more loses because they are usually more far away to the connection point than onshore wind turbines.

However, great advantages in the control field have promote wind turbines to go offshore in search of higher power production. Another common tendency during the last years has been to design bigger and taller wind turbines. This makes sense because on the one hand, the bigger is the wind turbine the more power output will have, and on the other hand, the taller are located the better wind source will experience.

One of the main challenges in offshore technology is to go more far away from the coast where even less obstacles are found and a better production achieved. However, it is difficult to go more far away because this means to go deeper.

Consequently, most of the most important wind turbines manufacturers are working to solve this problem. However, Statoil is the one who has come up with one of the most innovative solutions of wind turbines history by installing floating wind farms. This project called Hywind, has been developed by this Norwegian company at Buchan Deep, 25 km offshore Peterhead, harnessing Scottish wind resources (Statoil, Hywind, 2018).

This pilot wind farm is seen as an important step forward in offshore wind turbines technology. Thus, all these changes have revolutionized the wind industry up to the point to be competitive with non-renewable energies.



**Figure 5-** *Hywind floating farm model (Statoil, Hywind, 2018)*

## 2.4.2 Small wind

Another trendy field related to wind turbines is the so called “*Small wind*”. Small wind refers to small wind turbines that are able to produce power in both isolated places and cities. These small wind turbines are perfect for places where big wind turbines cannot be installed. Some of this target places are Airports, cities, roads and family houses.

Currently, because of the growing concern about global warming, a lot of families decide to install their own clean power source. Furthermore, small wind turbines offer to their customers the possibility to save money though self-consumption.

These wind turbines are usually not more than 20-25 m high and have rotors of 2-7m diameter. Their power production goes typically from 1KW to 10KW. In this sense, there are a lot of companies that have specialized in small wind rather than in big wind turbines. Some examples are the Spanish companies Enair and Bornay.

Although these small wind turbines have been operating since the early 1970s, they were typically used to produce off-grid energy production. In other words, they were used to produce power for isolated places like farms. However, they are nowadays used to improve the sustainability of cities, buildings and factories.

Furthermore, they are better than big wind turbines when talking to turbulent flow. Because of this, they are perfect for places where big wind turbines are not optimal. Thus, the use of small wind turbines in big cities and Airports have spread widely. Note that this technology is available for both horizontal and vertical axis.

As conclusion we can consider that this technology is fighting hand to hand with solar power to reduce the energy consumption of big companies, buildings and family homes.



**Figure 6-** Example of a horizontal two bladed small wind turbine (Bornay, 2018)



3

# Turbine design

### 3.1 Summary

The scope of this section is to describe the design of a small Horizontal Axis Wind Turbine. In this sense, all steps taken to achieve the final design will be extensively discussed. It is remarkable that the main objective of this project is to design a small two bladed HAWT with a total efficiency around 40%. Thus, all design decisions related to rotor, generator and their coupling will be discussed during this paper.

The first task of the project is the Blade design. This design gives us the optimal rotational speed and torque which will be input data for the generator design. In this sense, several blade designs have been developed to achieve the final blade profile. The aim of the rotor design is to achieve the highest possible  $C_p$  within the initial characteristics and size requirements. The higher is the  $C_p$ , the higher torque our blade will experience and therefore, the higher power output will offer. To do this, a Matlab Algorithm based on the Blade Element Momentum (BEM) given the airfoil **NREL S826** was elaborated.

The Matlab Algorithm gives an initial optimal blade distribution in terms of Chord Length and Twist Angle. Then, this distribution is written into a text file which was introduced in a simulation software called Ashes with the aim to start the iteration process. This simulation software offers high accurate output data like **total efficiency, coefficient of performance, torque and thrust forces**. Thus, Ashes has the double objective of checking the Matlab calculations and offering the designer an excellent tool to iterate the initial model.

Thus, these iterations are made by exploring small changes in the blade profile and simulating the new model performance. The two parameters to be optimize are the Chord length and twist angle. However, this project has been subjected to strict blade size requirements. In other words, the blade had to be inside of a milling box with the following size characteristics: **1000 x 100 x 50 mm**.

In general terms, the higher Chord length the blade has, the higher  $C_p$  the blade will present. Thus, a trade-off between the Chord Length and Twist Angle is necessary to compromise efficiency and rotor size. These iterations are made by changing one of the two parameters using an Excel sheet to maintain a smooth profile and checking the performance with Ashes.

On the other hand, the generator design depend on the rotor design. In this sense, the final rotor information was exported from Ashes to design the generator that later would be coupled with the turbine. Accordingly, the main input generator design parameters are the turbine torque and rotational speed which need to be matched by the generator torque achieving the highest possible generator efficiency. To do this, two Excel sheet have been needed to compromise generator torque with generator efficiency. This generator design will be explained later on this chapter under the section Generator design.



## 3.2 Blade design restrictions

During this section, a deep analysis of the blade design procedure will be presented. As it was mentioned in the objective, the aim of this project is to design a turbine with a total efficiency of 40% for the following initial given specifications:

- Maximum rotor diameter: **1 m**
- Number of blades: **2**
- Airfoil: **NREL S826**
- Maximum Tip Speed Ratio (TSR): **7.5**
- Minimum chord length: **20 mm**
- Design wind Velocity: **10 m/s**
- Minimum Blade thickness: **0.6 mm**

Note that these design specifications were given by the *Norwegian University of Science and technology* following the experience given by the course *TEP 4175 Design of Wind turbines*.

However, before going through the design procedure, all necessary theory fundamentals to design wind turbine will be presented.

## 3.3 Wind turbines and aerodynamic theory fundamentals

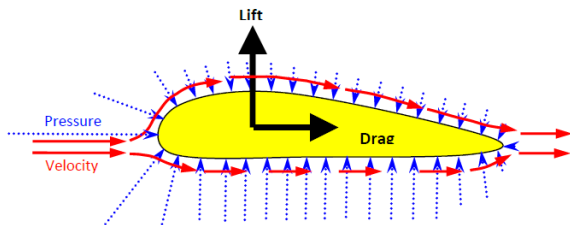
During this section, all theory fundamentals used during the project will be presented. The theory in this chapter is based on “*Wind Energy Handbook*” (Bossanyi, Burton, Jenkins, & Sharpe, 2001) Chapter 3, “*Fluid Mechanics and Thermodynamics of Turbomachinery*” (Dixon & Hall) Chapter 10 and “*Analysis and Design of Wind Turbines*” (Haugset & Frøyd) and the course *TEP 4175 Design of a Wind Turbine*.

### 3.3.1 Airfoil theory

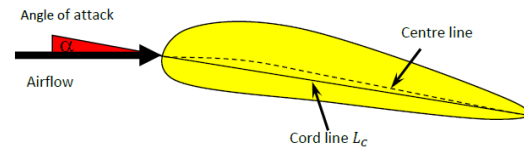
Wind turbines need to generate a torque to produce mechanical power on the shaft which is in turn essential to produce electrical power output. This torque is consequently generated by aerodynamic forces acting on the blade. The two forces acting on the blade are the lift force  $F_L$  and the drag force  $F_D$ . These two forces are caused by a pressure distribution around the airfoil.

A wing profile is shaped that the airflow is split over and under the wing. There is a pressure and speed difference between each split. The upper surface experiences a higher velocity and therefore has less pressure than the down surface. This pressure difference led to the wing to experience a lift force which is perpendicular to the airflow (Haugset & Frøyd).

In this sense, the lift force makes the blade move perpendicular to the flow. This is the force used by HAWT to rotate.



**Figure 8-** Airflow behaviour around the blade (Frøyd & Kjetil Haugset)



**Figure 7-** Definition of chord line and angle of attack (Frøyd & Kjetil Haugset)

However, this lift force does not come without a cost and a drag force will appear in the blade. As it can be observed in the **Figure 8** the lift force is perpendicular to the chord line while the drag force is parallel to it. The drag force reflects the resistance of the blade for facing the axial force produced by the wind.

On the other hand, another important parameter that controls the size of both lift and drag forces is the angle of attack. This angle is defined as the angle between the chord line and the relative air velocity (Dixon & Hall).

Consequently, we can define lift and drag force as:

$$F_L = \frac{1}{2} \rho W^2 C_L L_c dr$$

$$F_D = \frac{1}{2} \rho W^2 C_D L_c dr$$

**Equation 1-** Lift and Drag forces

Where,

$\rho$ : Air density

$W$ : Relative Air Velocity

$L_c$ : Chord length

$C_L$ : Lift coefficient

$C_D$ : Drag coefficient

$dr$ : Blade differential length

The coefficients  $C_L$  and  $C_D$  are also dependant to the **Reynolds** number for some values of angle of attack. The Reynolds number is a non-dimensional number used to determine the transition from laminar to turbulent flow. This number can be defined as:

$$Re = \frac{L_c W_2}{\mu}$$

**Equation 2- Reynolds number**

Where  $\mu$  is the kinematic viscosity.

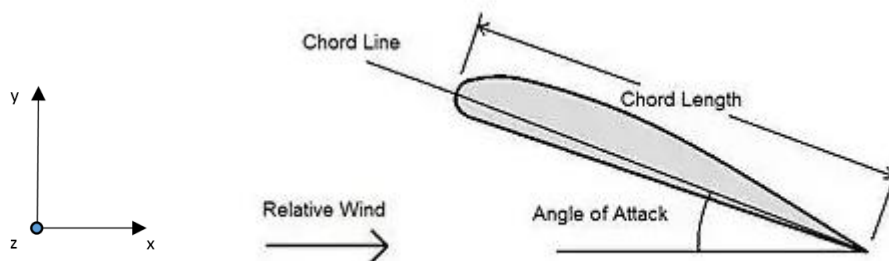
However, we can disregard the influence of the Reynolds in our blade design because this dependency happens only for some certain angles of attack that are not inside the turbine blade design spectrum. This allows us to disregard the Reynold influence when designing our turbine without much error.

### 3.3.2 Airfoil and blade parameters

Wind turbines are formed by aerodynamic profiles that allow them to take advantage of the aerodynamic forces to extract energy from the wind. Depending on the type of turbine, wind turbines will make use of a profile or another. In this way, aerodynamic profiles of HAWT are quite different from the ones used by VAWT. In this sense, we will focus on the theory which is behind HAWT profiles. Some key blade and airfoil parameters are the next:

#### 1. Chord length:

The chord length is defined as the airfoil length from the attack to the end edge. This can be simply understood by the next figure:



**Figure 9- Differences between chord lentgh and chord line (quora, 2018)**

## 2. Chord line:

The chord line is defined as the line that matches the attack to the end edge. This can be also seen graphically in **figure 9**.

## 3. Twist angle:

The twist angle is the angle between the chord line and a reference plane which usually is a vertical plane. In **figure 9** it would be the angle between the illustrated chord line and the plane YZ.

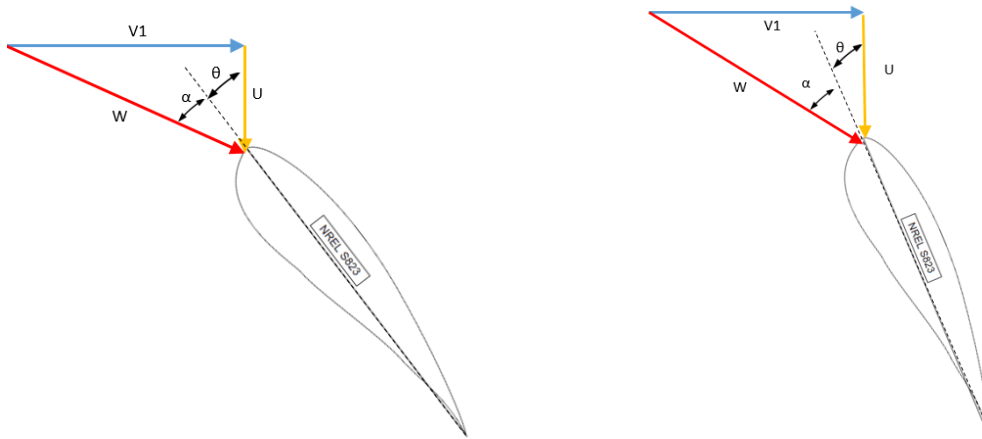
## 4. Angle of attack

The angle of attack is the relative wind velocity angle with respect to the chord line. During this project we have designed the blade to maintain this angle of attack along the blade. This can be done by twisting the blade.

### 3.3.3 Twisting the blade to maintain a constant angle of attack

The coefficients  $C_L$  and  $C_D$  are strongly dependent to the angle of attack. For blade design it is common to use tabulated data that comes from wind tunnel tests for some given airfoil. On the other hand, wind turbine blades should be designed for an optimal angle of attack along the blade. This optimal angle of attack is defined as the angle that achieves an optimal ratio between lift and drag coefficients and it is nearly constant through the blade.

To maintain this angle constant, the blade needs to be twisted. This can be easily understood by analysing the blade velocity triangles along its longitudinal direction. While the axial wind velocity is supposed to be constant along the blade, note that the more we distance from the blade's root, the more tip speed we have. This increase in tip speed led to an increase in relative velocity. Consequently, as it can be seen in **figure 10**, the only possibility to maintain the optimal angle of attack along the blade is to change every blade's section position.



**Figure 10-** *Twisting the blade to maintain an optimal angle of attack along the blade*

### 3.3.4 Energy and Power output

The aim of a wind turbine is to extract as much kinetic energy as possible from the wind source. As it will be explained later along the Actuator disc approach, wind turbines take the wind to experience a velocity decrease and a pressure drop through their rotor causing an energy exchange between the turbine and the wind.

Note that this energy exchange is a dynamic process since it depends on the axial wind velocity. As it was mentioned above, the wind source is constantly changing. In this sense, the total available kinetic energy in the wind at a given speed ( $V_1$ ) can be expressed as:

$$E_{total} = \frac{1}{2}mV_1^2$$

**Equation 3-** *Total available kinetic energy in the wind*

Where the mass flow rate is defined as:

$$m = (\rho V_1 A)t$$

**Equation 4-** *Definition of Mass flow rate*

As we discussed before, the wind velocity is constantly changing, and therefore when talking about energy outputs it is more interesting to talk in energy per unit time which is also known as power [KW]. Consequently, power output is parameter that varies over time. By applying this change we have:

$$\dot{E}_{total} = P_{total} = \frac{1}{2}\dot{m}V_1^2$$

$$P_{total} = \frac{1}{2} \rho V_1^3 A$$

**Equation 5-** *Ideal total power output available*

As power depends over time, to compute the total energy extracted from the wind in a certain period of time it is necessary to sum every product of power and time over that period. By doing this, we can report the energy in the most common energy unit, *KWh*. This product can be expressed as:

$$E_{total} = \int_{t_1}^{t_2} P(t) dt$$

**Equation 6-** *Total energy in KWh*

### 3.3.5 Characteristics parameters in wind turbines design

There are wind turbines of any kind and size. Consequently, to deal with this variability non-dimensional parameters are applied. These non-dimensional parameters give us the opportunity to compare various wind turbines for a wide range of conditions. This help us especially to compare different turbines for different sizes and wind sources. In this sense, the most important non-dimensional parameters in design of wind turbines are the following:

#### **Tip-Speed Ratio (TSR):**

Tip-speed ratio commonly known as TSR is one of the most important non dimensional parameter for HAWT. This parameter refers to the relation between tip and wind speed. Therefore, it can be defined as:

$$\lambda = \frac{\Omega r}{c_{x1}}$$

**Equation 7-** *Tip-Speed Ratio (TSR)*

Where,

$\Omega$ : Rotational Speed of the Turbine Rotor.

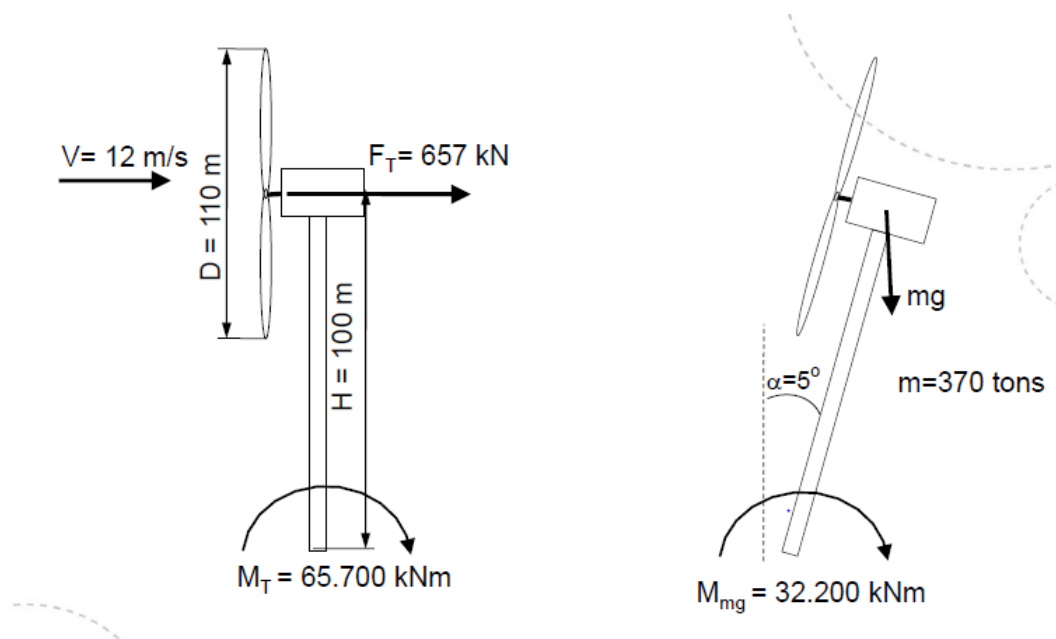
$r$ : Distance to the hub

$c_{x1}$ : Wind velocity far upstream.

Please, note that sometimes far upstream wind velocity may be sometimes called  $V_1$ .

## Thrust coefficient

The thrust force is a pressure force suffered by the turbine in the axial direction (wind direction). Wind turbines usually suffer from high thrust forces and consequently structure resistance is a key field in wind turbines design. The following figure illustrates the importance of the thrust force analysis, especially in offshore turbines where control mechanisms have to counteract the waves and oceanic storms. The next example shows how the bending moment produced by this force cause great stresses in the foundations.



**Figure 11-** Thrust and foundation momentum (NTNU, 2017)

In offshore turbines, it is really important to analyse this parameter because if a big storm is able to bow the turbine, the weight can cause an extra bending moment that in most of the cases will entail to the collapse. Because of this, offshore turbines have a maximum inclination angle allowed of 3 degrees.

However, the analyses of the tower and foundations are out of the scope of this project. This part of the project is fixed by a given structure which is usually used by the NTNU in their own experiments. In general terms, the higher is the efficiency the higher is the thrust force. This thrust force can be written as:

$$F_T = \frac{1}{2} \rho V^2 A_2 C_T$$

**Equation 8-** Thrust force

And the thrust coefficient is defined as:

$$C_T = \frac{T}{\frac{1}{2}\rho AV_1^2}$$

**Equation 9- Thrust coefficient**

Where,

$\rho$ : Air density

$A$ : Rotor Area

$T$ : Torque momentum

### **Lift coefficient**

HAWTs use the lift force to extract energy from the wind. As it can be seen from lift equation, it works as a reduction coefficient in the calculation of the total lift force. The lift coefficient relates the lift force experienced by the blade to the fluid density around the airfoil. It can be expressed as follows:

$$C_L = \frac{F_L}{\frac{1}{2}\rho AW^2}$$

**Equation 10- Lift coefficient**

### **Drag coefficient**

In general terms, engineers try to minimize the wind turbines drag force as much as possible. However, we can minimize this down to a limit because if we want maximize the lift force we will obtain a high drag. In a similar way to the lift coefficient, the drag coefficient works as a reduction parameter in the calculation of the total drag force. The drag coefficient can be defined as follows:

$$C_D = \frac{F_D}{\frac{1}{2}\rho AW^2}$$

**Equation 11- Drag coefficient**



## Power coefficient

As any energy process exchange, wind turbines cannot take full advantage of wind energy. Actually, no existing wind turbine is able to extract more than the 50% of the wind energy. This contrast to hydraulic turbines which are able to reach efficiencies around 95%.

The main reason for this low efficiency is the so called **Betz limit** which will be fully explained later in this section. This limit states that the maximum theoretical power extraction can never be more than 59.3%. Consequently, it is necessary to add a power reduction coefficient in the power output equation. This power coefficient known commonly as  $C_p$  is expressed as follows:

$$C_p = \frac{\text{extrated power}}{\text{power in the wind}}$$

**Equation 12-** Power coefficient

Thus,

$$P_{out} = \frac{1}{2} \rho V_1^3 A C_p$$

**Equation 13-** Total power output

Where,

Note that this  $C_p$  refers to the aerodynamics loses but not to mechanical and electrical loses. In this sense, to compute the power output, it is needed to take into account both mechanical turbine and generator loses. The product of power coefficient, mechanical turbine loses and generator loses is known as total efficiency.

As it has been mentioned before, the main goal of this project is to design a turbine that reach a total efficiency of around 40% for the given specifications. In this sense, the first task has been to optimize as much as possible the power coefficient to ensure an optimal turbine performance.

The theory behind this aerodynamic limit will be explained later in the next section.

### 3.3.6 Betz's limit

This law was stated by the German physicist Albert Betz in 1919. The Betz's implies that the maximum power percent that can be extracted from the wind is **59.3 %**.

The theory behind this law is derived from mass and momentum principles of conservation. It is common for manufacturers to express the aerodynamic performance of the turbine as a function of the Betz limit. In this way, a common turbine usually has an aerodynamic efficiency of 70% the limit of Betz.

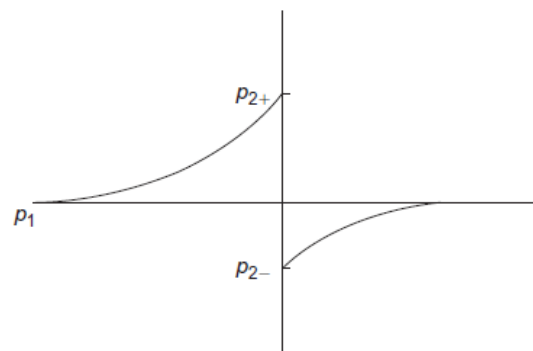
For a turbine to extract the 100% of the energy from the wind, it should be able to stop the wind which is physically impossible. This idea is shown later in the actuator disc approach.

### 3.3.7 Actuator disc approach

There are some assumptions made by this theory that must be taken into account:

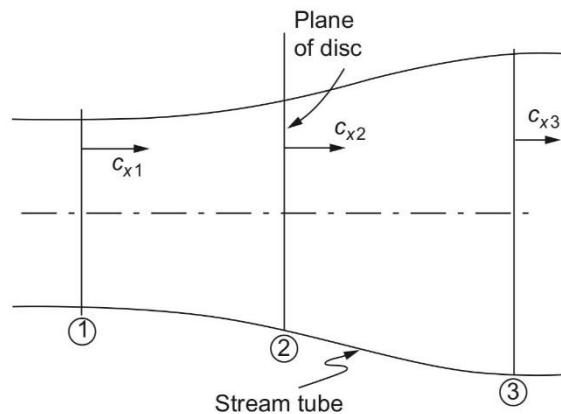
1. Steady and uniform flow upstream of the disc
2. Uniform and steady velocity at the disc
3. No flow rotation produced by the disc
4. The flow passing through the disc is contained both upstream and downstream by the boundary stream tube
5. The flow is incompressible

This theory suppose that the turbine is composed by an infinite number of blades and therefore it can be considered as a disc. Because the turbine offers a resistance to the flow, the velocity of the air is reduced as it approaches the disc, and therefore there will be a corresponding increase in pressure. Then, the fluid across the disc suffer a drop in pressure to finally experience a gradual recovery up to the ambient pressure (Dixon & Hall). This variation of energy can be seen in the following figure:



**Graphic 3-** Pressure behaviour through the wind turbine from far upstream to far downstream (Dixon & Hall)

The speed reduction will take place both before and after the wind turbine. Consequently, this theory analyses the airflow in three different regions as it can be seen in the **figure 12**. The first region refers to the undisturbed wind velocity also known as far upstream wind velocity. The second section refers to the rotor area which is divided in 2+ and 2- (before the turbine and after the turbine correspondingly). On the other hand, the third region is known as far downstream and refers to the section where the airflow recover the equilibrium (Bossanyi, Burton, Jenkins, & Sharpe , 2001) . The following figure illustrate the three different regions analysed by the actuator disc theory:

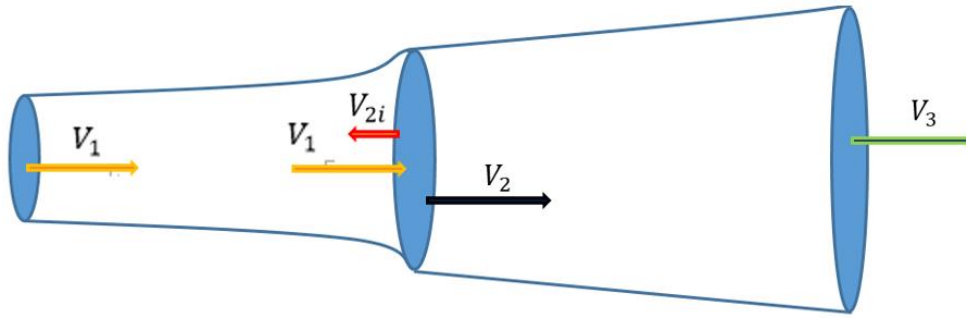


**Figure 12-** Velocity rate of change along the turbine (Dixon & Hall)

As it can be seen from **Figure 12** the wind velocity decrease along the turbine. This rate of change in the wind speed can be illustrated by the **Axial induction factor**. This loss of energy in the fluid is theoretically equal to the energy absorbed by the turbine in the form of rotational mechanical energy. However, there are always friction and mechanical losses that distance the results from being ideal. This is the main reason why wind turbines can never reach a power value equal to that estimated by the Betz limit set around 59%.

### 3.3.8 Axial Induction Factor

In the beginning the only key parameter we know about the airflow is the upstream wind velocity. Therefore, the axial induction factor come up from a try to express the rate of change of the wind between the three regions as function of wind far upstream velocity. Thus, we can see this rate of change as an induction of a negative velocity by the actuator disc (Haugset & Frøyd). In this sense, we can understand induction factor as a picture of wind speed lost, therefore the axial induction factor will take values between 0 and 1. This induction wind velocity is illustrated in **Figure 13**.



**Figure 13-** Axial induction velocity at the actuator disc

**Figure 13** illustrates an ideal model of axial wind through the actuator disc. This theory states that the wind out of the stream tube is unaffected by the turbine. In contrast, the wind inside the stream tube will slow down and consequently  $V_1 > V_2 > V_3$ . Following the continuity equation  $c_{x1}A_1 = c_{x2}A_2$  we know the following:

$$A_1 < A_2 < A_3$$

To estimate the axial induction factor ( $a$ ), we can apply Bernoulli between regions 1 and 2<sup>-</sup> and regions 2<sup>+</sup> and 3. We cannot apply Bernoulli between 1 and 3 because there is an energy exchange in the turbine and therefore Bernoulli does not hold between these two points.

To do this, some assumptions must be considered:

- The pressure in the region 3 and region 1 is the same  $P_1 = P_3$ .
- The wind velocity across the region 2 is constant  $V_{2-} = V_{2+}$

Therefore, applying Bernoulli we have the following relations (Haugset & Frøyd):

$$\frac{1}{2}\rho V_1^2 + p_1 = \frac{1}{2}\rho V_{2-}^2 + p_{2-}$$

$$\frac{1}{2}\rho V_3^2 + p_3 = \frac{1}{2}\rho V_{2+}^2 + p_{2+}$$

Thus,

$$\Delta p = p_{2+} - p_{2-} = \frac{1}{2}\rho(V_3^2 - V_1^2)$$

Taking into consideration the rate change of momentum, we obtain the following equations:

$$(p_{2+} - p_{2-})A_2 = (V_3 - V_1)(\rho V_2 A_2)$$

$$\frac{1}{2}\rho(V_3^2 - V_1^2) = (V_3 - V_1)(\rho V_2 A_2)$$

And thus,

$$V_3 = V_1(1 - 2a)$$

Therefore, we can relate all wind velocities to the far upstream velocity which is the only known parameter. In this sense, we obtain the following relations:

$$\left[ \begin{array}{l} \blacksquare V_1 \\ \blacksquare V_2 = V_1(1 - a) \\ \blacksquare V_3 = V_1(1 - 2a) \end{array} \right.$$

### 3.3.9 Expressing Power and power coefficient with respect to a

Express all wind velocities as function of far upstream wind (the only known wind parameter), gives us the opportunity to reformulate equation X as follows:

$$\Delta p = p_{2+} - p_{2-} = 2\rho V_1^2 a (1 - a)$$

On the other hand we know,

$$P_{extracted} = F_2 V_2$$

$$P_{extracted} = \Delta p A_2 V_2$$

$$P_{extracted} = (2\rho V_1^2 a (1 - a))A_2 V_1(1 - a)$$

$$P_{extracted} = 2\rho A_2 V_1^3 a (1 - a)^2$$

Therefore, coming back to **equation 12**, we can assume the power factor as:

$$C_p = \frac{\text{extrated power}}{\text{power in the wind}} = \frac{2\rho A_2 V_1^3 a (1-a)^2}{\frac{1}{2}\rho V_1^3 A_2} = 4a(1-a)^2$$

**Equation 14-** Power coefficient in function of the axial induction factor

### 3.3.10 Demonstration of the Betz limit

Relate power output and aerodynamic efficiency to axial induction factor gives us an easy way to demonstrate the Betz limit. In this way, we can do this by two procedures:

#### Analytical method:

We can demonstrate the Betz law by just differentiate the power coefficient by the axial factor and look for its maximum value.

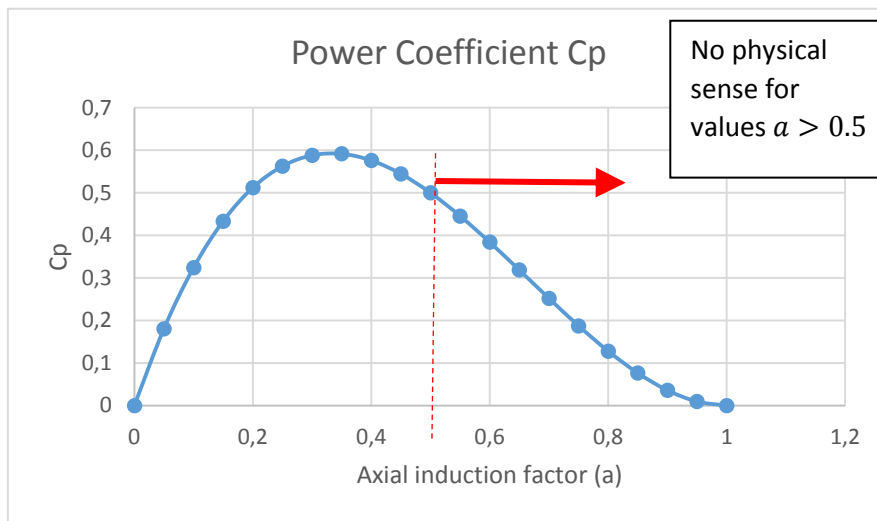
$$\frac{dC_p}{da} = \frac{d(4a(1-a)^2)}{da} = 0$$

From this equation we get that the power coefficient ( $C_p$ ) find its maximum for  $= \frac{1}{3}$ . Evaluating **equation 14** with this value of  $a$  we find the Betz limit:

$$C_p = 4 \frac{1}{3} \left(1 - \frac{1}{3}\right)^2 = 0.593 = 59.3\% \text{ qed}$$

#### Graphical method:

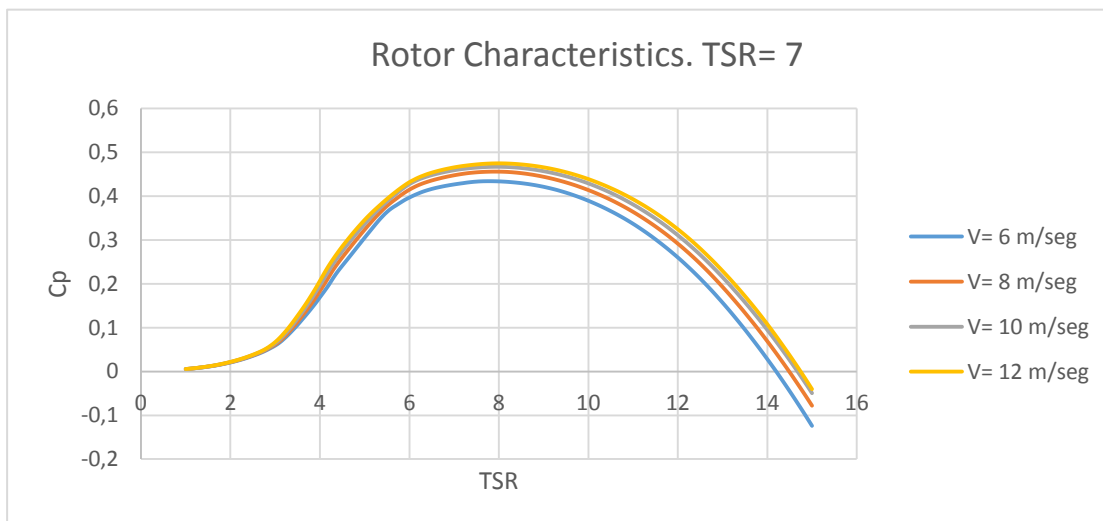
We can also demonstrate this by plotting the power coefficient ( $C_p$ ) in function of the axial induction factor ( $a$ ). Thus the power coefficient for an ideal blade is:



**Graphic 4-** Power coefficient in function of axial induction factor

Note that although there is a mathematical sense to express the power coefficient for axial induction factors between  $[0,1]$ , there is no physical sense for values higher than  $a = 0.5$  since the wind velocity  $V_2$  would be negative. This also happens when analysing the thrust coefficient in function of axial induction factor.

On the other hand, a common power coefficient graphic would be:



**Graphic 5-** Power coefficient in function of Tip Speed ratio (TSR)

In contrast to **Graphic 4** this one related the power coefficient to the TSR. This is a quite typical way to proceed when choosing the optimal TSR of the prototype.

### 3.3.11 Expressing the thrust coefficient with respect to $a$

This can be done in a similar way to the power coefficient. However, it must be noted that real turbines experience a thrust force that cannot be explained by using only momentum theory (Haugset & Frøyd). Thus, in contrast to the power coefficient, we will limit to show how the thrust coefficient can be expressed in function of  $a$  and not to discuss the procedure to come to this expression.

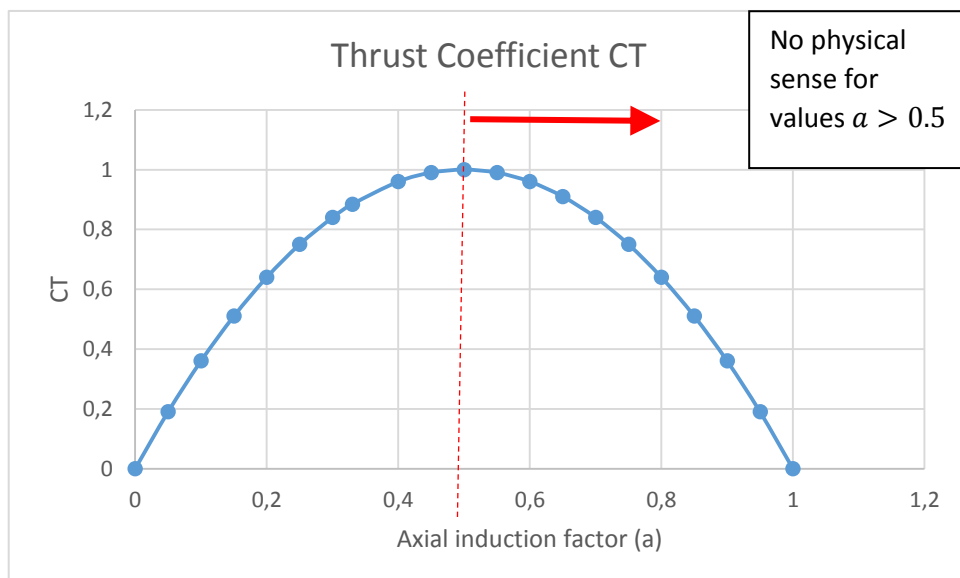
In this sense, the thrust coefficient becomes:

$$C_T = \frac{\Delta p A_2}{\frac{1}{2} \rho V^2 A_2} = 4a(1 - a)$$

**Equation 15-** Thrust coefficient in function of the axial induction factor

### 3.3.12 Demonstration of the maximum thrust coefficient

In a similar way to the Betz limit demonstration, we can compute the maximum thrust coefficient by graphical method:



**Graphic 6-** Thrust coefficient in function of axial induction factor



As it was mentioned before, there is physical sense to illustrate the thrust coefficient for values higher than  $a > 0.5$  because the wind velocity after the rotor would be negative.

Therefore, if we analyse the thrust coefficient for a supposed optimal power coefficient

$a = \frac{1}{3} \rightarrow C_p = 0.593$ , we will obtain the following thrust coefficient:

$$C_T = 4a(1 - a) = 4 \frac{1}{3} \left(1 - \frac{1}{3}\right) = \frac{8}{9}$$

### 3.3.13 Rotatory disc Theory

As wind turbines are not composed by disc rotors but by bladed rotors, the flow will be also affected in the rotational direction. Thus, the airflow will experience some variations in the tangential/rotational direction in addition to those experienced in the axial direction. The wind induces a force on the blade and the blade induces a force on the wind. While the airflow velocity is decreased in the axial direction, it will be increase in the tangential direction.

Following the second and third newton laws, the rotor will cause the airflow that goes through the rotor to experience acceleration in the opposite direction of the resultant force of the blade. This led the airflow to experience an induced rotational velocity in the opposite direction of the blade rotation. This induced velocity in the same way increase the velocity experienced by the blades. (Haugset & Frøyd)

### 3.3.14 Rotational induction factor

The rotation of the blades induces a rotational speed in the airflow. In the same way the axial induction factor is used, the rotational induction factor helps to analyse how the wind velocity changes through the rotor in then tangential direction. This factor is commonly denoted  $\alpha'$ .

Although this theory assumes there is no rotational speed in the airflow before the turbine, it must be noted that the rotation of the blades will induce a small rotation both upstream and downstream. This upstream rotational induction is explained by the necessity of verify continuity equation and viscous friction (Haugset & Frøyd).

The rotor transfers energy to the airflow through the rotational induction, in contrast to the axial induction factors where energy was extracted from the wind. In this sense, the rotational induction factor cause an inevitable energy loss (Haugset & Frøyd).

However, this rotational induction factor is much smaller than the axial induction factor. A brief example of what the airflow experience across the turbine is illustrated in the velocity triangles of the next figure:

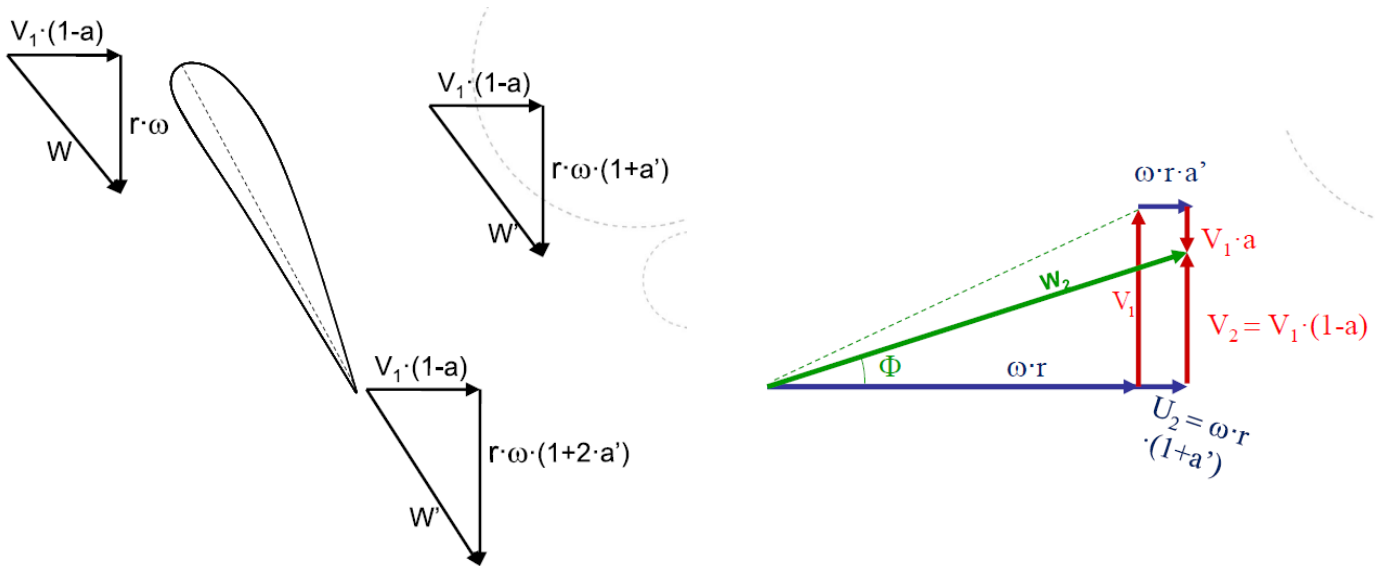


Figure 14- Wind velocity changes through the turbine. Velocity triangles (NTNU, 2017)

In order to simplify the calculations, we can assume that every section is dominated by a mean velocity triangle. This simplification is close to the physics and can be done without much error. This method is shown in the **figure 14**.

### 3.3.15 The rotor disk wake model

The rotor disk wake model is essential to understand the Blade Element Momentum (BEM) method which will be widely explained during the blade design. This BEM method has been the chosen to design the blade because of its simplicity and accuracy. The rotor disk wake model is a model that describe the airflow behaviour across the turbine. This model is illustrated in the following figure:

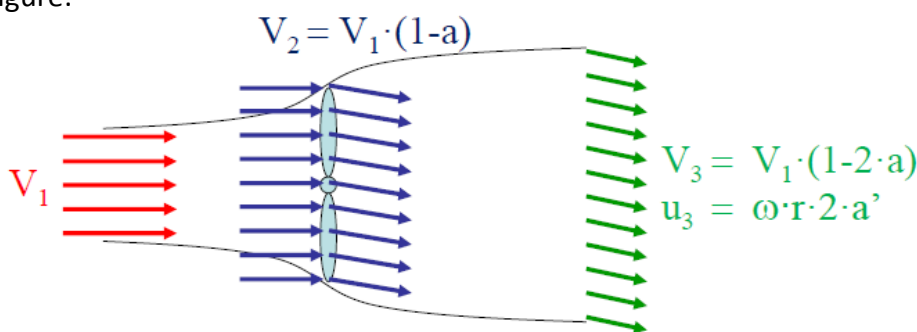


Figure 15-Illustration of rotor disk wake model (NTNU, 2017)

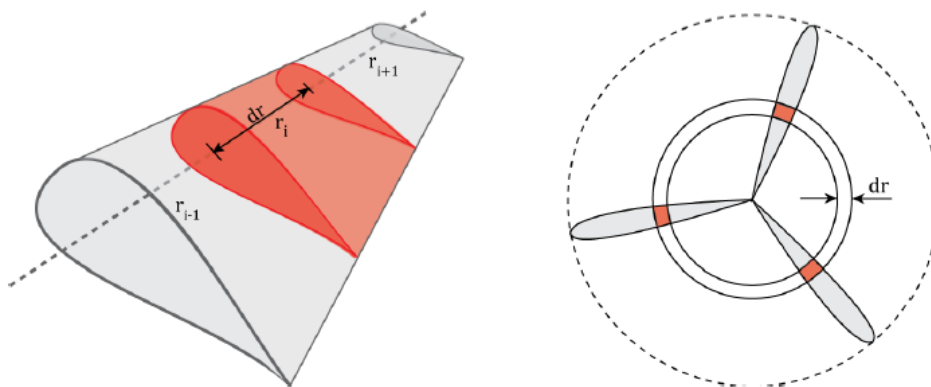
To solve this model it is necessary to relate wind velocity to aerodynamic forces. To do this, we need to go through the airfoil theory, which was first discussed in this Chapter.

While the Matlab program gives the first skeleton of the blade, the Ashes program was used to verify the BEM Calculations. “These calculations follow the Glauert’s optimization analysis which is developed and used to determine the ideal blade shape for a given lift coefficient and to show how the optimum rotor power coefficient is influenced by the choice of tip-speed ratio” (Dixon & Hall).

### 3.3.16 Blade element momentum theory

The theory of this section is mainly based on “*Analysis and Design of Wind Turbines Blades*” (Haugset & Frøyd), which in turn is based on “*Aerodynamics of Wind Turbines*” (Hansen, 2008) and “*Wind Energy Handbook*” (Bossanyi, Burton, Jenkins, & Sharpe, 2001) and last but not least on “*Wind Energy Explained: Theory, Design and Application*” (Manwell, McGowan, & Rogers, 2002)

Although the *airfoil theory* presented in this paper is valid only for an infinitely long wing, Blade element momentum theory assumes that airfoil theory is valid for a wing element of limited length  $dr$  by dividing the infinite length into a finite number of blade elements (Haugset & Frøyd). This is illustrated in **figure 16**.



**Figure 16-** Illustration of the turbine blade elements (Haugset & Frøyd)

The aim of this theory is to find the torque  $M$  and thrust  $T$  forces. To do this, it is necessary to analyse the forces in the axial and tangential direction on each blade element. In this sense, we need to analyse the lift force ( $F_L$ ) and drag force ( $F_D$ ) along each of the blade elements.

A common way to proceed is to sum lift and drag forces to calculate the resultant force ( $F_R$ ), and then decompose this resultant force into axial and tangential directions. To do this, we use the flow angle which is the sum of the twist angle and the angle of attack. Remember that the flow angle is

also defined as the angle between relative flow velocity and the plane the blade is rotating in (Haugset & Frøyd).

Therefore, recalling the lift and drag force equations (**Equation 1**) we have:

$$F_L = \frac{1}{2} \rho W^2 C_L L_c dr$$

$$F_D = \frac{1}{2} \rho W^2 C_D L_c dr$$

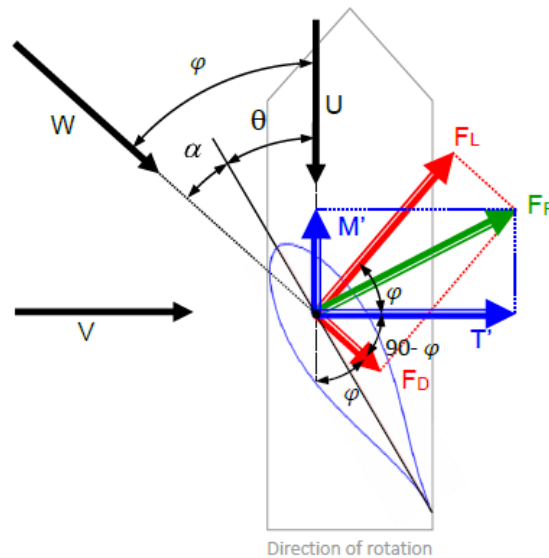
Then, projecting the sum of these two forces into the axial and tangential direction we obtain:

$$T' = F_L \cos \phi + F_D \sin \phi$$

$$M' = F_L \sin \phi - F_D \cos \phi$$

**Equation 16-** Decomposition of the total force in the axial and tangential direction

These decomposition is shown in the following figure:



**Figure 17-** Decomposition of lift and drag forces along the horizontal and vertical axis (Frøyd & Kjetil Haugset)

To simplify the theory and avoid decompositions, we can introduce two new parameters: *the axial force coefficient* ( $C_a$ ) and *rotational force coefficient* ( $C_r$ ). These two coefficients can be denoted as:

$$C_a = C_L \cos \phi + C_D \sin \phi$$

$$C_r = C_L \sin \phi + C_D \cos \phi$$

**Equation 17-** Axial force coefficient and rotational force coefficient

Thus,

$$dT' = C_a \frac{1}{2} \rho W^2 L_c dr$$
$$dM' = C_r \frac{1}{2} \rho W^2 L_c dr$$

**Equation 18-** Axial and tangential components for one blade element

Note that this theory applies to turbines with different number of blades. However, all blades should be taken into account by considering the total number of blades ( $Z$ ). Consequently, we have to multiply the torque and thrust forces for the total number of blades in order to compute the total forces in each blade section. By doing this, we have:

$$dT = C_a \frac{1}{2} \rho W^2 L_c dr Z$$
$$dM = C_r \frac{1}{2} \rho W^2 L_c dr Z$$

**Equation 19-** Axial and tangential forces components for the total number of blades per disc section

Note that  $dT$  and  $dM$  are the forces of one annulus section of thickness  $dr$  (as it is shown in **figure 16** for a three bladed wind turbine). On the other hand, to obtain the moment contribution for every blade section we must have multiplied the  $dM$  with the local radius ( $dM \times r$ ).

### 3.3.17 Blade Element Momentum (BEM) Method

The Blade Element Momentum (BEM) Method states that the turbine blade is divided into elements and treated independently. Then, the forces on each of the element are calculated using both the aerodynamic forces on each blade element and the change of momentum in the air. This, method is mainly based on the Blade Element theory (Haugset & Frøyd).

In other words, the basic idea behind the BEM method is to divide the blade in several elements and compute the aerodynamics forces and airfoil geometry for each element. This method is the most preferred when designing and analysing Wind Turbines because it is exceptionally fast and yet sufficiently accurate for the majority of the applications. However, BEM method is based on some assumptions and simplifications that must be considered (Haugset & Frøyd):

- Steady-state situation
- Uniform wind speed over the whole turbine rotor
- There is no flow in the radial direction of the blade
- The blades have a perfect stiffness and does not flex or bend
- The blades are straight

These assumptions will not be verified in all applications, however the BEM method still providing an average performance and will work as an approximation method when talking to design of wind turbines. There are more advanced approaches like CFD but they are out of the scope of this paper.

In conclusion, it can be said that the BEM method is an excellent approximation approach that may be useful in the initial design phase where a lot of calculations must be computed. Therefore, BEM method is a perfect tool to compute an initial design.

This Matlab code performs an iterative process based on an initial design to be optimized. To be able to carry out a steady state analysis of a wind turbine blade, the next information about the blades is needed (Haugset & Frøyd):

- Chord length distribution along the blade.
- Twist distribution along the blade.
- Airfoil distribution along the blade if more than one airfoil is used.
- Lift and drag curves for each airfoil. Preferably ranging from -180 to 180 degrees.

Because of this, we need to have an initial starting design. In this project, we have chosen to start with the Glauert design, however we could have started with an arbitrary design. But as it was stated before, we are able to obtain better solutions when iterating with a starting geometry based on Glauert calculations.

### 3.4 Blade design

#### 3.4.1 Blade design Method

During this subsection, it will be presented the procedure by which the blade was designed and optimized. The first step is to create a Matlab algorithm inspired on the Blade Element Method (BEM) to obtain a first iteration blade model. After this, an iteration process between Ashes, Inventor and Excel is realized to achieve an optimal blade within the initial requirements.

This procedure is illustrated step by step in the following figure:

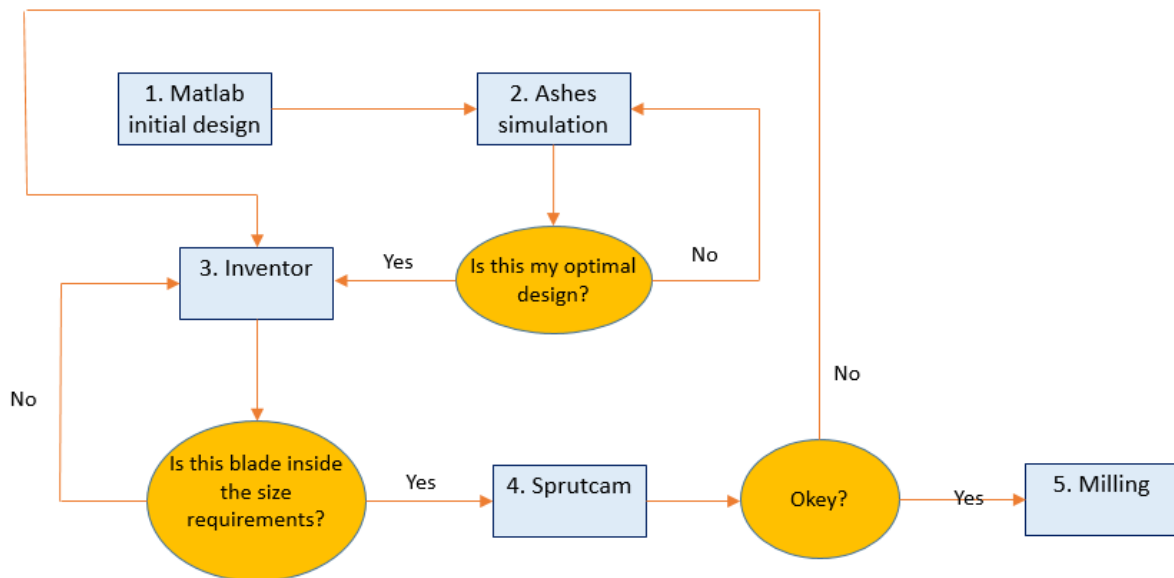


Figure 18- Blade design procedure Algorithm.

## 3.4.2 Design under Matlab

### 3.4.2.1 Introduction

First, I had to create a Matlab code based on BEM algorithm which is reported in **Appendix A**. The BEM Blade Element Momentum algorithm divides the turbine blade into elements and treat every airfoil independently. Thus, the forces on each element are calculated using both aerodynamic forces on each blade element and the change of momentum in the air as it was stated in the theory fundamentals (Haugset & Frøyd).

In this sense, applying the Matlab program I started to evaluate the distributions of the main output parameters such as chord length and twist angle for different input **TSR**. In this sense, different designs for values of TSR regarding from 5,5 to 7,5 were tested. After a few iterations, I decided to design my Blade for a **TSR = 6,5**, which it is a good compromise between size and efficiency. It is important to consider that BEM method gives bigger designs (bigger Chord length and higher Twist angle) for smaller TSR. In this sense, the slower is the rotational speed of the turbine, the bigger distribution will present.

This Matlab code is inspired on the BEM theory which was discussed during the course **TEP 4175- Design of a wind Turbine** and along its text book “Analysis and Design of Wind Turbine Blades” (Haugset & Frøyd). This Matlab code uses the BEM theory to analyse the aerodynamic performance of each blade element at every iteration point and thus estimate an optimal blade geometry.

As it can be observed in figure X, all calculations and convergences comes from a starting initial design. Note that the Blade Element Momentum (BEM) algorithm does not need to use Glauert method (which is discussed below) to find a starting geometry. However, I was said by my supervisors that using this initial idealized design we can come up with a better solution.

Also note that all the operations showed in the **figure 18** must be calculated for each of the blade elements. For this design 20 blade elements have been chosen to discretize the blade profile. In other words, the algorithm will be run 20 times calculating the aerodynamic forces, torque and thrust forces for each of the elements.

The number of blade elements was decided based on a compromise between accuracy and optimal Inventor 3D design work. This Inventor 3D modelling will be explained later on this section.



### 3.4.2.2 Initial design

This initial design is characterised for compute every blade element by rejecting the drag force coefficients. By using this initial design based on Glauert method, we can obtain a better solution in terms of ratio between twist angle and chord length that led the BEM algorithm to reach a more optimal coefficient of performance.

This initial design was implemented into the Matlab code by the given function *adisk* which is reported in Appendix B. Note that this function was not designed by myself but it was given by the “Norwegian university of Science and technology”.

#### Ideal blade element momentum theory

Glauert called this theory “blade element theory”. This theory consist in removing the drag elements from the momentum equations. It is an ideal BEM theory that supposes no drag in each of the analysed elements. In this sense, the axial and rotational force coefficients  $C_a$  and  $C_r$  become:

$$C_a = C_L \cos \phi$$

$$C_r = C_L \sin \phi$$

**Equation 20-** *Ideal axial and rotational forces coefficients without drag*

With these two simplified force coefficients we can compute the new blade elements forces. However, these elements still implicit and therefore require iteration to solve them. To simplify this problem, all the factors involved in the blade elements forces can be moved to a non-dimensional parameter called *Blade element parameter*  $B_{EP}$ . This parameter is defined as follows:

$$B_{EP} = \frac{Z L_c C_L w}{2\pi V_1}$$

**Equation 21-** *Blade Element Parameter*

This  $B_{EP}$  parameter contains very valuable input design parameters like the wind speed  $V_1$  (which in general terms should be the most concurrent wind velocity in the area), the number of blades  $Z$ , the lift coefficient  $C_L$  and the rotational turbine speed  $w$ .

The ideal blade element momentum theory is implemented in a given MATLAB function *adisk*. This MATLAB function is reported in Appendix B and comes from the course TEP 4175 Design of a Wind Turbine.

In this sense, the designed algorithm proceed as follows:

1. Compute the  $B_{EP}$  and flow angle  $\phi$ , for a certain input  $TSR$  and 20 blades elements using and the given function  $adisk$ . The value of this TSR depends on the criteria of the designer. However, the number of elements is a compromise between accuracy and Inventor work. Note that the more blade elements, the more accurate would be the calculations but the more work will be needed for the 3D drawing design.

2. Compute the chord length of each blade parameter through the use of the  $B_{EP}$  parameter:

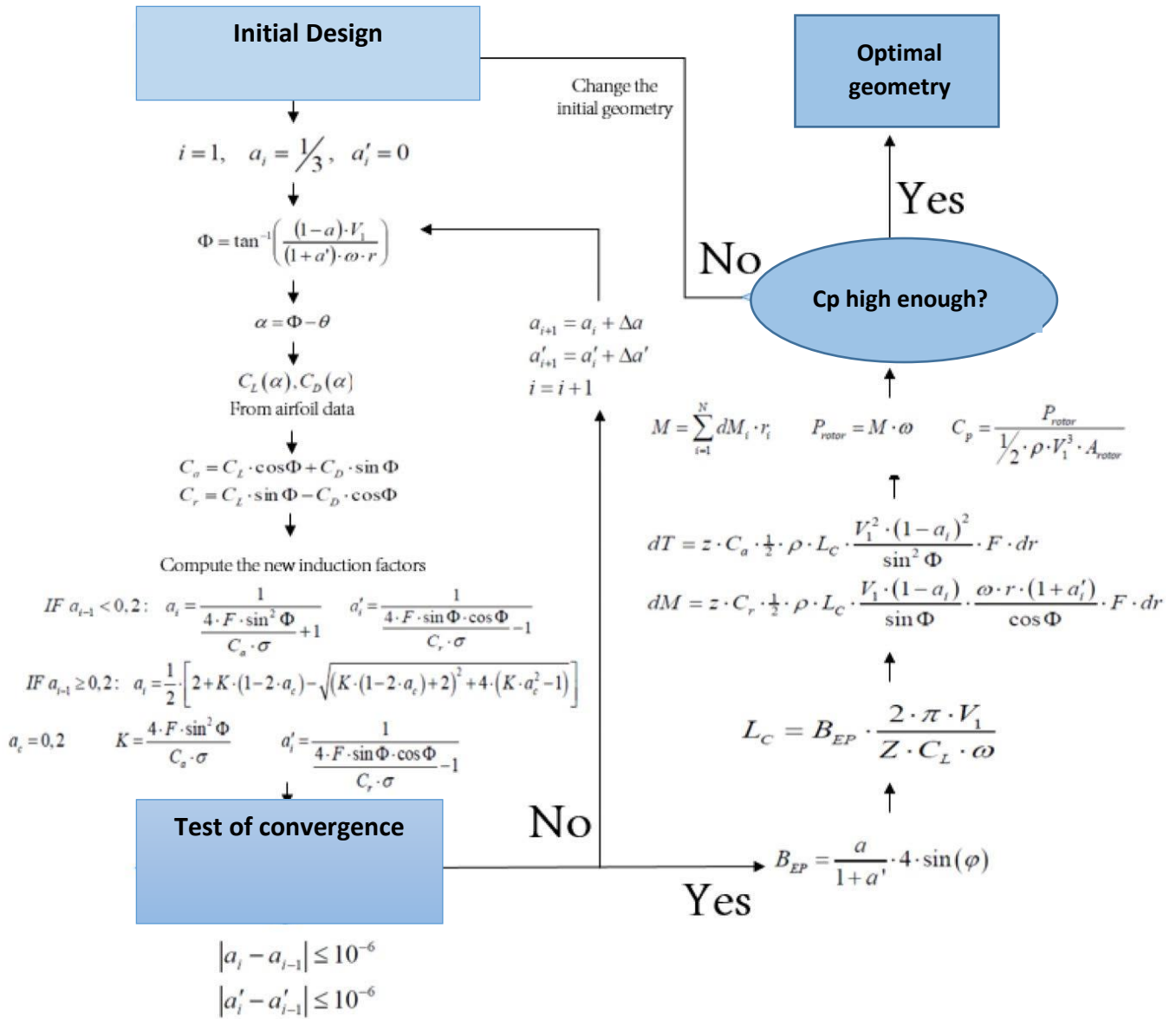
$$B_{EP} = \frac{2\pi B_{EP} V_1}{Z C_L V_1}$$

3. Compute the Twist Angle  $\theta$ . This can be done as follows:

$$\theta = \phi - \alpha_{opt}$$

### 3.4.2.3 The algorithm

The code reported in **Appendix A** follows the next algorithm:



**Figure 19- BEM Algorithm. Blade optimization. (Haugset & Frøyd)**

Also it is important to consider that this algorithm deal with some simplifications. Some of the most important ones to be taken into account are the following:

- **Steady-state situation.** This assumption means that the flow around the blade is in steady-state situation. In this sense, loses due to turbulences are neglected by this method.
- **Uniform wind speed over the rotor.** This means that Wind shear due to boundary layer effects are also neglected.
- **The BEM theory only takes into account the 2D flow.** In this sense, there is no flow in the radial direction of the blade. This assumption usually gives good results except on the tip of the blade. However, I have included a correction factor in my Matlab program in order to make a more robust code.
- **The Blades have a perfect stiffness and does not flex or bend.** This assumption gives us a fair approximation. However, due to this fact, I have been recommended to have a minimum chord length of 20 mm and a minimum thickness of 0.3 mm.

These simplifications make my Matlab program to be only a first approximation to the final model. Although I tried to make the program as robust as possible taking into account correction factors, my Matlab program was always overestimating all my models. Thus, the purpose of designing this Matlab program was to have a first design of the blade to be optimize.

To improve this first pre-design, it is necessary to go through more advanced simulation softwares based on finite element method (FEM).

#### 3.4.2.4 Matlab Results

As it was discussed in the introduction, the aim of this part of the project is to maximize as much as possible the power coefficient within the initial constraints. Thus, a compromise between size and efficiency was needed. In this sense, an evaluation for different TSR regarding from 5.5 to 7.5 was realized. The next reported tables contains the most important characteristic rotor parameters. Therefore, we have the following blade information:

TSR	$C_p$	Power[KW]	Torque [Nm]	Thrust [KN]	$L_c max$	$L_c min$	n [rpm]
5,5	0,55	0,22	1,76	0,03	0,1099	0,0383	1167
6	0,51	0,2	1,49	0,03	0,998	0,0323	1273
6,5	0,47	0,18	1,28	0,03	0,93	0,0276	1379
7	0,44	0,17	1,11	0,03	0,0868	0,0238	1485
7,5	0,41	0,16	0,96	0,03	0,081	0,0207	1592

Table 1- Matlab Rotor characteristics

Please note that the chord length is given in meters [m]. This design have been computed maintaining an optimal angle of attack along the blade, which is defined as the angle given by the most optimal ratio between lift and drag coefficient. It must be considered that at first I used a distribution of lift and drag coefficients for the given airfoil **NREL S826** founded in a text book.

However, with this first distribution there was a big difference between Matlab calculations and simulations of the next phase. In a try to solve this, I decided to use the relations of lift, drag and optimal angle of attack given by the simulation software. This data is reported in Appendix C. By doing this, the difference was minimized. In this sense, the optimal angle of attack, drag and lift coefficients that have been used to compute these performances are the following:

$C_L$	$C_D$	Alphaopt
1,25	0,02	6

**Table 2-** Aerodynamic parameters used to run the Matlab algorithm

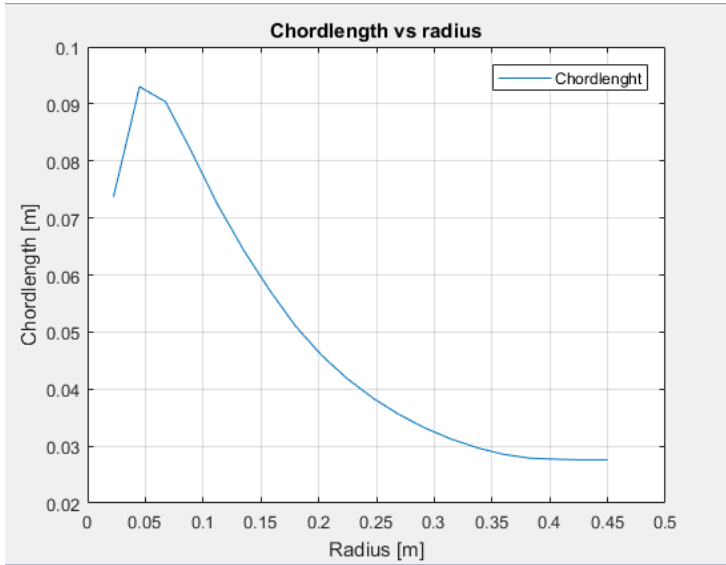
Note that this relations are usually computed by wind tunnel tests for a given airfoil and depending on what data is used the final solution may change a little.

Finally, to compromise efficiency and size I decided to take as the solution the blade geometry for  $TSR = 6.5$ . Thus, the reported Matlab code gives the following blade geometry pre-design:

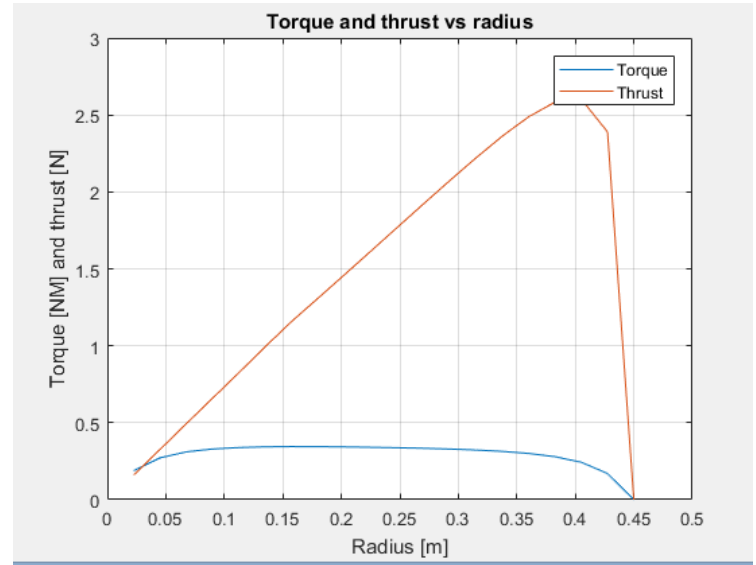
Blade Geometry from BEM and Matlab. TSR=6,5.				
Blade Element []	Mean Radius Ri [m]	Chord Length [m]	Twist Angle [deg]	Angle of Attack [deg]
1	0,0225	0,0737	42,4453	6
2	0,045	0,093	32,6529	6
3	0,0675	0,0904	25,2568	6
4	0,09	0,0816	19,8305	6
5	0,1125	0,0724	15,8174	6
6	0,135	0,0644	12,7321	6
7	0,1575	0,0573	10,4179	6
8	0,18	0,051	8,69	6
9	0,2025	0,0459	7,2538	6
10	0,225	0,0418	6,0463	6
11	0,2475	0,0383	5,01	6
12	0,27	0,0355	4,1289	6
13	0,2925	0,0331	3,3466	6
14	0,315	0,0312	2,6427	6
15	0,3375	0,0297	1,9894	6
16	0,36	0,0286	1,3554	6
17	0,3825	0,0279	0,6948	6
18	0,405	0,0277	-0,0836	6
19	0,4275	0,0276	-1,263	6
20	0,45	0,0276	-1,263	6

**Table 3-** Blade geometry from BEM and Matlab. TSR= 6.5

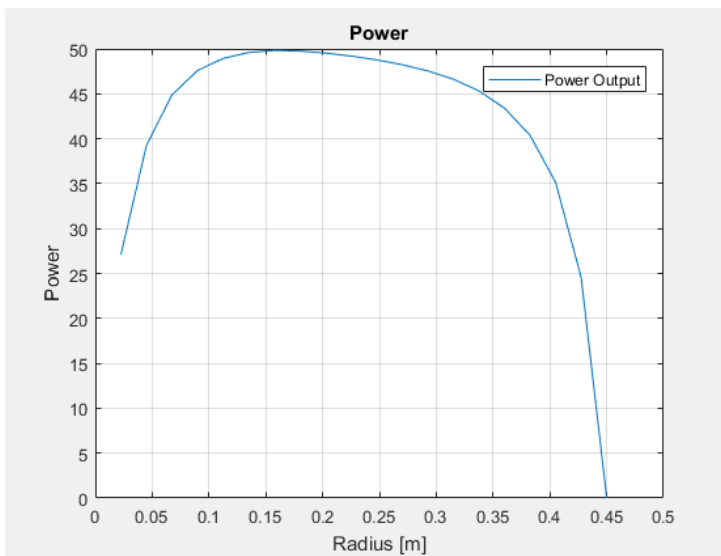
Moreover, we have obtained the next key rotor characteristics:



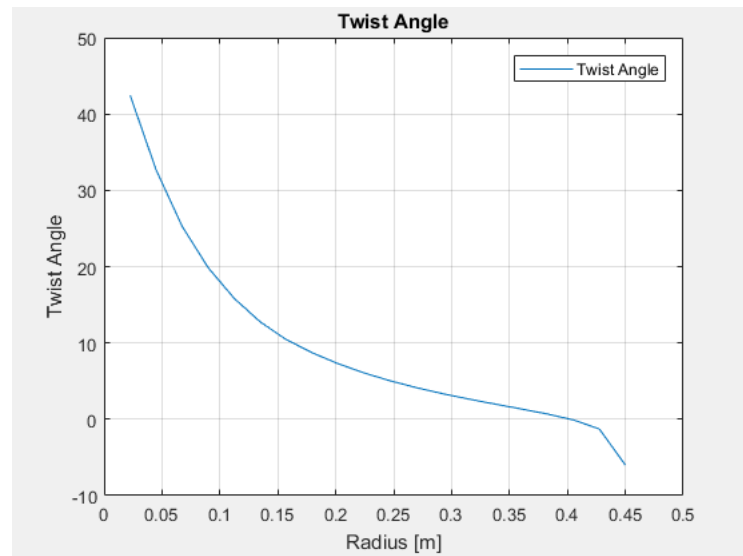
**Graphic 8-** Distribution of the Chord length at every blade section



**Graphic 7-** Torque and Thrust forces at every blade section



**Graphic 10-** Power output at every mean radius



**Graphic 9-** Twist angle at every mean radius

### 3.4.2.5 Conclusion

In conclusion, the Matlab Code and BEM method give a pre-design that must continue to be optimized by more accurate methods. Although the most common use of BEM method is to analyse wind turbines blades, it is also a good starting tool to be included in design turbine blades methods because of its accuracy and speed.

The final solution has been chosen as a compromise between efficiency, size and resistance. Although bigger designs were giving better power coefficients, we decided to go for an intermediate design to avoid size problems during the design in Inventor. However, as it was stated before, this code does not give the optimal design and a more complex iteration process is needed to check the turbine performance. In this sense, small changes in the blade geometry can result in more optimal design.

### 3.4.3 Design under Ashes and Excel

#### 3.4.3.1 Introduction

To verify and iterate this first pre-design blade geometry given by the Matlab Code, a simulation program called Ashes have been used. Ashes *“(Aero-Servo-Hydro-Elastic Simulation) is a software code for aero-elastic analysis developed by Simis AS. Ashes utilizes the finite element method (FEM) in conjunction with a co-rotational formulation of beam elements to determine the dynamic response of the structure. The co-rotational formulation leads to accurate results in arbitrarily large displacements and rotations in space. For instance, centrifugal forces appear naturally in e.g. the blades. A linear solution of the equations of motion can be used in cases where nonlinear effects are unimportant, while a full Newton-Raphson iterative scheme can be utilized when nonlinear effects are of interest. Ashes automatically selects the appropriate solver based on the model, analysis type and characteristics of the load cases. Linearized buckling can further be studied. Aerodynamic loads are determined by using the blade element momentum (BEM) theory, which are fully coupled to the structural response. Ashes includes models of losses due to the presence of the tower and the hub, as well as tip losses. Steady wind, yawed inflow, wind shear and different turbulence models are supported. Wave loads are computed using the Morison equation coupled with the structural response”* (AS, s.f.)

This software has been extensively used for both turbine and generator design and their coupling. In this sense, in order to import the blade to Ashes, a text file with the distribution of the Chord length and Twist angle obtained from Matlab program for the designed  $TSR = 6,5$  was created.

This program helps the designer with both generator and rotor design. Also, it gives the opportunity to analyse how the blade is behaving in different situations. Moreover, Ashes gives us the opportunity to check the velocity triangle and aerodynamic performance of each blade element. This function is shown in **figure 21**.

This program was used to make an iteration process and see how small changes in the blade geometry could increase the  $C_p$  value. My goal during this part of the project is to get the highest  $C_p$  value, which is unfortunately limited by the Betz limit (value close to 59%). Although a great number of iterations have been done to come up with the final model, this paper is focus on the final solution. In this sense, only the final turbine geometry will be presented.



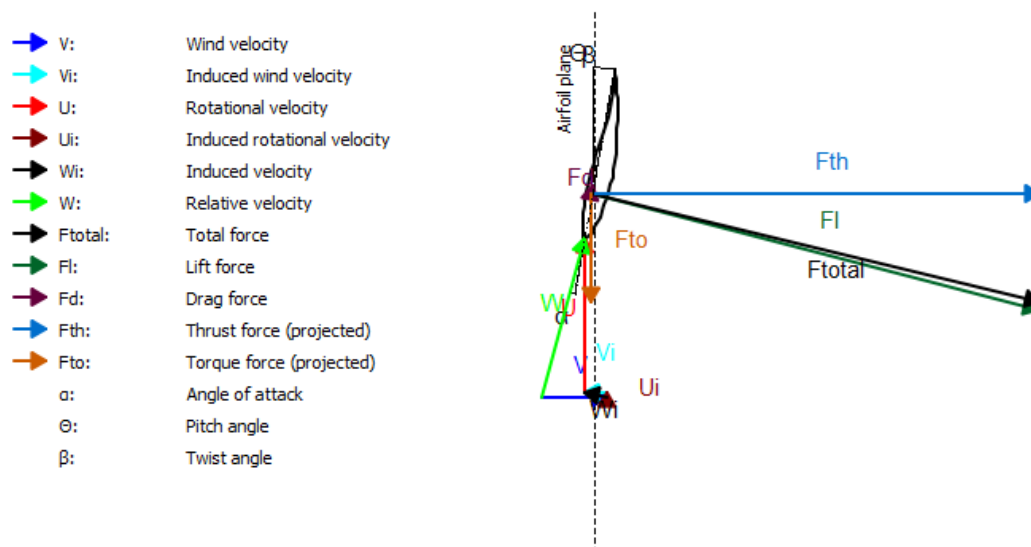


Figure 21- Ashes wind velocity triangles

### 3.4.3.2 Introduction of the pre-design into Ashes

To introduce the pre-design of the blade produced by Matlab in the Ashes program, the creation of a text file was necessary as the one is reported in figure X. Then, this text file was modified by trying different Chord lengths and twist angles. On the other hand, the excel sheet was created to maintain a smooth profile during the iterations.

```

Diseño Final. Intento 8.txt main.c main.c
1 ----- ASHES BLADE DEFINITION INPUT FILE -----
2 Output format based on AeroDyn v15.03
3 ===== Airfoil Information =====
4 1 NumAF - Number of airfoils used (-)
5
6 "S826"
7 ===== Blade Properties =====
8 22 NumBlNds - Number of blade nodes (-)
9 BlSpn BlCrvAC BlSwpAC BlCrvAng BlTwist BlChord BlAFID BlRelThick BlPAD
10 (m) (m) (m) (deg) (deg) (m) (-) (-) (-)
11
12
13 0.0450 0 0 0.0 23.2568 0.090000 1 0.140381 0.333333
14 0.0675 0 0 0.0 19.3000 0.089000 1 0.140381 0.333333
15 0.0900 0 0 0.0 15.8175 0.083600 1 0.140381 0.333333
16 0.1125 0 0 0.0 12.7321 0.074400 1 0.140381 0.333333
17 0.1350 0 0 0.0 10.4179 0.066400 1 0.140381 0.333333
18 0.1575 0 0 0.0 8.69000 0.059300 1 0.140381 0.333333
19 0.1800 0 0 0.0 7.25380 0.053000 1 0.140381 0.333333
20 0.2025 0 0 0.0 6.04630 0.047900 1 0.140381 0.333333
21 0.2250 0 0 0.0 5.01790 0.043800 1 0.140381 0.333333
22 0.2475 0 0 0.0 4.12890 0.041300 1 0.140381 0.333333
23 0.2700 0 0 0.0 3.34660 0.039600 1 0.140381 0.333333
24 0.2925 0 0 0.0 2.64270 0.038800 1 0.140381 0.333333
25 0.3150 0 0 0.0 1.98940 0.038200 1 0.140381 0.333333
26 0.3375 0 0 0.0 1.35540 0.037600 1 0.140381 0.333333
27 0.3600 0 0 0.0 0.69480 0.037200 1 0.140381 0.333333
28 0.3825 0 0 0.0 0.15000 0.036800 1 0.140381 0.333333
29 0.4050 0 0 0.0 -0.2500 0.036400 1 0.140381 0.333333
30 0.4275 0 0 0.0 -0.6000 0.036000 1 0.140381 0.333333
31 0.4500 0 0 0.0 -0.7500 0.035600 1 0.140381 0.333333

```

Figure 22- Text file example to enter the blade profile into Ashes

With this text file, Ashes was able to create the blade geometry. After this, we could apply a wide range of test parameters like: *wind velocity, number of blades, size, TSR* and a lot of more. Furthermore, it gives us the possibility to analyse the rotor characteristics.

Ashes results are more accurate than the Matlab program ones because they use more complex and accurate calculations. However, Matlab results were not far away from the simulations realized by Ashes. Although, the BEM method gives an optimal profile, our design may be improved by changing a little the twist angle and the Chord length. In general, the more chord length the more power and better CP (coefficient of performance). However, size requirements must be taken into account when doing the design. This requirements were too strict and make the trade-off between size and efficiency a difficult task.

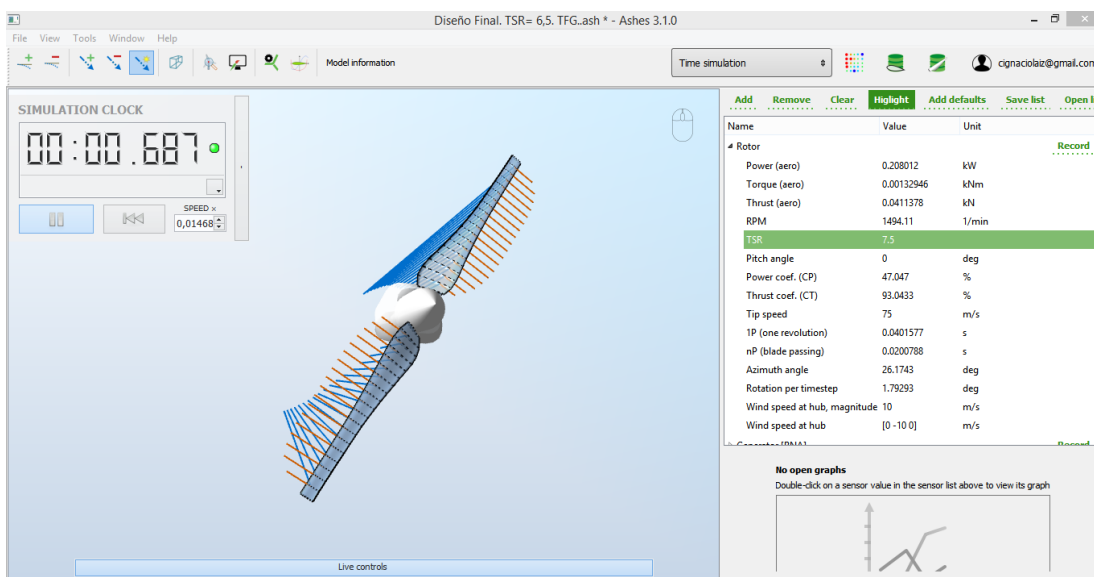
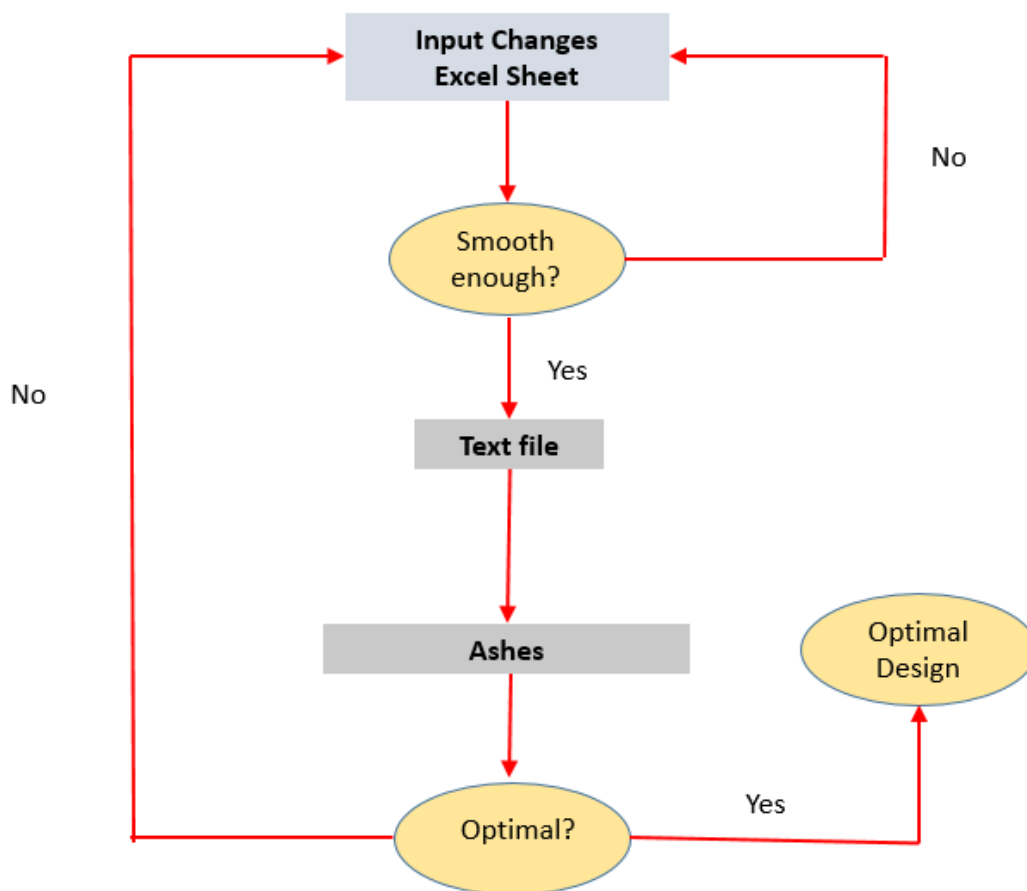


Figure 23- Ashes simulation example

### 3.4.3.3 Iteration process with Ashes and Excel

The next step, is to start a try and error process using Excel and Ashes. The Excel program is used to maintain a smooth profile during the iteration changes. Having a smooth profile is important for two reasons: first because aerodynamics likes smooth edges and secondly because we will prevent the blade from breaking in the milling process. The next figure illustrates the iteration process in form of an algorithm:

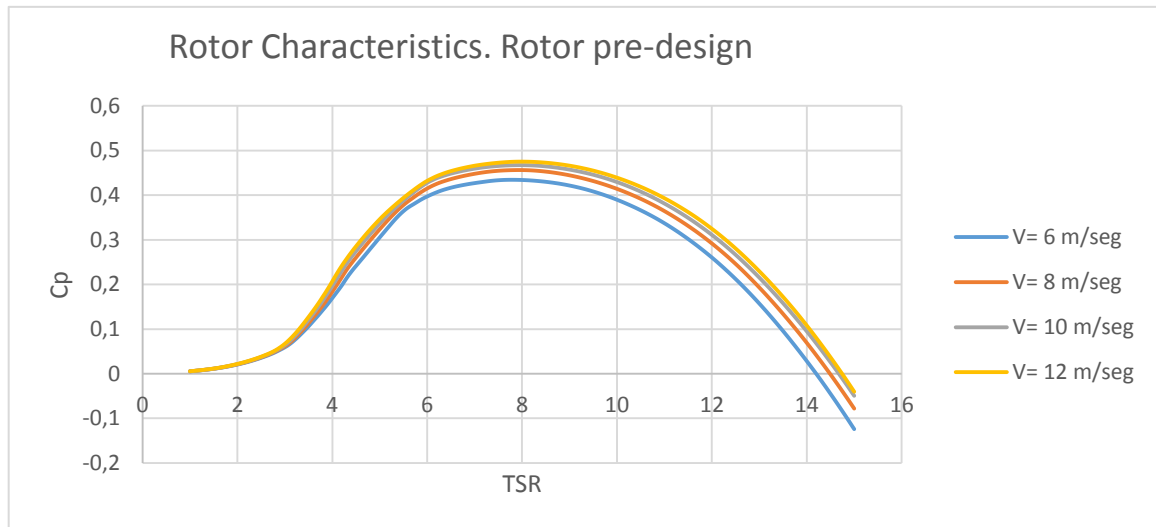


**Figure 24-** Ashes and Excel iteration algorithm to compute the final design

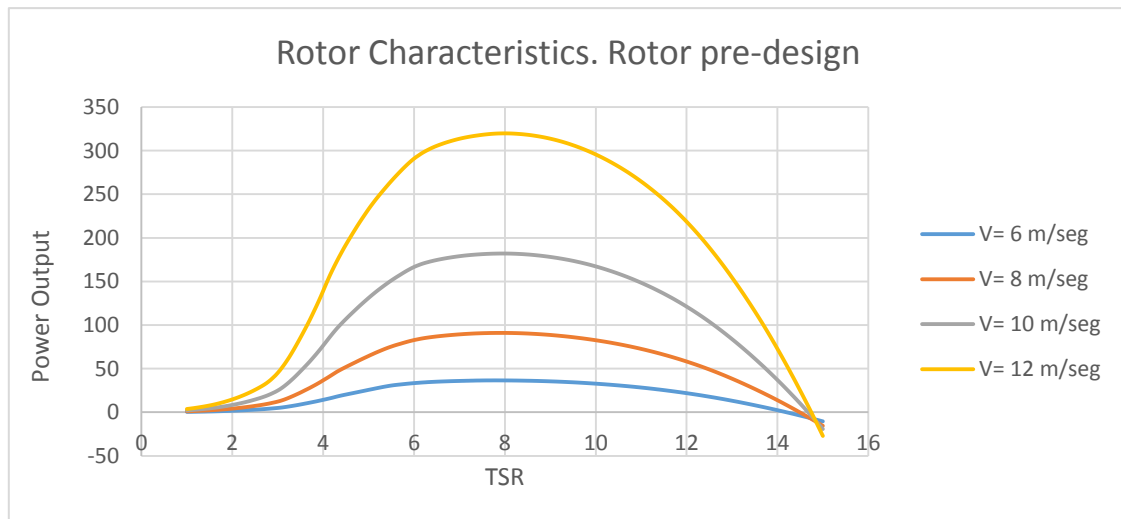
These two softwares were used to optimize the first predesign. The first step to do this, was to compute the rotor characteristics once the turbine have been included in Ashes. By doing this under rotor characteristics, we discovered the first difference compared to the pre- design.

The first difference found between Matlab and Ashes calculations was the different value of the optimal TSR and thus the rotational speed for the designed rotor. Indeed, although the blade was initially optimized for a  $TSR = 6,5$  in Matlab, the optimal  $C_p$  value corresponded for a  $TSR$  close to  $7 - 7,5$ .

As the Ashes calculations are more advanced I decided to maintain the blade geometry given by Matlab but to consider the optimal value of TSR calculated by Ashes. The pre-design rotor characteristics are illustrated in the next graphic:



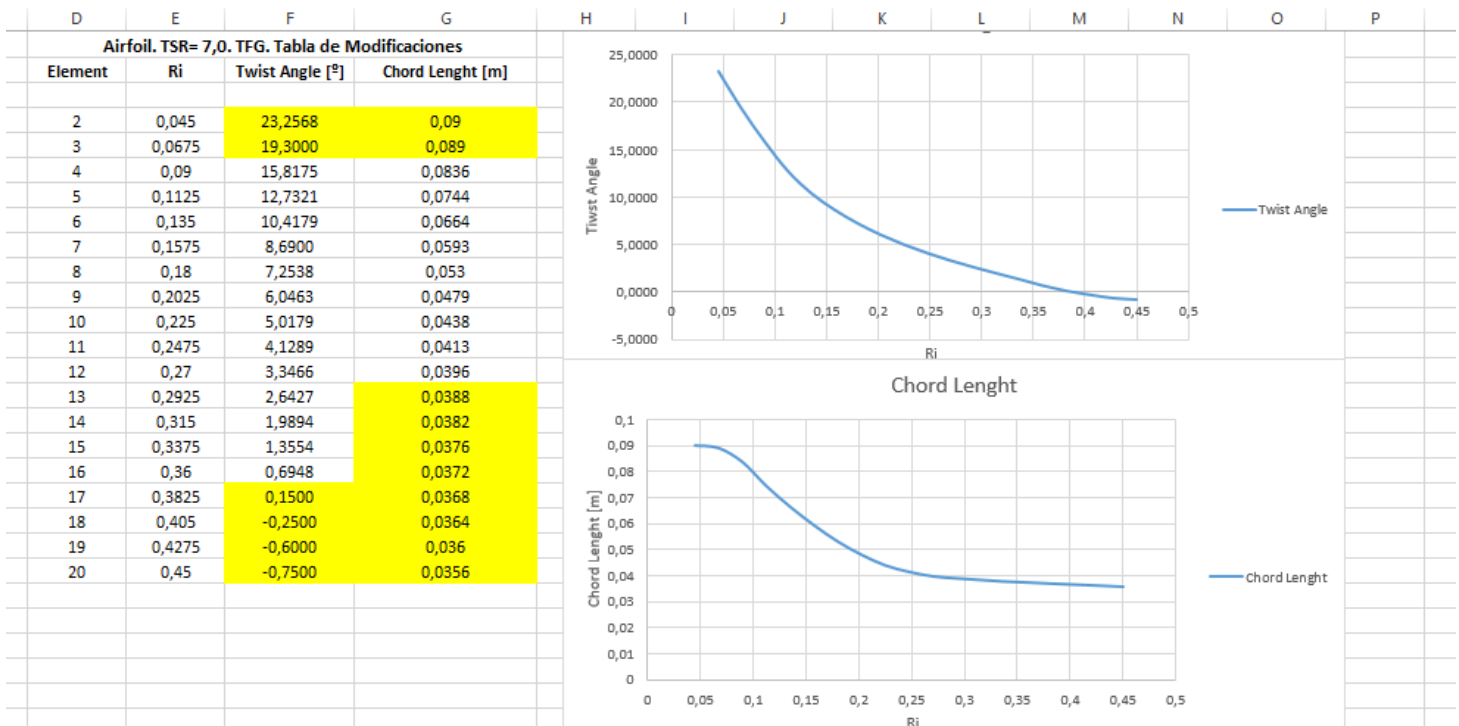
**Graphic 11-** Power coefficient of the first pre-design



**Graphic 12-** Power output of the first pre-design

Note that all geometry changes realized during the iteration process have been considered small enough to assume all designs to have an optimal  $TSR \approx 7$ . Hence, since now all calculations and iterations will be done by considering an optimal  $TSR = 7$ .

Therefore, two graphics and a table were elaborated in Excel to ensure smoothness in the chord length and twist angle when making changes. In this sense, the first step of the process was to ensure blade smoothness. We made this by using the following Excel sheet:



**Figure 25-** Illustration of the Excel used to maintain a smooth profile at every iteration

After this, the new geometry was written in the text file and the new design was imported to Ashes. By using Ashes we could check whether the changes were achieving a more optimal design in terms of compromise between size and power coefficient ( $C_p$ ). The next figure illustrates the Ashes simulation performance:

In this sense, small changes were made in the pre-design models until coming up with the best solution. After some iterations, it was seen that small changes in the chord length were more effective than in the twist angle when optimizing the power coefficient. Moreover, the bigger is the chord length the more tough it is. This is good for both milling process and testing conditions. However, blade load resistance is supposed to be already fixed by the given constraints of minimum thickness and minimum chord length.

Consequently, I decided to focus the iteration process on the chord length instead on the twist angle. However, some small changes were also made in the twist angle to achieve the final design, but this parameter can be considered to have less weight in the iteration process.

Thus, size constraints should not be forgotten, more specifically near the root of the blade where there was a high chord length and a high twist angle value. In this sense, I decided to decrease a little the twist to be able to increase a little the chord length.

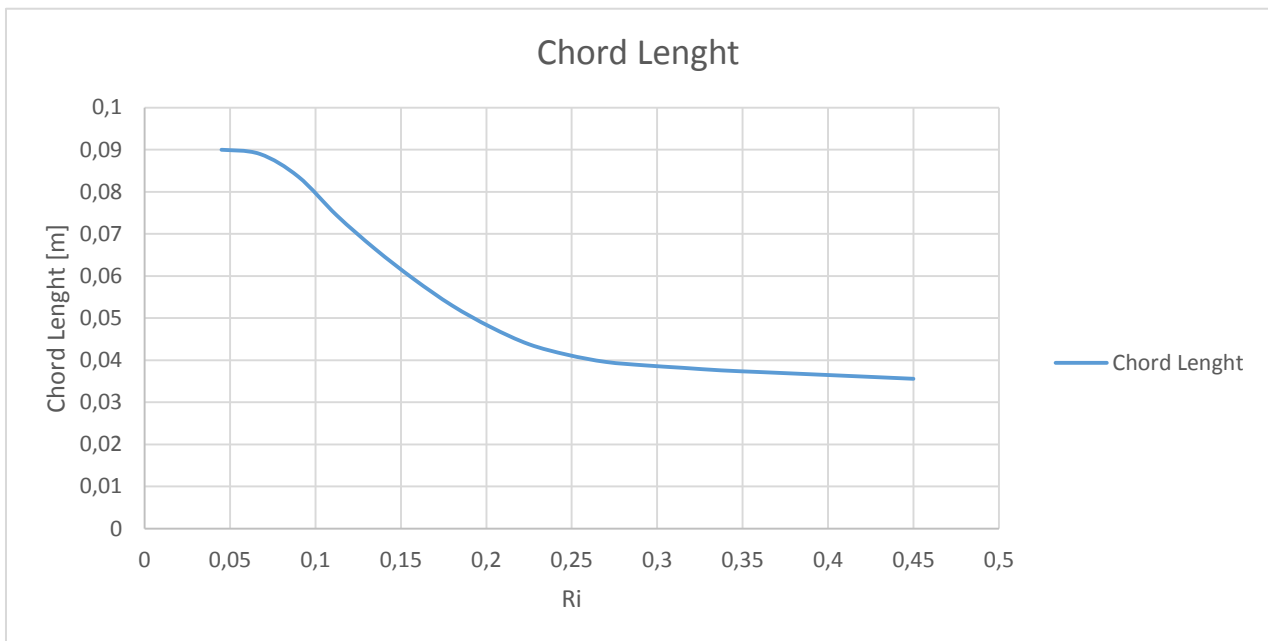
Thus, after several iterations the final geometry was obtained. This final model is reported in **table 4**.

Airfoil. TSR= 7,0. TFG. Tabla de Modificaciones			
Element	Ri	Twist Angle [°]	Chord Length [m]
2	0,045	23,2568	0,09
3	0,0675	19,3	0,089
4	0,09	15,8175	0,0836
5	0,1125	12,7321	0,0744
6	0,135	10,4179	0,0664
7	0,1575	8,69	0,0593
8	0,18	7,2538	0,053
9	0,2025	6,0463	0,0479
10	0,225	5,0179	0,0438
11	0,2475	4,1289	0,0413
12	0,27	3,3466	0,0396
13	0,2925	2,6427	0,0388
14	0,315	1,9894	0,0382
15	0,3375	1,3554	0,0376
16	0,36	0,6948	0,0372
17	0,3825	0,15	0,0368
18	0,405	-0,25	0,0364
19	0,4275	-0,6	0,036
20	0,45	-0,75	0,0356

**Table 4-** Modifications Excel table to maintain a smooth blade profile at every iteration. These illustrated results are from the final design



**Graphic 13-** Distribution of the twist angle at the final iteration



**Graphic 14-** *Distribution of the Chord length at the final iteration*

Note that the first blade element has been removed to give some extra space to the hub.

#### 3.4.3.4 Conclusion

The aim of this this part of the project was to achieve the highest power coefficient as possible. After several iterations between Matlab, Excel and Ashes, the final blade which is reported in **table 4** reach a power coefficient of **48%** and Torque of  $1.41 Nm$ .

To do this, I increased as much as possible the chord length. More specifically, I decided to increase the chord length of the last blade sections. Doing this have a double porpoise as it was commented before: first to increase the  $C_p$  and secondly ensuring blade resistance. Finally, the design was imported to Inventor as a Step file to extrude the blade.

By achieving this power coefficient and torque, I was on my way to obtain a good total efficiency. However, it should not be forgotten that to achieve a high total efficiency not only a good rotor is necessary but a good generator and a good coupling.

### 3.4.4 Design under Inventor

#### 3.4.4.1 Introduction

Once the final optimal blade was chosen, I created the 3D model of the final design with Autodesk Inventor Professional. Autodesk Inventor Professional is a 3D mechanical Solid modelling software that is widely extended around the world.

I have been using Inventor for creating the 3D drawing and the assembly of my turbine. In this sense, this program was the one in charge to verify if I was respecting the strict size requirements. Thus, I have to find an appropriate balance between size, robust and efficiency. In order to see if my turbine was inside the size constraints I had to verify if the assembly of my turbine fits inside a 1000 x 100x 10 mm rectangle.

Consequently, I have been working with Ashes and Inventor simultaneously. While I was using Ashes to check the efficiency of the blade I have been using inventor to verify the size requirements of every designed turbine. Finally, I used the geometry from **Table 4** to come up with my final design.

#### 3.4.4.2 Importing the blade into Autodesk Inventor

To import the blade geometry into Inventor it was necessary to save the final geometry as a Step file. This could be easily done by Ashes. This step file will load in Inventor the non-solid blade geometry distribution. This step file is reported in the **figure 26**.

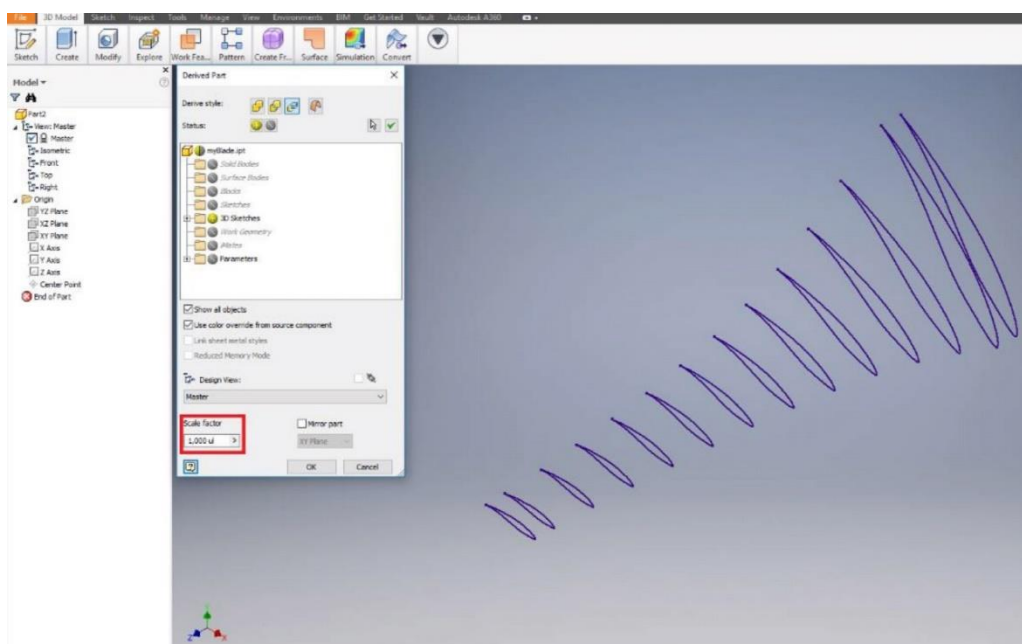
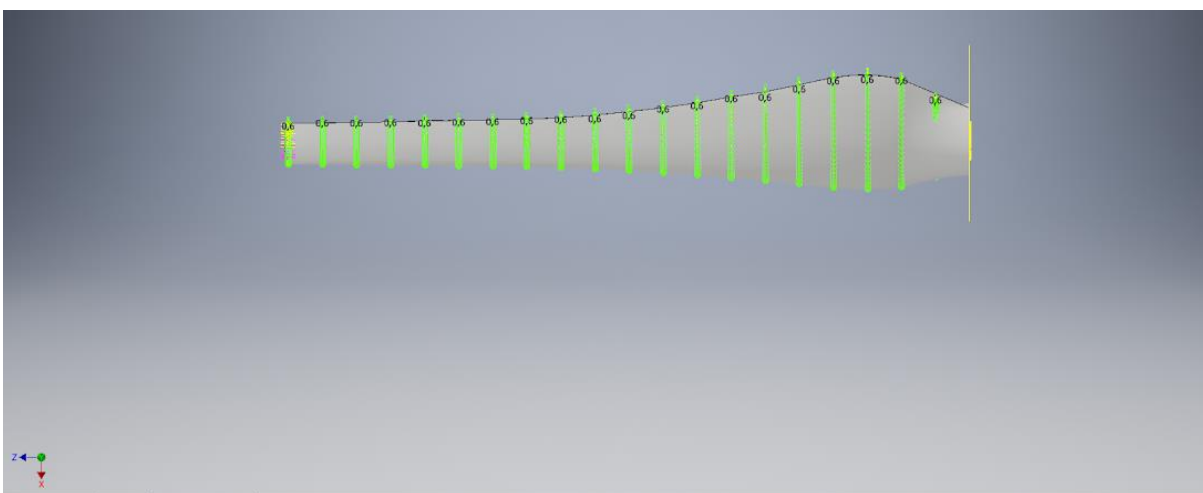
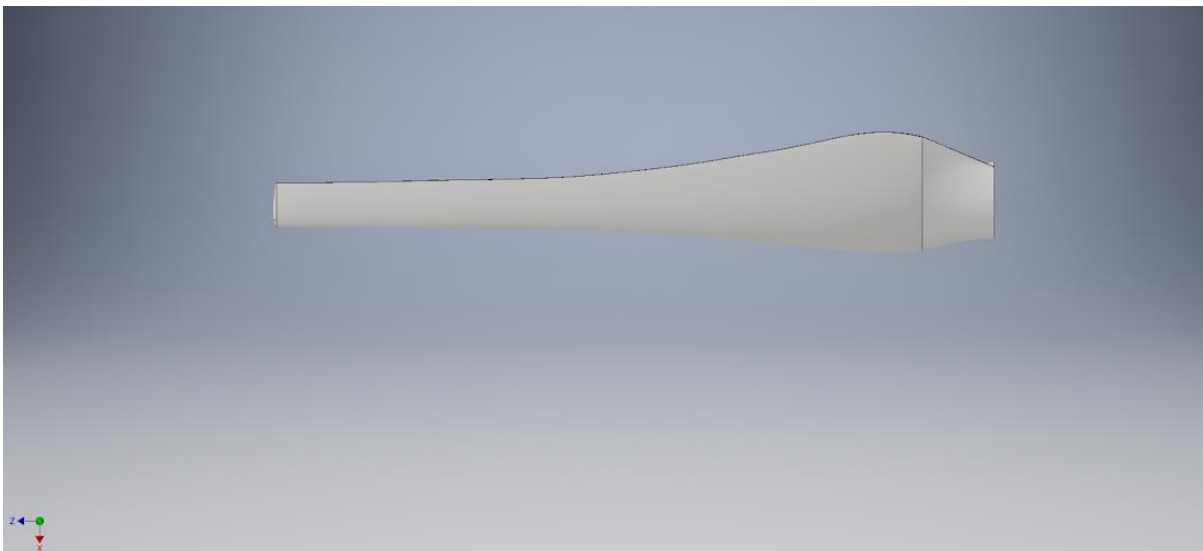
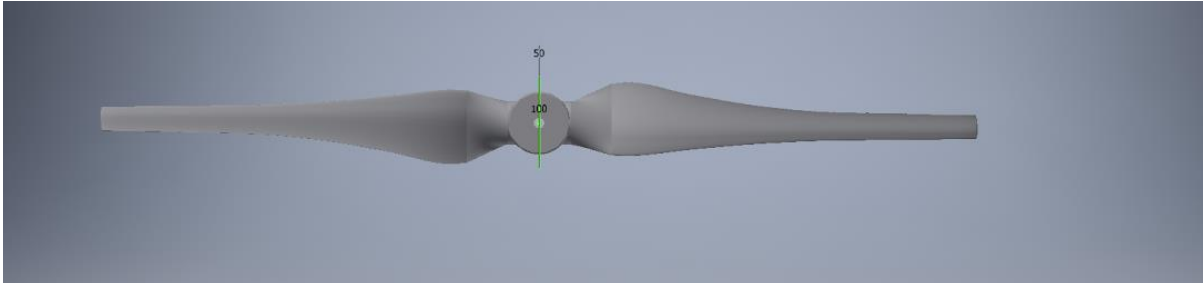


Figure 26- Blade geometry in Step file format exported into Inventor



### 3.4.4.3 Modelling process and results

The final design and its assembly is presented in the following figures.



**Figure 27-** Final 3D drawing created by Inventor. Blade extrusion and turbine assembly

The first step after importing the blade geometry distribution is to create an individual 3D sketch for every blade element. This must be done for every blade elements to be able to extrude the turbine and make it solid. Note that Inventor needs to follow a sequence of 3D sketches to be able to make an extrusion using Loft function.

This makes sense, because two blade sections in the same sketch will led to a mathematical indertermination and therefore to an extrusion error.

After this, it was necessary to modify all 3D sketches to ensure the minimal blade thickness which is 0.6 mm. To do this, the profile edge was analysed to reject the blade profile thinner than 0.6 mm. Thus, a 2D sketch was elaborated for every blade elements with edges thinner than the minimal thickness. This 2D sketches served to make cuts and disregard the profile that did not comply with the restriction. This procedure is illustrated in the following figure:

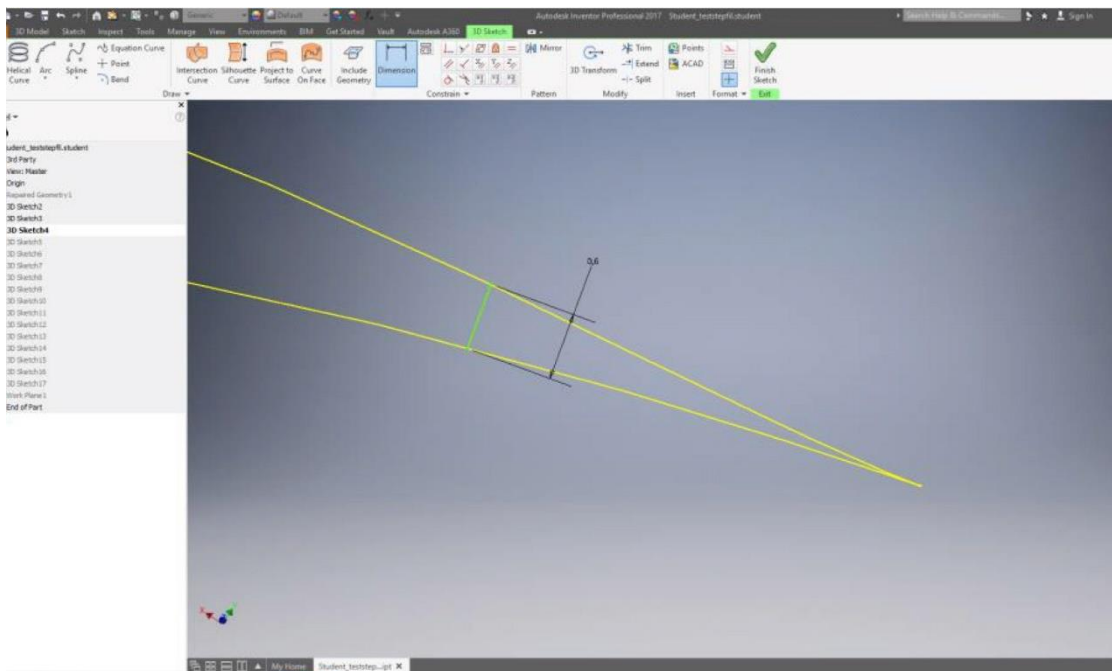
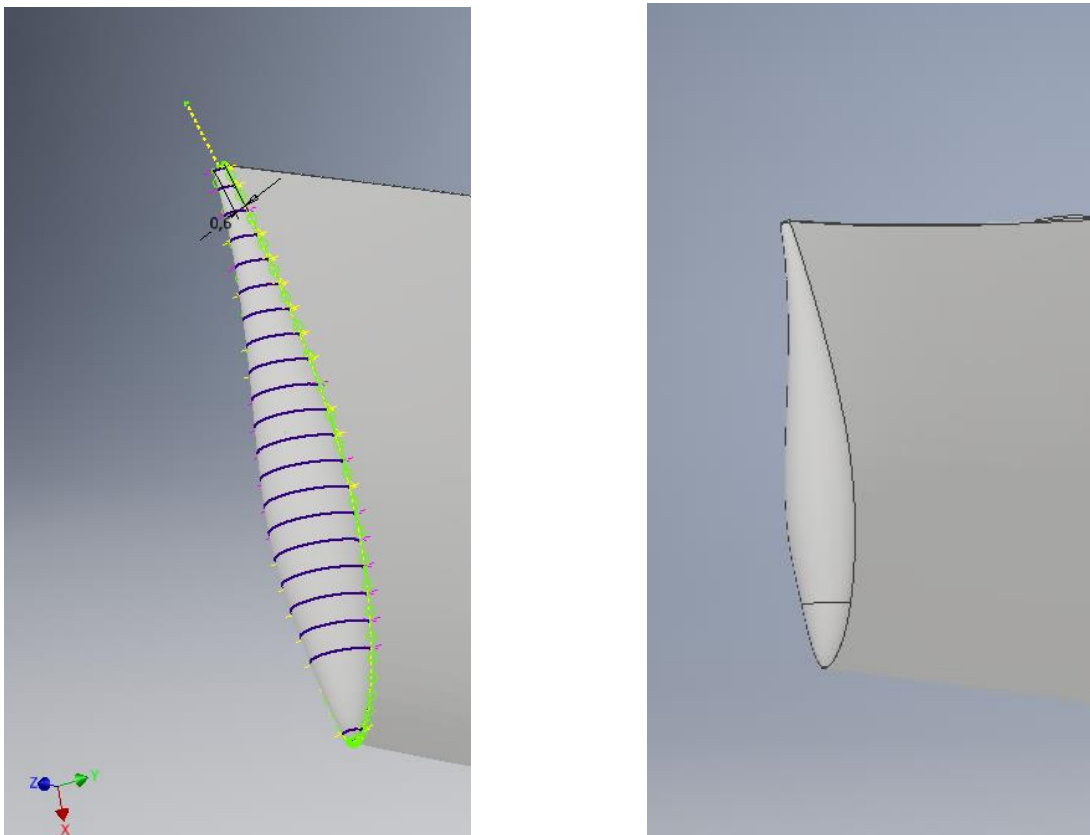


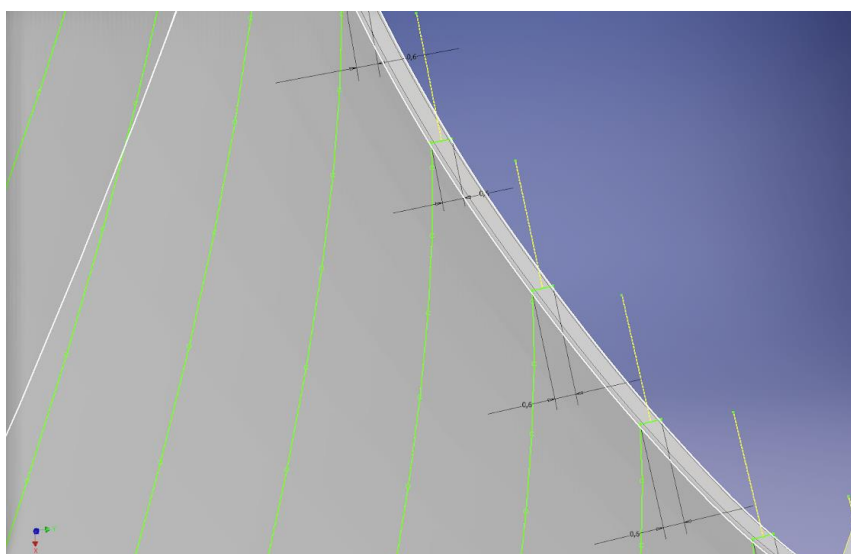
Figure 28- Minimum thickness correction procedure

On the other hand, I also made 3D loft in the tip in order to have a smother Tip profile and avoid loses around the tip. This will prevent a delay in the release of the boundary layer and the flow will not flow from one part of the blade to the other. This final result is presented in **Figure 26**.



**Figure 29-** Blade tip extrusion to create a smoother profile

After this, the final step to create the blade was to round the edges. This was done to avoid problems during the milling process. This is reported in **Figure 27**.



**Figure 30-** Roundness procedure to ensure a good manufacturing process and a smoother profile

## 3.5 Generator design

### 3.5.1 Introduction

To achieve a high total efficiency it is important to design not only a good generator but a good coupling with the rotor. In this sense, the aim of this section is to achieve an optimal coupling with the highest efficiency as possible. In other words, the generator torque should match the turbine torque at the design point.

Hence, all decisions made to come up with the final design will be commented along this section. As the generator rotor was provided by the “*Norwegian university of Science and technology*”, this paper is mainly focus on the stator design.

Two options of generators were given:

1. **One phase axial generator.** This four pole generator is composed by a wooden plane stator formed by four coils and a circular permanent magnet. Both stator and rotor parts are located in front of each other in the axial direction.
2. **Three phase radial generator.** This four pole generator is composed by a plastic cylindrical stator formed by six coils and a cylindrical permanent magnet. In the configuration of this generator, the rotor is set inside the stator. Find its configuration in Appendix F.

While the axial generator is easier to design and to manufacture, three phase radial generators are normally more efficient. To ensure that the extra work was worth, I design one of each to compare both two models. In this sense, this paper will present a brief comparison analysis between the two models to illustrate why the three phase radial generator was chosen.

On the other hand, the final design was realized by using Ashes and Excel. In a similar way that it happened with the blade, the design was performance by Excel and validated though Ashes. Moreover, Ashes give the designer the opportunity to simulate the performance of the whole turbine (rotor and generator together).

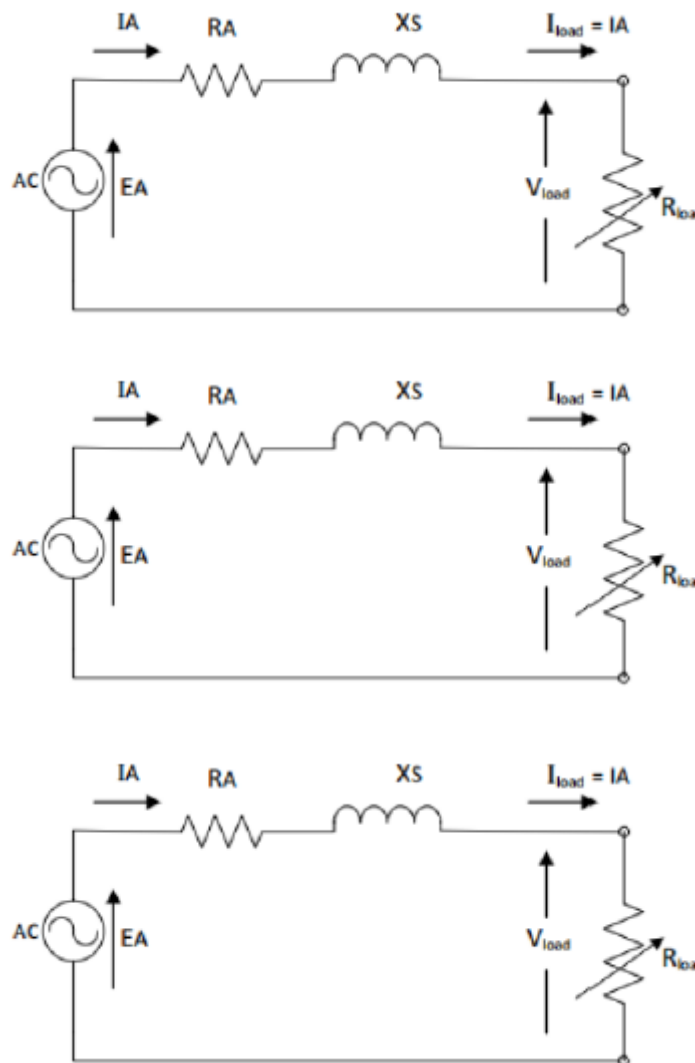
Finally, the generator design is based on some turbine parameters. These parameters are *turbine rotational speed* and *turbine torque*. In this sense, although this project is focus on obtaining the highest total efficiency as possible, it is interesting that our turbine has a high torque. In general terms, the higher is the power coefficient the higher is the torque and therefore this led to a high generator power output.

### 3.5.2 Theory Fundamentals

The generator converts the mechanical rotation generated by the turbine into electrical power by using in this case permanent magnets. Thus, the rotation of the rotor makes the stator coils see a variable magnet flux in time. According to the Faradays law, the presence of this variable magnet flux in time induces a current in the coils.

$$E = -\frac{d\Phi_m}{dt}$$

It is important to underline that only designing the stator will be designed. In this sense, the stator of a three phase radial generator can be analyzed as the following simplified circuit:



**Figure 31-** Electrical equivalent circuit for a three phase radial generator (Frøyd & Kjetil Haugset)

### 3.5.3 Comparison of Axial generator and Radial Generator in terms of efficiency

The NTNU suggested me two options, a one phase Axial Generator, or a three phase radial generator. The strong point of the one phase axial generator is its simplicity. Nevertheless, I decided to investigate both generators and see how this choice could affect to my total efficiency.

In this sense, both radial and axial generator were design by using an Excel sheet that was provided by NTNU. This Excel sheet is reported in Appendix E. Thus, we obtain the following data:

Axial Generator Designs. Small Wire.				
Number of Turns	Load Resistance [ $\Omega$ ]	Torque [Nm]	Efficiency [%]	Flux Density [T]
60	10	1,402	70,9	0,319184
75	14	1,43	72,1	0,3056
90	18,5	1,428	72,7	0,292664
105	23	1,427	73,1	0,280376
120	27,5	1,42	73,3	0,268736
135	32	1,407	73,3	0,257744
150	35	1,422	73,4	0,2474

**Table 5-** Different possible designs for one phase Axial generator

Radial Generator Designs. Small Wire. TSR= 6,5						
Number of Turns	Load Resistance [ $\Omega$ ]	Torque [Nm]	Efficiency [%]	Flux Density [T]	Power Output [W]	Ashes Check
63	32,5	1,509	78,6	0,283904	160,9	OK
54	26	1,517	78,5	0,295256	161,6	OK
45	20	1,507	78,2	0,3074	159,8	OK
36	14	1,507	77,8	0,320336	159	OK
27	8,5	1,516	77,2	0,334064	158,7	OK

**Table 6-** Different possible designs for three phase Radial generator

By doing this analysis, note that the differences between these two models for small generators may be neglected. In this sense, although radial generators are better for big generators and a great number of poles, axial generators may be competitive for small number of poles.

However, the radial generator still achieving a better performance (5% better). Moreover, I was told by my supervisor that Axial generators usually give more loses in the final test and radial generator are more close to their design during the tests. Because of this, I finally decided to go for a three phase radial generator.

### 3.5.4 Design under Excel

Therefore, the choice was finally the radial generator. In this sense, although some axial designs were performed during the project, this paper will be focus on the design, manufacture and coupling of a three phase radial generator.

To design the generator I used the Excel sheet reported in Appendix E. The aim of this design is to reach the turbine torque at its rotational speed with the highest efficiency as possible. Thus, the main input parameters for the generator design are:

- Number of turns per coil ( $N_{turns}$ ).
- Load Resistance ( $L_A$ ).
- Flux density in the middle of the coil
- Resistance in the wire

Both load resistance and number of turns per coils are variable parameters that can oscillate between  $[0.5\Omega - 50\Omega]$  and  $[20 - 60]$  respectively. Thus, some designs for various combinations of  $N_{turns}$  and  $L_A$  were computed using the Excel sheet reported in Appendix X.

Moreover, there were two different wires to design the generator:

- 1.2 mm diameter wire with a unit length resistance of :  $0.015110 \Omega/m$
- 1.5 mm diameter wire with a unit length resistance of:  $0.009756 \Omega/m$

These two wires will be kwon as “*Small wire*” and “*Big wire*” respectively. In this sense, the generator design procedure can be summarized by the following algorithm:

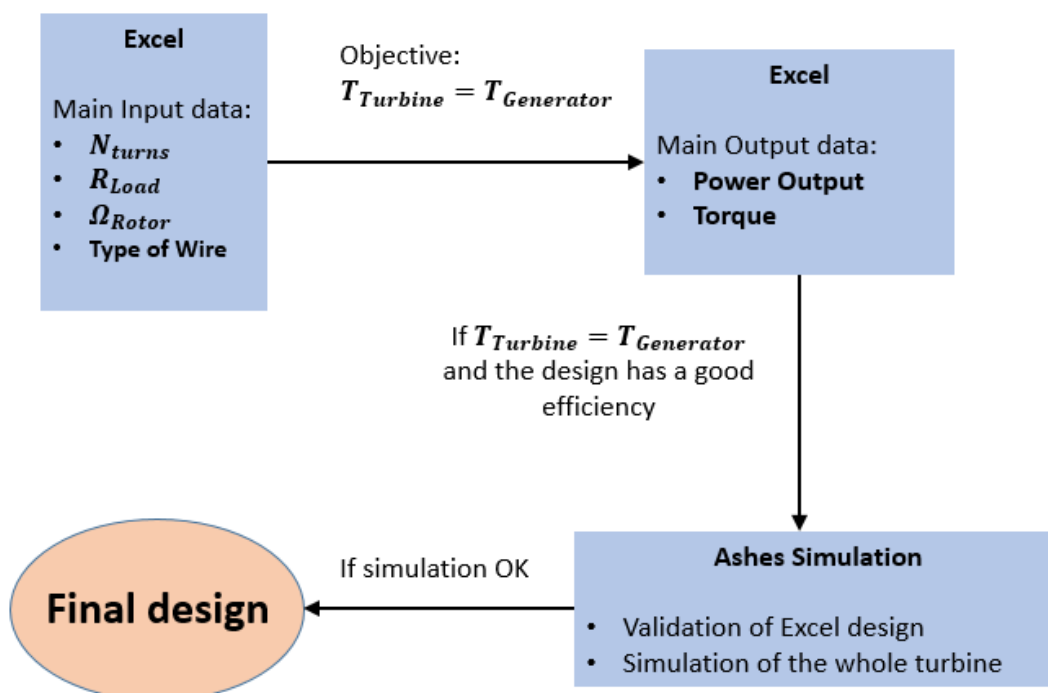


Figure 32- Generator design algorithm



### 3.5.5 Selection of the wire

After choosing the type of generator, the next step is to choose the wire of the coils. As it was stated above, there were two options:

- Big Wire:  $R_{Wire} = 015110 \Omega/m$
- Small Wire:  $R_{Wire} = 0.009756 \Omega/m$

To select which wire is better for the final design, two pre-design were needed. The procedure by which the following information has been found is shown below in “*Excel calculations and results*”. Thus, the following results were obtained for a three phase radial generator with both Small and Big wire:

Generator Designs. Small Wire.							
Number of Turns	Load Resistance [ $\Omega$ ]	Torque [Nm]	Efficiency [%]	Flux Density [T]	Power Output [W]	Ashes Check	
63	38	1,434	78	0,283904	163,3	OK	
54	31	1,421	77,7	0,295256	161,3	OK	
45	23	1,444	77,8	0,3074	164	OK	
36	16	1,449	77,5	0,320336	164	OK	
27	10	1,428	76,7	0,334064	160	OK	

**Table 7-** Three phase Radial generator designs with small wire

Generator Designs. Big Wire.							
Number of Turns	Load Resistance [ $\Omega$ ]	Torque [Nm]	Efficiency [%]	Flux Density [T]	Power Output [W]	Ashes Check	
24	6,5	1,444	77,2	0,3074	162,9	OK	
30	9	1,452	77,6	0,2923	164,6	OK	
36	12	1,418	77,4	0,278525	160,3	OK	
42	14	1,452	77,9	0,265944	165,2	OK	
48	17	1,416	77,5	0,2546	160,4	OK	
54	19	1,423	77,6	0,244494	161,4	OK	
60	21	1,419	77,6	0,235625	160,8	OK	

**Table 8-** Three phase Radial generator designs with big wire

As it could be seen from the comparison above, both types of wire present a good efficiency in the matching point. However, the small wire design require less number of turns. Note that less number of turns led to less coil length which is cheaper. Moreover, the less number of turns the less work will be needed during the manufacturing process. Because all of these reasons, I decided to design based on Small wire.

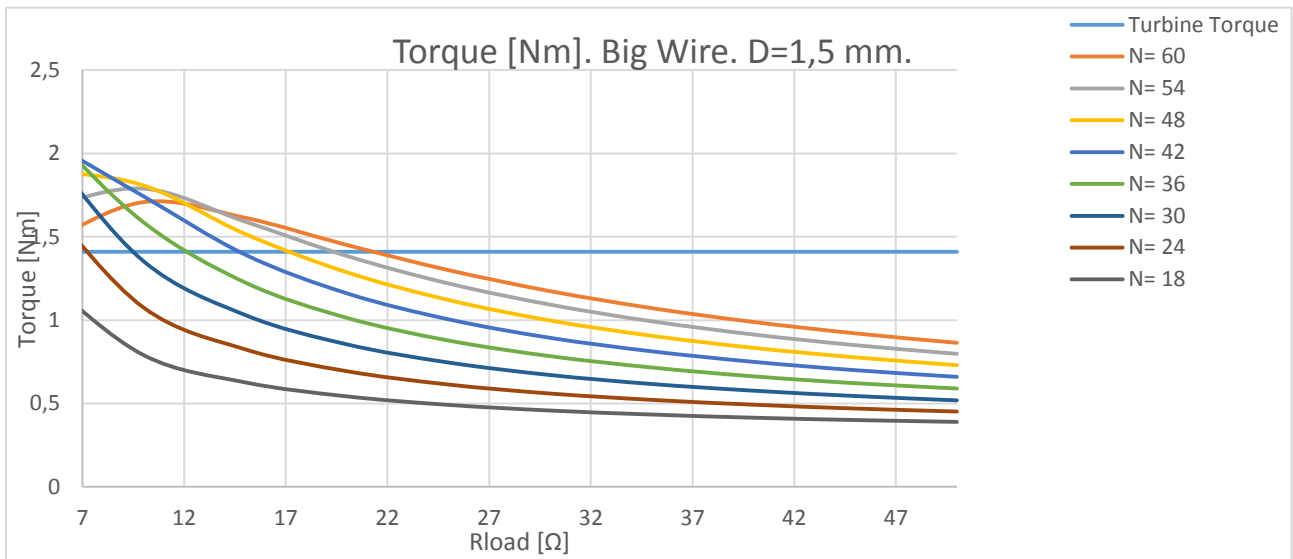
### 3.5.6 Excel calculations and results

Although a lot of pre-designs were developed, this paper is focused on the final design. Hence, the final calculations are shown to illustrate the Excel procedure. To get the final design, it was necessary to perform different designs in terms of number of turns and load resistance. In most of the cases, there will be a match between the turbine torque and the generator torque for a combination of load resistance and number of turns.

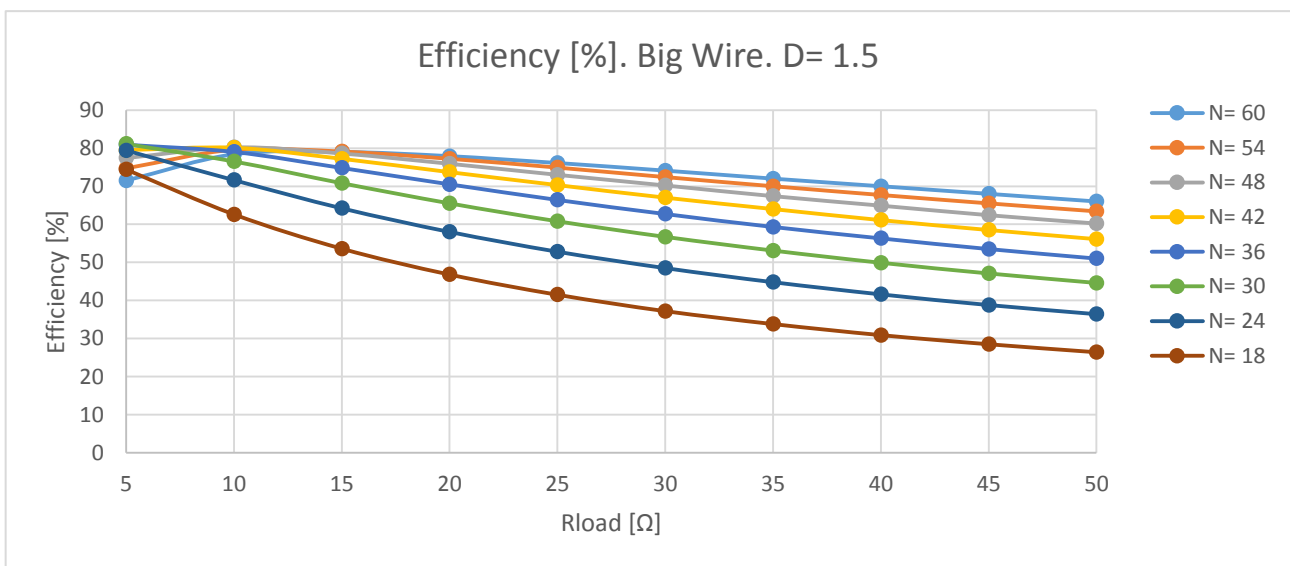
Therefore, the aim of this part is to compute the best match by optimizing the generator efficiency. To do this, I created an Excel to store all main output parameters for every iteration with the aim to find the best design. Thus, after some iterations with the big wire, the data of the following designs were obtained by using the Excel sheet which is reported in Appendix X:

Generator Designs. Big Wire.						
Number of Turns	Load Resistance [Ω]	Torque [Nm]	Efficiency [%]	Flux Density [T]	Power Output [W]	Ashes Check
24	6,5	1,444	77,2	0,3074	162,9	OK
30	9	1,452	77,6	0,2923	164,6	OK
36	12	1,418	77,4	0,278525	160,3	OK
42	14	1,452	77,9	0,265944	165,2	OK
48	17	1,416	77,5	0,2546	160,4	OK
54	19	1,423	77,6	0,244494	161,4	OK
60	21	1,419	77,6	0,235625	160,8	OK

**Table 9-** Final Three phase Radial generator design



**Graphic 15-** Generator Torque matching the Turbine torque. Different possibilities for the final design



**Graphic 16-** Generator efficiency for all different designs in function of Load resistance

Thus, the final solution which is marked in blue is:

- Number of turns: 30
- Load Resistance:  $9\Omega$
- Resistance is the wire:  $0.009756 \Omega/m$
- Rotational Speed:  $1395 \text{ rpm}$

### 3.5.7 Ashes validation

Finally, the final design need to be imported into Ashes to validate the Excel results. By doing so, I realized that Excel calculations were accurate enough to not present problems during the real test. In this sense, a simulation like the following was realized for the final design:

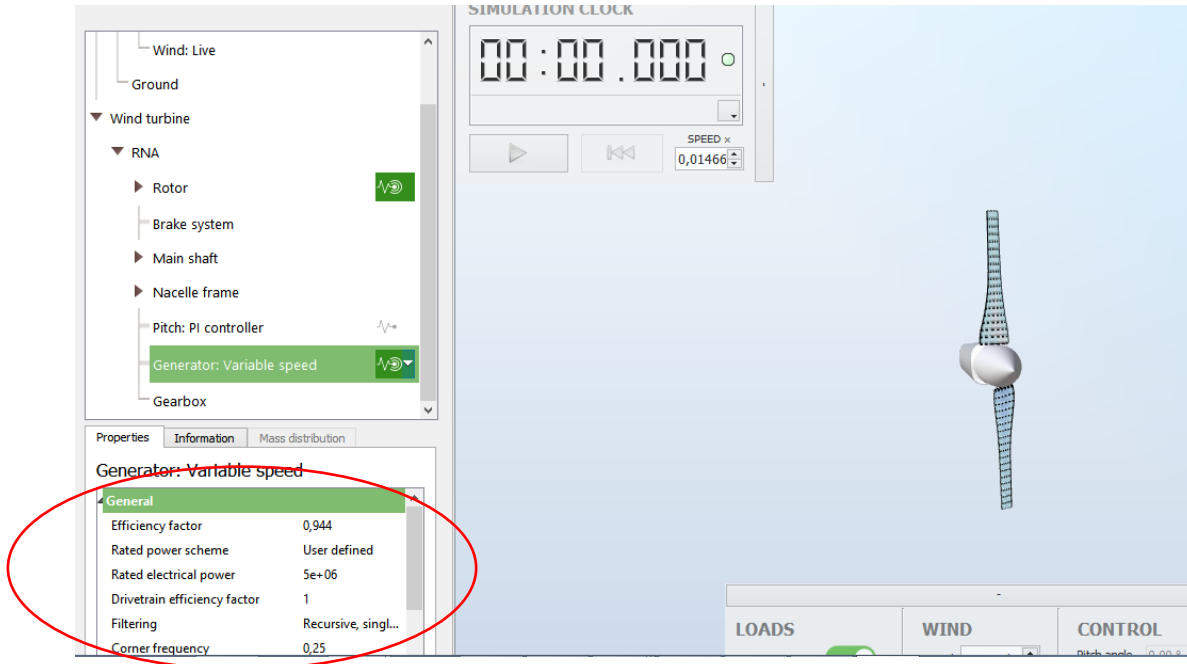


Figure 33- Ashes generator simulation example

4

# Turbine making

## 4.1 Rotor milling

The “*Norwegian University of Science and Technology*” was in charge of the turbine manufacturing process. Thus, the turbine was manufactured by the NTNU by a milling process. However, there were some steps that should be done myself. In this sense, this section is focus on the processes I did during the project.

### 4.1.1 CNC programming: SprutCAM

After finishing the blade 3D drawing, the rotor is imported to **SprutCAM** which is manufacturing process simulation software based on CNC programming. In general terms, this software is used to simulate the milling operation and confirm that the turbine will not break during the process.

To do this simulation, I followed the “*SprutCAM Guide*” (Berg). Note that the most critical parts during the milling process are the tips and edges. This is the reason why we had rounded all edges and set the minimal thickness constraint. An example of the **SprutCAM** simulation process is illustrated in the following figures:

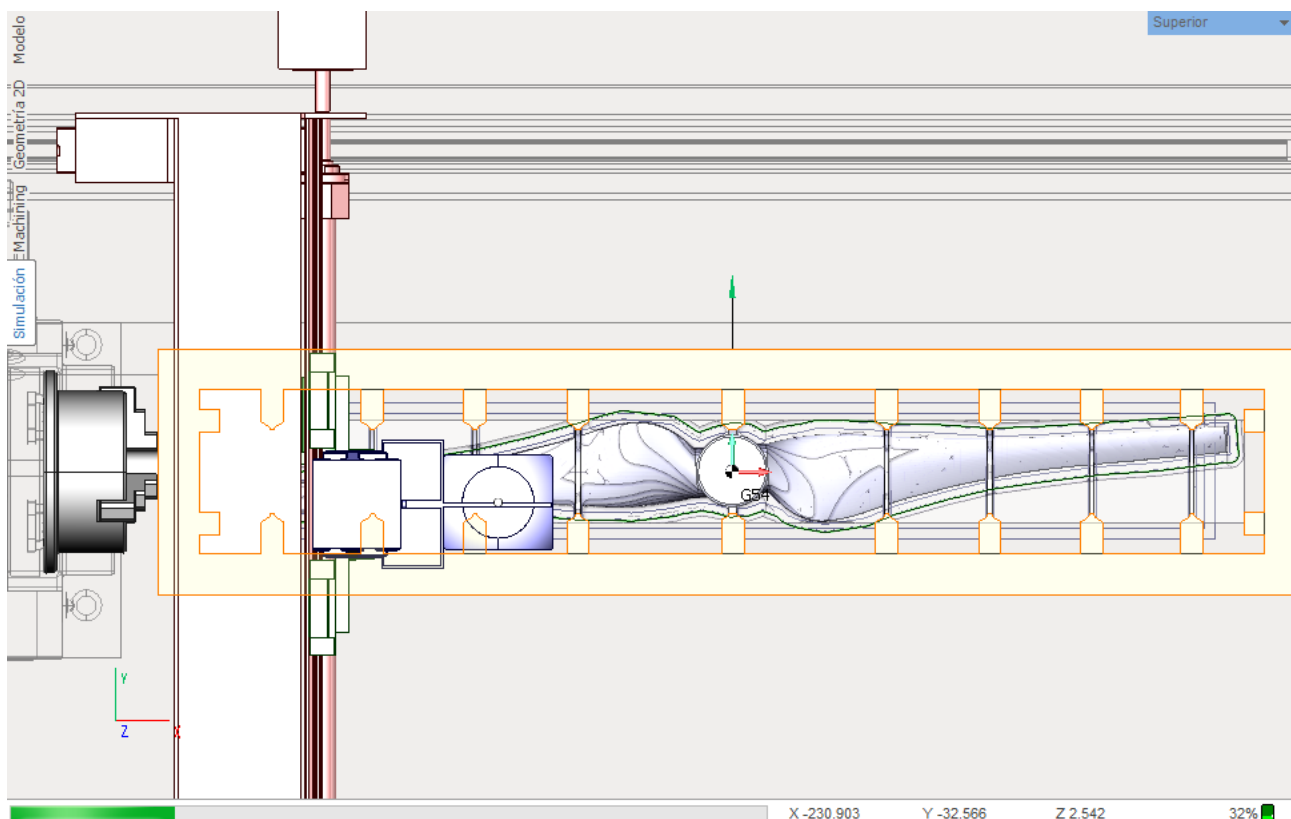
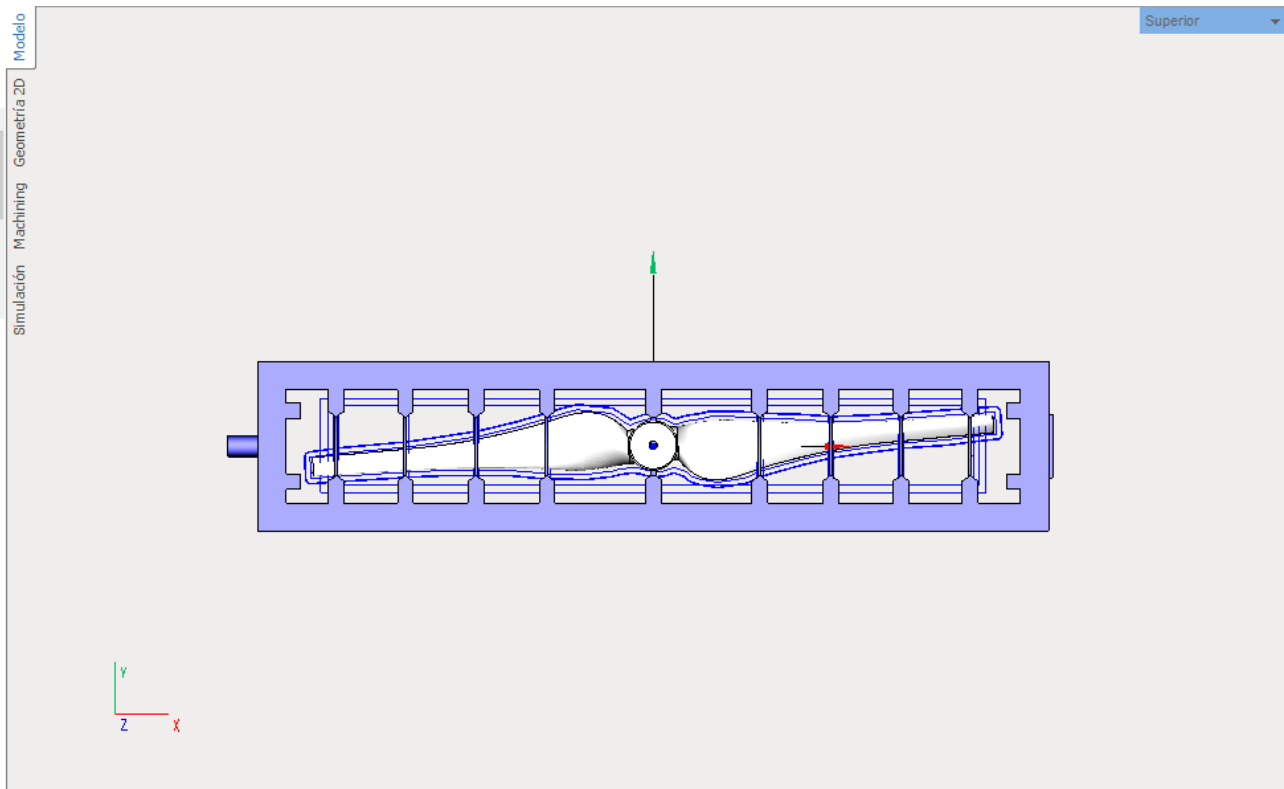


Figure 34- SprutCAM simulation for the final design before the manufacturing process

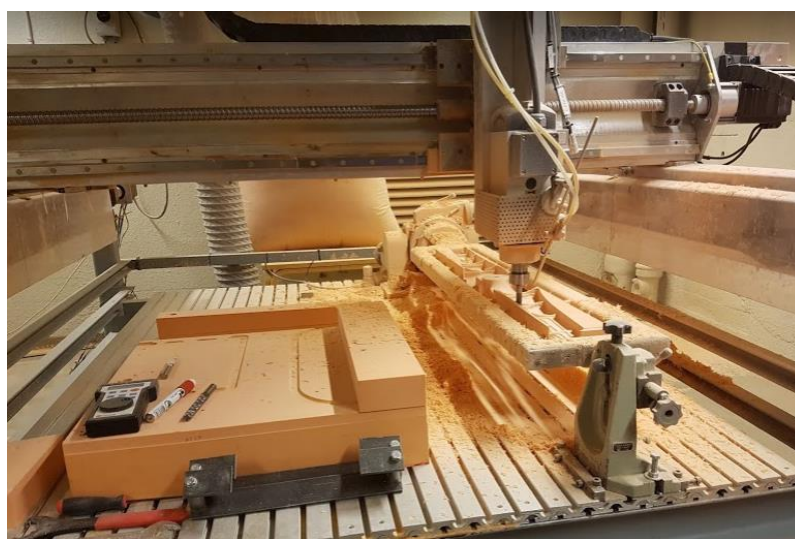


**Figure 35-** SprutCAM matrix necessary to simulate the CNC program for the final design before the manufacturing process

After confirming through these simulations that the manufacturing process would not show problems, the turbine was sent in Step format to the manufacturing department of the NTNU.

## 4.1.2 Milling process

*“Milling is the machining process of using rotary cutters to remove material from a workpiece by advancing (or feeding) the cutter into the workpiece at a certain direction. The cutter may also be held at an angle relative to the axis of the tool” (Wikipedia, 2018)*

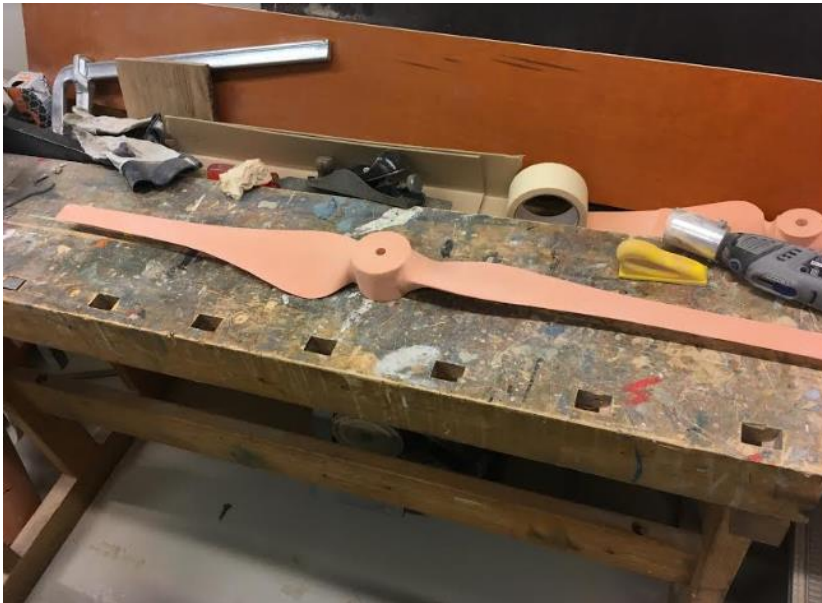


**Figure 36-** Milling process



### 4.1.3 Final result and polishing process

The milling process does not ensure accurate finish. Thus, after the milling it was needed to polish the blade. To do this we used some tools that were in the NTNU laboratory. In the following pictures the final result is illustrated:



**Figure 37-** *Turbine after the polishing process*



**Figure 38-** *Turbine before the polishing process*

## 4.2 Generator manufacture

In contrast to the rotor manufacturing process, the generator manufacture relies more on manual labour. The stator is composed by a plastic cylinder and six coils. To fix the coils in the plastic cylinder, I made some holes in the plastic and join the coils using bridle. As it was stated in the introduction, the four pole rotor is provided by the NTNU. Moreover, they provide me the geometrical design which is reported in Appendix X.

Furthermore, the NTNU also provided me all the necessary materials to elaborate the stator but on the other hand, I was given some freedom to elaborate the stator as I preferred. The next materials were used to elaborate the stator of the three phase radial generator:

- Wood
- Plastic cylinder
- Drill
- Saw
- Bridle
- Cello

The most critical point during this part of the project was to the accuracy. Although it was difficult to stay accurate when elaborating something manually, finally a good result was achieved by focusing on the matrix.

### 4.2.1 Coils creation

This is the main part of the generator construction. To elaborate the six coils needed to manufacture the three phase radial generator, I decided to create a wood matrix. This matrix had to be the more accurate as possible. To achieve a good result, the wood matrix was finally polished.

The objective was to create a generator as the reported in Appendix X but with six coils instead of four coils. After creating the wood matrix (which I am afraid I will not be able to report because I left it in Norway), the coils were creating winding the wire around the wood matrix.

In this sense, it was needed to wind the wire as many times as the number of turns per coil. Moreover, after several tries, I realized that to get a good shape it was necessary to tension the wire as much as possible. However, after removing the coils from the wood matrix, it was necessary to tie the coils with bridles. The coil should be the more compact as possible to experience less loses.

By doing this, the following result was obtained:



**Figure 39-** *Coils manufacture for the three phase Radial generator*

## 4.2.2 Generator assembly

After producing the coils, the next and final step was to assembly the coils into the plastic cylinder. To do this, some holes were made in the cylinder to then hold the coils with the bridles. Note that the coils had to be fixed one of top of the other to create a three phase generator. This is the main different with the documents the NTNU gave me as orientation. As it was stated, these documents are reported in Appendix X.

By doing this, the final design was obtained:



**Figure 40-** *Generator final design. After the assembly*

5

# Testing and results

## 5.1 Generator test

Before testing the whole turbine, a generator test was performed in the NTNU electrical laboratory. This test was performed without the turbine. Thus, the turbine was replaced by an electric engine.

The test was composed by the two phases:

1. Armature resistance measurements ( $R_A$ )
2. Generator test

In this way, the following average armature resistance was obtained:

$$R_A = 295 \text{ m}\Omega/\text{phase approx}$$

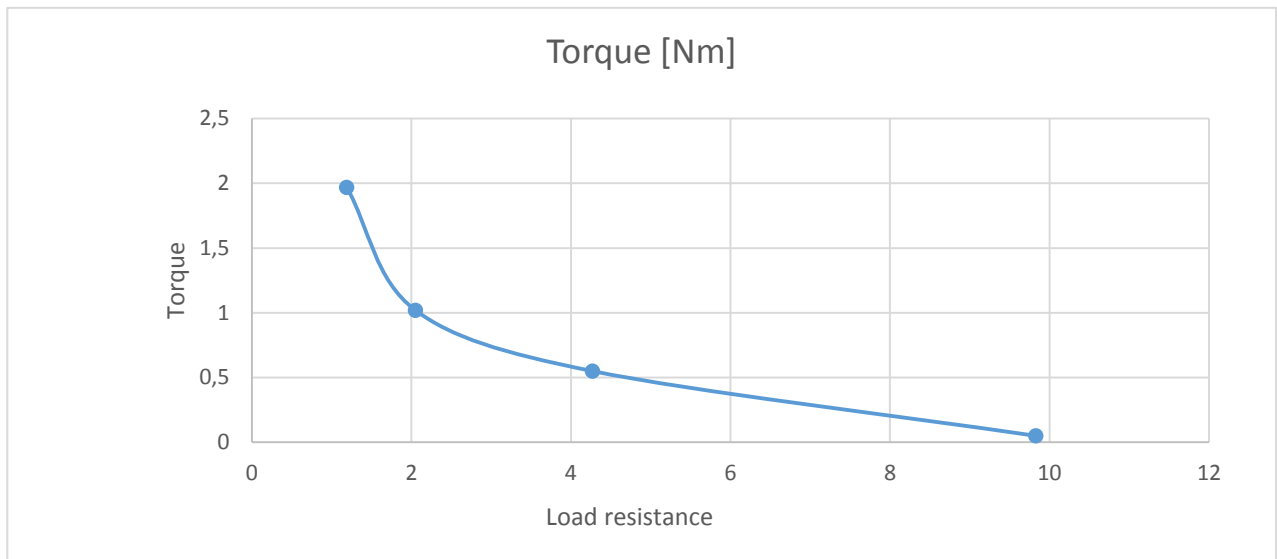
Then, the generator was tested for different rotational speed with the aim of simulate off-design turbine working points. The goal of this test is to verify Ashes and Excel calculations before going through the wind tunnel where the whole turbine was tested.

In this sense, several values of load resistance were investigated for each rotational speed. By doing this, it could be investigated whether the generator present some differences in comparison to **Graphic 15** and **Graphic 16** and therefore see the uncertainties that may appear during the wind tunnel test.

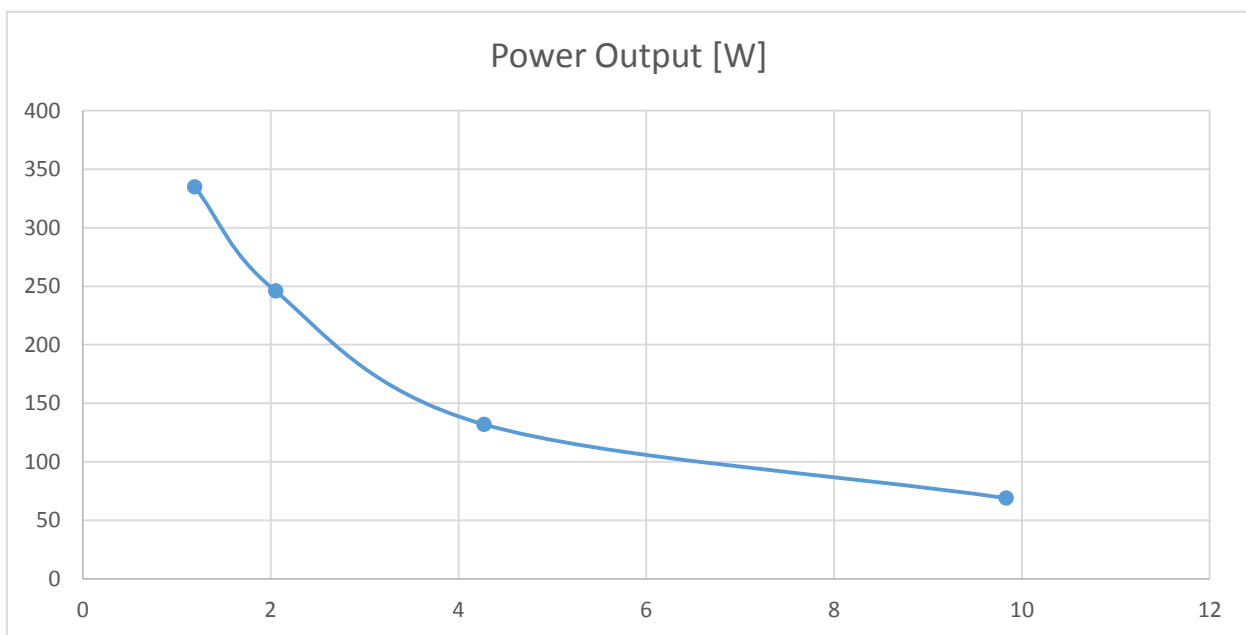
Although this test was realized for three different rotational speed, this paper will present only the comparison of the main parameters at the design point. Thus, by testing the generator for a rotational speed of 1395 rpm for different values of load resistance, the following data was obtained:

Rpm [ ]	Torque [Nm]	R1 [ $\Omega$ ]	R2 [ $\Omega$ ]	R3 [ $\Omega$ ]	Power [W]	Efficiency [%]
1395	0,05	inf	inf	inf	0	-
1395	0,55	9,557692308	9,346153846	10,6	69	86,38
1395	1,02	4,705882353	4,644736842	3,448275862	132	88,48
1395	1,97	2,169105691	2,195	1,796116505	246	85,52
1395	2,90	1,32173913	1,306521739	0,941860465	335	79,15

**Table 10-** Generator test data for the design rotational speed



**Graphic 17-** Generator torque at the design rotational speed for different values of tested load resistance



**Graphic 18-** Power Output at the design rotational speed for different values of tested load resistance

Note that there are three values of load resistance because we are working with a three phase design. Moreover, It should be underlined the comparison between torque, power output and necessary load resistance with their respective simulated values. To do this it is necessary to compute a linear interpolation between the torque values and see the load resistance necessary to achieve that torque and that power output. Hence, the next comparison is obtained:

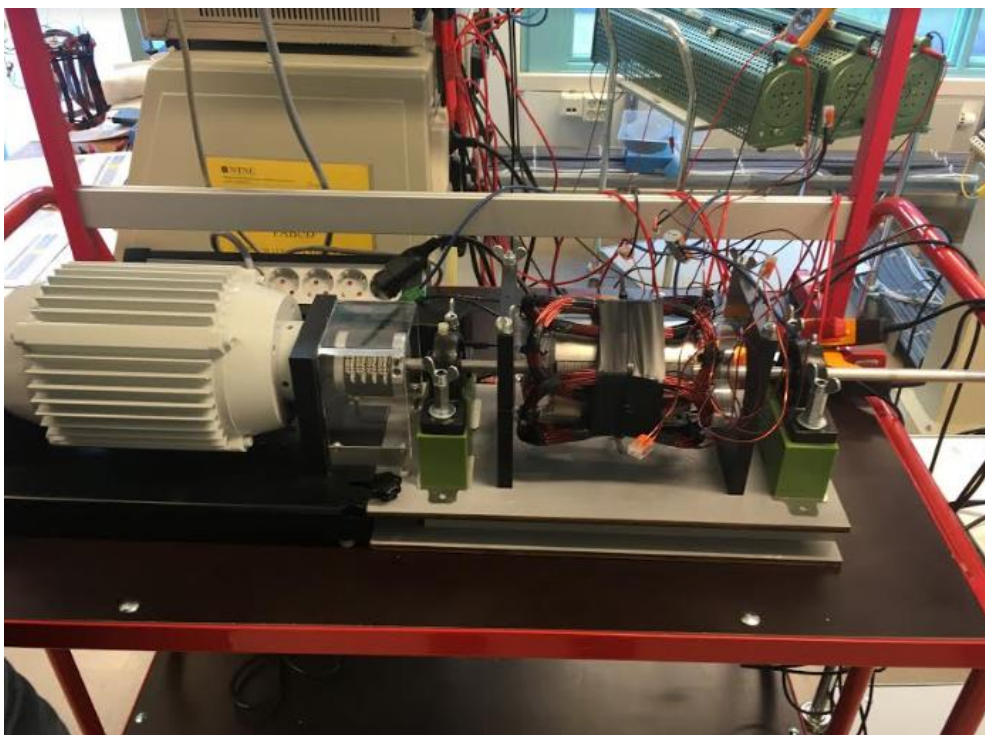


	Torque	Load Resistance [ohm]	Efficiency [%]
<b>Simulated</b>	1,44	9	77,6
<b>Tested</b>	1,44	1.80	80

**Table 11-** Generator comparison between simulated and tested needed load resistance to achieve the turbine torque

Although seems to be a big difference, it should be underlined that this difference was smaller in the wind tunnel test. Therefore, it is rejected in the discussion of this paper. Thus, the generator test was not accurate enough. This may be for multiple reasons like uncertainties in measurement equipment, decalibrations, manufacturing uncertainties and mistakes or human errors among many other reasons.

The rest of the generator test results can be found in Appendix X.



**Figure 41-** Three phase radial generator test



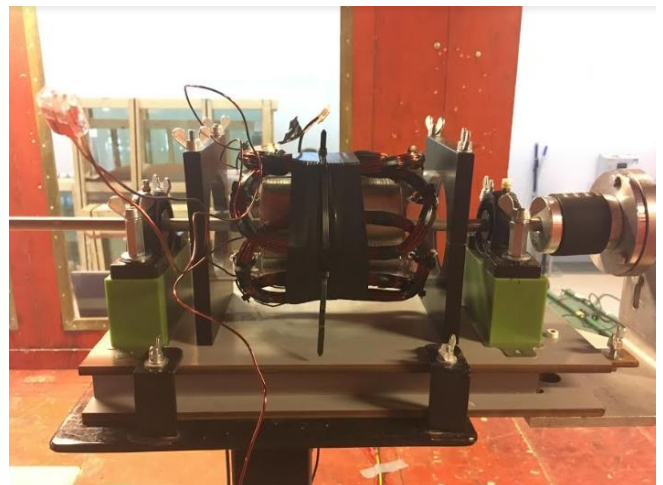
## 5.2 Wind tunnel test

The NTNU gives me the opportunity to test the whole turbine in their Wind tunnel. In this sense, the turbine coupled with the generator was tested for a wind velocity of 10 m/s and a TSR= 7. However, I also had the opportunity to play with different values of TSR and wind velocities to investigate the turbine behaviour at off-design conditions.

In a similar way to the generator test, the aim of this test is to verify the total performance of the wind turbine. To do the test, the first step was to fix the turbine in the tower and the turbine four pole rotor inside the three phase radial generator.



**Figure 43-** Rotor assembly in the wind tunnel



**Figure 42-** Wind turbine assembly in the wind tunnel

The wind turbine was located more or less at 1m height. However, in contrast to what happen in the reality, the wind resource is supposed to be uniform, steady and constant without depending on the height. Consequently, this report do not take into consideration wind resource estimation and neither tower height.

As a curiosity it can be highlight the difficulty of the turbine to start rotating. However, this situation is normal in some small two bladed wind turbines. Thus, to help the turbine rotate I had to inside the wind tunnel and make the first turns for it.

The main reason behind this phenomenon is the low starting torque. Two and three bladed wind turbines have high tip speed ratio but low starting torques. Because of this, both turbines usually need some assistance at the startup before going through their range of operation.

Once the turbine was put into operation it was possible to obtain the turbine performance which is reported in appendix X.

First of all, I had the opportunity to test individually the aerodynamic performance of the rotor. This give me the opportunity to verify Ashes results. Thus, the following key data was obtained:

### Test of turbine blade only

Rotational speed	Wind speed	Tip speed ratio			Anglar velocity	Torque	Output mechanical power	Turbine efficiency
n [rpm]	V [m/s]	TSR			$\omega$ [rad/s]	[Nm]	P <sub>mech</sub> [W]	$\eta_T$ [%]
1590	9,5	7,9			166,5	0,95	158,2	49,15%
1500	9,5	7,4			157,1	0,96	150,8	46,86%
1520	9,5	7,5			159,2	0,97	154,4	47,98%
1450	9,5	7,2			151,8	0,96	145,8	45,30%
1350	9,5	6,7			141,4	0,96	135,7	42,17%
1270	9,6	6,2			133,0	0,95	126,3	38,05%
1650	9,6	8,1			172,8	0,93	160,7	48,39%

**Table 12-** Test of turbine blade only

As it can be seen above, I obtained incredible results during the experiment. The turbine power coefficient ( $C_p$ ) referred in **table 12** as ( $\eta_T$ ) is close and even better to the simulations. However, an overestimation of this parameter may have been done by the wind tunnel measure instruments. But what it can be ensured is that the turbine efficiency was as good as expected. In this sense, the turbine design and manufacture processes have been a completely success.

On the other hand, I has also the opportunity to observe the performance of the total wind turbine. In this sense, this experiment gives me also the opportunity to evaluate the coupling of both turbine and generator. Thus, the following data was obtained:

Rotational speed	Wind speed	Tip speed ratio	Torque	Anglar velocity	Electrical Power Output	Mechanical Power Output	Total Efficiency	Generator Efficiency
n [rpm]	V [m/s]	TSR	[Nm]	$\omega$ [rad/s]	Pe [W]	Pm [W]	$\eta$ [%]	$\eta$ [%]
1390	9,24	7,1	1,22	145,6	111,7	177,6	37,73	62,9
1425	9,18	7,3	1,25	149,2	116,6	186,5	40,16	62,52
1372	9,2	7,0	1,3	143,7	113,4	186,8	38,79	60,69
1340	9,2	6,9	1,1	140,3	113,8	154,4	38,94	73,72

**Table 13-** Summary table of output wind tunnel test

Although the turbine efficiency and to a lesser extent the generator efficiency are close to their simulations. The produced torque produces by the rotor was smaller than it was supposed (1.22-1.45) and consequently the power output is less than the expected.

However, the aim of the project which is to achieve a good total efficiency was confirmed by the testing. The expected turbine efficiency was 39% and all tested values close to the design point present efficiencies around 40%. Thus, this part of the project has been a completely success.

The discrepancies between *“turbine blades only”* test and the *“global”* test may be explained by the uncertainties and errors in the wind tunnel measuring instruments. The NTNU wind tunnel staff and professors confirm me that this differences are normal taking into account the generator manual manufacturing process and uncertainties and errors in the wind tunnel equipment.



6

# Conclusions

## Conclusions

As a global summary, this report presents the design, construction and testing of a small horizontal two bladed wind turbine. The aim of this project is to design a wind turbine that achieves a total efficiency of around 40% within the initial given conditions.

To do this, I have try to find the best compromise solution between size and efficiency. To find this solution, several design steps and verifications are needed. However, the final result has been in terms of rotor efficiency a total success. Indeed, the results obtained are even better than the presented during the simulations.

In this sense, I am afraid that there was an overestimation in the wind tunnel test. Nevertheless, turbine efficiency is sure to be close to the simulations. There may be a lot of reasons behind this overestimation like human errors, disturbances, inconsistencies and errors of the measuring instruments of the wind tunnel.

On the other hand, our prototype presented a lower torque than expected. This phenomenon can be explained by differences in the estimations of key loses like tip loses and tower shadow or other neglected loses among many other reasons.

However, the biggest challenge has been the generator manufacture. This manufacturing process has been performed manually with basic tools. Moreover, I had a handicap in electrical engineering and big effort and time were needed to develop both design and manufacture processes.

Although the generator performance can be considered satisfactory, big differences have been found between the generator design and tests. In a similar way as happens with the rotor, these differences are difficult to explain and may depend on many factors. However, I am happy with the total performance taking into consideration the difficulty to achieve accuracy in an engineering manual manufacturing process.

Regarding to the wind tunnel test, I would like to thank again the NTNU for the opportunity to experiment the performance of my small wind turbine. In general terms, the wind tunnel test can be considered a complete success. The rotor has achieved a power coefficient around 48% which it is a value close to what industrial wind turbines manufacturers present. Moreover, the total efficiency has been around 37-40% in the design point and its surrenders. Thus, the main goal of this project has been successfully accomplished.

# References

## References

- [1] Acciona. (n.d.). *Acciona*. Retrieved from <https://www.acciona.com/renewable-energy/wind-power/wind-turbines/>
- [2] aeeolica. (2018, July 15). *aeolica*. Retrieved from <https://www.aeeolica.org/es/sobre-la-eolica/la-eolica-en-el-mundo>
- [3] AS, S. (n.d.). *Simis AS*. Retrieved from [https://www.simis.io/#Products\\_Ashes\\_Technical-specifications](https://www.simis.io/#Products_Ashes_Technical-specifications)
- [4] Berg, T. (n.d.). *SprutCAM Guide*. Trondheim, Norway: NTNU.
- [5] Bornay. (2018, July). *Wind +*. Retrieved from <https://www.bornay.com/es/productos/aerogeneradores/wind-plus>
- [6] Bossanyi, E., Burton, T., Jenkins, N., & Sharpe, D. (2001). *Wind Energy Handbook*. In E. Bossanyi, *Wind Energy Handbook*. Wiley.
- [7] Dixon, S., & Hall, C. (n.d.). In *Fluid Mechanics and Thermodynamics of Turbomachinery* (p. 419). Elsevier.
- [8] Dreamstime. (n.d.). *Dreamstime*. Retrieved from <https://es.dreamstime.com/foto-de-archivo-turbina-de-viento-bipala-debajo-del-cielo-azul-image82204786>
- [9] Elcacho, J. (2016, Febrero 11). China suma en un año mas Energía eólica que España en toda su historia. *La Vanguardia*.
- [10] Frøyd, L., & Kjetil Haugset, S. (n.d.). *Analysis and Deisgn of Wind Turbines Blades*. .
- [11] Gamesa. (n.d.). *Turbina de viento bipala*. Retrieved from [https://www.google.es/search?q=turbina+de+viento+gamesa&source=lnms&tbm=isch&sa=X&ved=0ahUKewjUnYKlwbAhWKthQKHcFPDk4Q\\_AUICigB&biw=1161&bih=594#imgsrc=rpubSWUj6Vy4rM:](https://www.google.es/search?q=turbina+de+viento+gamesa&source=lnms&tbm=isch&sa=X&ved=0ahUKewjUnYKlwbAhWKthQKHcFPDk4Q_AUICigB&biw=1161&bih=594#imgsrc=rpubSWUj6Vy4rM:)
- [12] Geographic, N. (n.d.). *National Geographic*. Retrieved from <https://www.nationalgeographic.org/encyclopedia/global-warming/>
- [13] Hansen, M. O. (2008). Chapter 4. In M. O. Hansen, *Aerodynamics of Wind Turbines*.
- [14] Haugset, S. K., & Frøyd, L. (n.d.). *Analysis and Design of a Wind Turbine Blades*. Trondheim.
- [15] Manwell, J., McGowan, J., & Rogers, A. (2002). *Wind Energy Explained: Theory, Design and Application*. Wiley.
- [16] NTNU. (2017). *TEP-4175 Desig of a Wind Turbine*. Trondheim.
- [17] quora. (2018). *quora*. Retrieved from <https://www.quora.com/What-is-the-difference-between-chord-length-and-blade-length-in-wind-turbine>
- [18] Statoil. (2018). *Hywind*. Retrieved from <https://www.equinor.com/en/news/hywindscotland.html>
- [19] Statoil. (2018). *Staoil*. Retrieved from <https://www.equinor.com/en/news/hywindscotland.html>
- [20] WePower. (n.d.). *WePower*. Retrieved from <https://wepower.network/>



[21] Wikipedia. (2018, July 12). Milling Process.



# Appendixes

## Appendix A: Matlab Code based on BEM method

```
%Bachelor Thesis. Blade Element Momentum Method (BEM)
%Carlos Ignacio Laiz Querada. NTNU and ICAI.

clear all;
clc;
    %Te cuento el secreto? Es maximizar el cp pero tss...clc

    %Parameters

D=0.9;           %Diametro del Rotor (Blades + Hub)
V=10;           %Velocidad del viento
TSR=6.5;        %Tip Speed Ratio, Relaciónb entre la velocidad de la punta
de alabe y la velocidad del viento
R=D/2;          %Radio del Rotor (Blades+Hubs)
omega=TSR*V/R;  %Velocidad angular del Rotor
Z=2;            %Número de Álabes
N=20;           %Número de divisiones a analizar en el álable
rho=1.225;      %Densidad del aire
dr=D/(2*N);     %Distancia entre el centro del elemento de cada division con
el cento del Rotor (Blades + Hub)
viscosidad= 1.47*10^(-5)
Tref= 15;

%Leemos el Archivo de Texto dado por mi Universidad de destino.
%Relaciones entre Ángulo de Ataque, CL, y CD.

NRELS826='NRELS826';

    %Leyendo Cl og Cd del Airfoil file

%Dos formas de leer un archivo de texto, mucho mejor leer con feof
airfoil=sprintf('%scoef.txt',NRELS826);
fid=fopen(airfoil,'r');
for i=1:102 %Set the marker at the right line
line=fgetl(fid);
end
i=1;
frewind(fid);

while ~feof(fid);
    tline = fgetl(fid);
    disp(tline);
end

frewind(fid);

%Creamos los vectores cargando la informacion de mi archivo de texto a los
%diferentes vectores a estudiar (Ángulo de Ataque, CL,CD). En esta ocasión
%al tener que extraer los datos he preferido realizar un excell antes que
%un archivo de texto. TEORIA: OBERVAMOS QUE PARA ANGULOS DE ATAQUE ENTRE
%0-11,5 EL CL VA INCREMENTANDO SU VALOR, LLEGA UN MOMENTO EN EL QUE CL SE
%HACE NEGATIVO, EN OTRAS PALABRAS ENTRA EN PERDIDA. POR OTRO LADO, CD
%DEPENDE EN MENOR MEDIDA DE APLHA (ANGULO DE ATAQUE) QUEDANDO PRACTICAMENTE
%CONSTANTE ALREDEDOR DE VALORES CERCANOS A 0.0
```

```

%Datos en forma de vectores horizontales

airfoildata=xlsread('AirfoildataAshes','A10:C102');
ALPHA=transpose(airfoildata(:,1));
CL=transpose(airfoildata(:,2));
CD=transpose(airfoildata(:,3));

%Encontramos el ángulo de ataque óptimo.
alphaopt=ALPHA(CL./CD==max(CL./CD));
Cl0=CL(ALPHA==alphaopt);
Cd0=CD(ALPHA==alphaopt);

% alphaopt=8;
% Cl0=1.3388;
% Cd0=0.0280;

%Iteración mediante el método BEM (Blade Element Momentum Method)

Cpmax=0;
Mmax=[]; %Así es como se inicializa un vector de "n" posiciones.
Lmax=[];
Tmax=[];
Pmax=0;
Mtot=0;
Ttot=0;
Pmaxtot=[];
Thetamax=[];
Tl=zeros(1,N);
Ml=zeros(1,N);

%Initializing resultvariables per iteration
M=0; %Total Torque
T=0; %Total thrust
P=0; %Total power
Ca=zeros(1,N);
Cr=zeros(1,N);
phi=0;
L=zeros(1,N);
r=0;
r1=zeros(1,N);
PHI=zeros(1,N);
tetha=zeros(1,N);
Vel=zeros(1,N); % Velocidad del viento para cada Airfoil.
Wrel=zeros(1,N); % Velocidad relativa del viento para cada Airfoil.
Reynolds=zeros(1,N); % Número Reynolds para cada Airfoil.

%Diseño incial
[x, at, am, phi, Bep]=adisk(TSR); %ideal blade
phiG = phi.*180./pi;
tetaG= phiG - alphaopt;
%Comenzamos el Bucle Iterativo

for i=1:N
r=r+dr;
r1(i)=r;
U=omega*r;
Vel(i)=U

```

```

%Diseño inicial a la espera de ser corregida, es decir esta L(i) no va a
%ser la correcta! La correcta es la de abajo.
L(i)=Bep(i)*((2*pi*V)/(Z*C10*omega));

```

```

%iteration start

```

```

a=at(i);
a1=am(i);
a_old=0;
a1_old=0;
Sigma=Z*L(i)/(2*pi*r);

```

```

while ((abs(a-a_old)>=0.000001)|| (abs(a1-a1_old)>=0.000001))
a_old=a;
a1_old=a1;
phi =atan((1-a)*V/((1+a1)*U));
Ca=C10*cos(phi)+Cd0*sin(phi);
Cr=C10*sin(phi)-Cd0*cos(phi);
F=2/pi*acos(exp(-(Z*(R-r))/(2*r*sin(phi))));
if ~isreal(F) %F converges towards 0, need to correct a and a1
F=0;
a=1;
a1=0;
else
if a_old<0.2 %Glauert's correction
a=A(phi,Ca,F,Sigma);
else
a=Ac(phi,Ca,F,Sigma);
end
a1=A1(phi,Cr,F,Sigma);
end
phi=atan((1-a)*V/((1+a1)*U));
bep=(4*a*sin(phi))/(1+a1); %Need to correct the bep-value
L(i)=bep*(2*pi*V)/(Z*C10*omega);
PHI(i)=phi*180/pi;
tetha(i)=PHI(i)-alphaopt;
Wrel(i)=Vel(i)/cos(PHI(i));
Reynolds(i)= (Wrel(i)*L(i))/viscosidad;
% if(L(i)<=0.0275)
% L(i)=0.0275;
% end
end
if i==N
dT=0;
dM=0;
L(i)=L(i-1);
else
dT=Thrust(L(i),phi,F,Ca,a);
dM=Moment(L(i),phi,r,F,Cr,a,a1);
end

% if L(1)< L(2)
% L(1)=L(2);
% end

```

```

T1(i)=dT;
M1(i)=dM;

```

```

T=T+dT

```

```

M=M+dM*r;
dP=dM*omega;
P(i)=dP;
end
Ptot=M*omega;
Cp=Ptot/(0.5*rho*V^3*pi*R^2);
if (Cp>Cpmax)
Cpmax=Cp;
Lmax=L;
Mmax=Ml;
Tmax=Tl;
Pmax=Ptot;
Pmaxtot=P;
Mtot=M;
Ttot=T;
Thetamax=tetha;
Ct=Ttot/(0.5*rho*V^2*pi*R^2);
end

fprintf('\n'); %Obtebemos como resultados los siguientes
datos:
fprintf('Los resultados obtenidos son los siguientes:\n');
fprintf('\n');
fprintf('alphaopt= %.1f, Cp= %.2f, Ct= %.2f\n',alphaopt,Cpmax,Ct);
fprintf('P= %.2f KW, Torque= %.2f NM, Fthrust= %.2f KN
\n',Pmax/1000,Mtot,Ttot/1000);
rpm=omega*60/(2*pi);
fprintf('n= %.0f rpm, CL=%.2f, CD=%.2f \n',rpm,Cl0,Cd0);

%Dibujamos las gráficas y resultados obtenidos:
figure(1)
plot(r1,Mmax,r1,Tmax);
title('Torque and thrust vs radius');
xlabel('Radius [m]');
ylabel('Torque [NM] and thrust [N]');
legend('Torque','Thrust');
grid on

figure(2);
plot(r1,Lmax);
title('Chordlength vs radius');
xlabel('Radius [m]');
ylabel('Chordlength [m]');
legend('Chordlenght');
grid on

figure(3);
plot(r1,Pmaxtot);
title('Power');
xlabel('Radius [m]');
ylabel('Power');
legend('Power Output')
grid on

figure(4);
plot(r1,tetha)
title('Twist Angle');
xlabel('Radius [m]');

```

```
ylabel('Twist Angle');  
legend('Twist Angle')  
grid on
```



## Appendix B: Matlab Code function adisk

```
function [x, a, am, phi, Bep]=adisk(TSR); % (x es local speed ratio: )
% Para Valores Positivos de x, a esta definida como:
aomin=0.25; aomax=0.3333; %Factor de Inducción Axial
e=20; % número de elementos en la tabla;
di=(aomax-aomin)/e; mi=aomin+di;ao=mi:di:aomax;
TSR=6.5;
% La geometría nos da x=f(a)
for j=1:e
    x1(j)=(4*ao(j)-1)*sqrt((1-ao(j))/(1-3*ao(j))); % Equation (89)
end
% Calculando a=f(x) mediante un proceso de interpolación,
dx=TSR/e; % Incremento usado
x=dx:dx:TSR; ne=length(x);
for k=1:e
    a(k)=interp1(x1,ao,x(k),'pchip');
    am(k)=(1-3*a(k))/(4*a(k)-1); % Equation (88)
    phi(k)=atan((1-a(k))/((1+am(k))*x(k))); % Equation (105)
    Bep(k)=(4*a(k)*sin(phi(k)))/(1+am(k)); % Equation (104)
end
```

## Appendix C: Generator test Results

Measured values													
		RA1 =			RA2 =			RA3 =					
n (rpm)	Torque (Nm)	U1 (V)	I1 (A)	P1(W)	U2 (V)	I2 (A)	P2(W)	U3 (V)	I3 (A)	P3 (W)	$\omega_m$ (rad/s)	$\omega_e$ (rad/s)	
18	1000	0	11,10	0	0	10,80	0	0	10,90	0	0	104,72	209,44
19	1000	0,34	10,80	1,00	10,70	10,50	1,04	10,90	10,60	1,00	10,60	104,72	209,44
20	1000	0,92	10,10	2,90	29,30	9,90	2,90	28,80	10,00	2,90	28,30	104,72	209,44
21	1000	1,60	9,40	5,00	46,90	9,15	5,24	47,80	9,25	5,15	47,60	104,72	209,44
22	1000	2,66	8,10	8,60	68,90	7,95	8,70	69,30	8,10	8,60	68,20	104,72	209,44
23	1000											104,72	209,44
24	1000											104,72	209,44
25	1000											104,72	209,44
26	1395	0,05	15,44	0	0	15,07	0	0	15,16	0	0	146,08	292,17
27	1395	0,55	14,91	1,56	23,30	14,58	1,56	22,70	14,66	1,60	23,40	146,08	292,17
28	1395	1,02	14,40	3,06	44,00	14,12	3,04	42,90	14,15	3,18	44,93	146,08	292,17
29	1395	1,97	13,34	6,15	81,80	13,17	6,00	79,00	13,18	6,25	85,30	146,08	292,17
30	1395	2,90	12,16	9,20	111,90	12,02	9,20	110,50	12,07	9,30	112,90	146,08	292,17
31	1395											146,08	292,17
32	1395											146,08	292,17
33	1395											146,08	292,17
34	1800	0,05	19,90	0	0	19,44	0	0	19,62	0	0	188,50	376,99
35	1800	0,54	19,33	1,59	30,70	18,93	1,55	29,30	19,10	1,53	27,90	188,50	376,99
36	1800	1,30	18,50	3,98	73,60	18,13	3,96	71,80	18,23	3,99	72,70	188,50	376,99
37	1800	2,00	17,60	6,40	112,30	17,30	6,50	111,90	17,50	6,30	110,10	188,50	376,99
38	1800	3,10	16,70	10,00	161,50	15,90	10,10	163,23	16,10	9,93	156,10	188,50	376,99
39	1800											188,50	376,99
40	1800											188,50	376,99
41	1800											188,50	376,99
42	1800			0	0		0	0		0	0	188,50	376,99
43	1800											188,50	376,99
44	1800											188,50	376,99
45	1800											188,50	376,99
46	1800											188,50	376,99
47	1800											188,50	376,99
48	1800											188,50	376,99
49	1800											188,50	376,99

Table 14- Generator test results (NTNU, 2017)

## Appendix D: Wind tunnel test

### Test of turbine blade with generator

Rotational speed n [rpm]	Wind speed V [m/s]	Tip speed ratio TSR	Torque [Nm]	Anglar velocity $\omega$ [rad/s]	Current I1 [A]	Voltage U1 [V]	Output electrical power P1el [W]	Current I2 [A]	Voltage U2 [V]	Output electrical power P2el [W]	Current I3 [A]	Voltage U3 [V]	Output electrical power P3el [W]	Total efficiency $\eta$ [%]	Output mechanical power Pmech [W]	Turbine efficiency $\eta_T$ [%]
1390	9,24	7,1	1,22	145,6	2,35	14,86	34,9	2,53	14,19	35,9	2,9	14,1	40,9	37,73%	177,6	59,97%
1425	9,18	7,3	1,25	149,2	2,476	15,15	37,5	2,574	14,5	37,3	2,892	14,45	41,8	40,16%	186,5	64,24%
1372	9,2	7,0	1,3	143,7	2,554	14,53	37,1	2,608	13,98	36,5	2,863	13,9	39,8	38,79%	186,8	63,91%
1340	9,2	6,9	1,1	140,3	2,63	14,11	37,1	2,7	13,52	36,5	2,99	13,44	40,2	38,94%	154,4	52,81%
1200	10	5,7	0,8	125,7	1,95	12,75	24,9	1,9	12,26	23,3	1,89	12,34	23,3	19,04%	100,5	26,78%
1450	9,19	7,4	1,1	151,8	2,63	15,28	40,2	2,66	14,7	39,1	2,66	14,82	39,4	40,75%	167,0	57,33%
1260	9,19	6,5	1,16	131,9	2,93	13,04	38,2	3,03	12,51	37,9	3,04	12,52	38,1	39,19%	153,1	52,54%
1200	9,2	6,1	1,16	125,7	2,87	12,37	35,5	3,15	11,75	37,0	3,16	11,77	37,2	37,54%	145,8	49,87%

### Test of turbine blade only

Rotational speed n [rpm]	Wind speed V [m/s]	Tip speed ratio TSR	Anglar velocity $\omega$ [rad/s]	Torque [Nm]	Output mechanical power Pmech [W]	Turbine efficiency $\eta_T$ [%]
1590	9,5	7,9	166,5	0,95	158,2	49,15%
1500	9,5	7,4	157,1	0,96	150,8	46,86%
1520	9,5	7,5	159,2	0,97	154,4	47,98%
1450	9,5	7,2	151,8	0,96	145,8	45,30%
1350	9,5	6,7	141,4	0,96	135,7	42,17%
1270	9,6	6,2	133,0	0,95	126,3	38,05%
1650	9,6	8,1	172,8	0,93	160,7	48,39%

Table 15- Wind tunnel test (NTNU, 2017)

## Appendix E: Generator Design Excel Sheet

USER INPUT					Input Parameters	Output Parameters	Wide of the Coil [mm]	9
<b>Stator (armature)</b>							Diameter of the Wire [mm]	1,5
Resistance in wire	Rwire	0,009756	ohm/m	0.01-0.03			Number of Wires per Revolution	6
Number of turns per. coil	Nturn	30	[-]	20-60			Number of Coils in the Hight Direction	5
Number of threads (wires)	m (NumThreads)	1	[-]	1-4			Total Height of the Coil [mm]	7,5
Active length of coil side	Lactive	0,12	m					
Winding factor	fw	1	[-]	0.8 - 0.99				
Number of coils in series (i.e. per phase)	Ns	2	[-]		Ns =< P			
<b>Radial only</b>								
Distance from axle to magnet surface	DistMin	0,045	m		Distance from center axle to magnet surface.			
Distance from pole surface	DistPole	0,01	m					
Number of phases	Nphase	3	[-]	1 or 3				
Length factor	Lcorr	1,05						
<b>Rotor and flux</b>								
Number of poles	P	4	[-]	4	The number of poles on the rotor. This is also the number of magnets. For the pre-built axial flux and radial flux generator the number is 4.			
Flux density (middle of coil in radial dir.)		0,29234375	Tesla				Measured by Thea K. Løken 2016 at distance approx. 10 mm for magnet su	
<b>Misc.</b>								
Ref. number of turns per coil	NO	28	[-]	28 for radial, 40 for axial				
Ref. stator coils inductance pr phase (SINGLE-PHASE)	Ls0	0,0015	H				Reference value for 28 turns SINGLE-PHASE and specified coil shape	
Ref. stator coils inductance pr phase (THREE-PHASE)	Ls0	0,008	H				Reference value for 28 turns THREE-PHASE and specified coil shape	
Ref rpm for loss		1000	RPM					
Ref friction and ventilation loss	Floss ref	30	W					
<b>Dynamic properties</b>								
Rotational speed of rotor	RPM	1395		100-2000				
Resistance of load per phase	Rload	9	ohm	0.5-50				0 means short circuit, infinity means idling (tomgang)/broken curcuit

Table 16- Generator design Excel Sheet User Input (NTNU, 2017)

ASHES OUTPUT						
Static generator characteristics (independent of RPM) - presented in 'Information' tab						
Stator characteristics						
Wire length per turn	Lturn	0,425	m	0.5	$2 * L_{active} * L_{corr} + 2 * (DistMin + DistPole) * 2 * \pi / P$	Length of thread per turn times a factor to get close
Length of wire per coil	Lcoil	12,7	m		$L_{turn} * N_{turn}$	
Total length of wire in stator	Lstator	76,5	m		$L_{coil} * N_s * N_{phase}$	
<b>Stator coil inductance per phase</b>	<b>Ls</b>	<b>0,00918</b>	<b>H</b>		<b><math>Ls0 * (N_{turn} / N0)^2</math></b>	
Load resistance						
Additional resistance from terminal connections		1,14		1,14		Found from measurements on 4-pole generator 56 t
Coil resistance temp. correction		1,08		1.05-1.1		The temperature increases when the generator is ir
<b>Total resistance in stator per phase</b>	<b>Rtot</b>	<b>0,31</b>	<b>ohm</b>		<b><math>R_{wire} * L_{coil} * N_s / m</math></b>	
Dynamic properties (RPM dependent)						
Friction and ventilation loss	Floss	41,85	W			
Mechanical angular velocity	omega	146,1	rad/s		$RPM * 2 * \pi / 60$	
Electrical angular velocity	omega_e	292,2	rad/s		$omega * P / 2$	
Linear speed	v_avg	8,0	m/s		$omega * (DistMin + DistPole)$	
Power loss (copper wire losses)	Ploss	5,6	Watt		$N_{phase} * R_{tot} * I^2$	
Power in (from wind)	Pin	212,1	Watt		$P_{loss} + P_{load} + F_{loss}$	
Proportionality factor	k	0,00994			$T_{gen} / omega$	
Terminal voltage (all phases)	Vterminal	38,49	Volt		$V_{term,ph} * \sqrt{N_{phase}}$	
Presented in Sensor (these can be measured)						
<b>Power (electrical)</b>	<b>Pload</b>	<b>164,6</b>	<b>Watt</b>	<b>158,9</b>	<b><math>N_{phase} * R_{load} * I^2</math></b>	
<b>Generator torque</b>	<b>Tgen</b>	<b>1,452</b>	<b>Nm</b>	<b>1,766</b>	<b><math>P_{in} / omega</math></b>	
<b>Efficiency</b>	<b>eta</b>	<b>77,6%</b>			<b><math>P_{load} / P_{in}</math></b>	
Induced voltage (EMF) per phase, rms	Einduced	23,9	Volt (rms)		$N_{turn} * 2 * B_{max} * L_{active} * v_{avg} * f_w * N_s / \sqrt{2}$	
Voltage (terminal) per phase	Vterm,ph	22,2	Volt		$P_{load} / (N_{phase} * I) = R_{load} * I$	
Current per phase	abs(I)	2,5	amp	0-10	$E_{induced} / (\sqrt{R_{tot} + R_{load}})^2 + X_{gen}^2$	
Frequency	freq	46,5	Hz		$P * RPM / 120$	
Max power	PL,max	285,4	Watt		$N_{phase} * R_{L,max} * E_{induced}^2 / ((R_{tot} + R_{L,max})^2 + X_{gen}^2)$	This is the maximum power output from the genera
Load resistance per phase giving max power generator	RL,max	2,70	ohm		$\sqrt{X_{gen}^2 + R_{tot}^2}$	This is the load resistance that would give the maxi
Stator coil reactance per phase	Xs	2,68	ohm		$Ls * omega_e$	

Table 17- Generator design Excel sheet Ashes Output (NTNU, 2017)

# Appendix F: Generator Structure

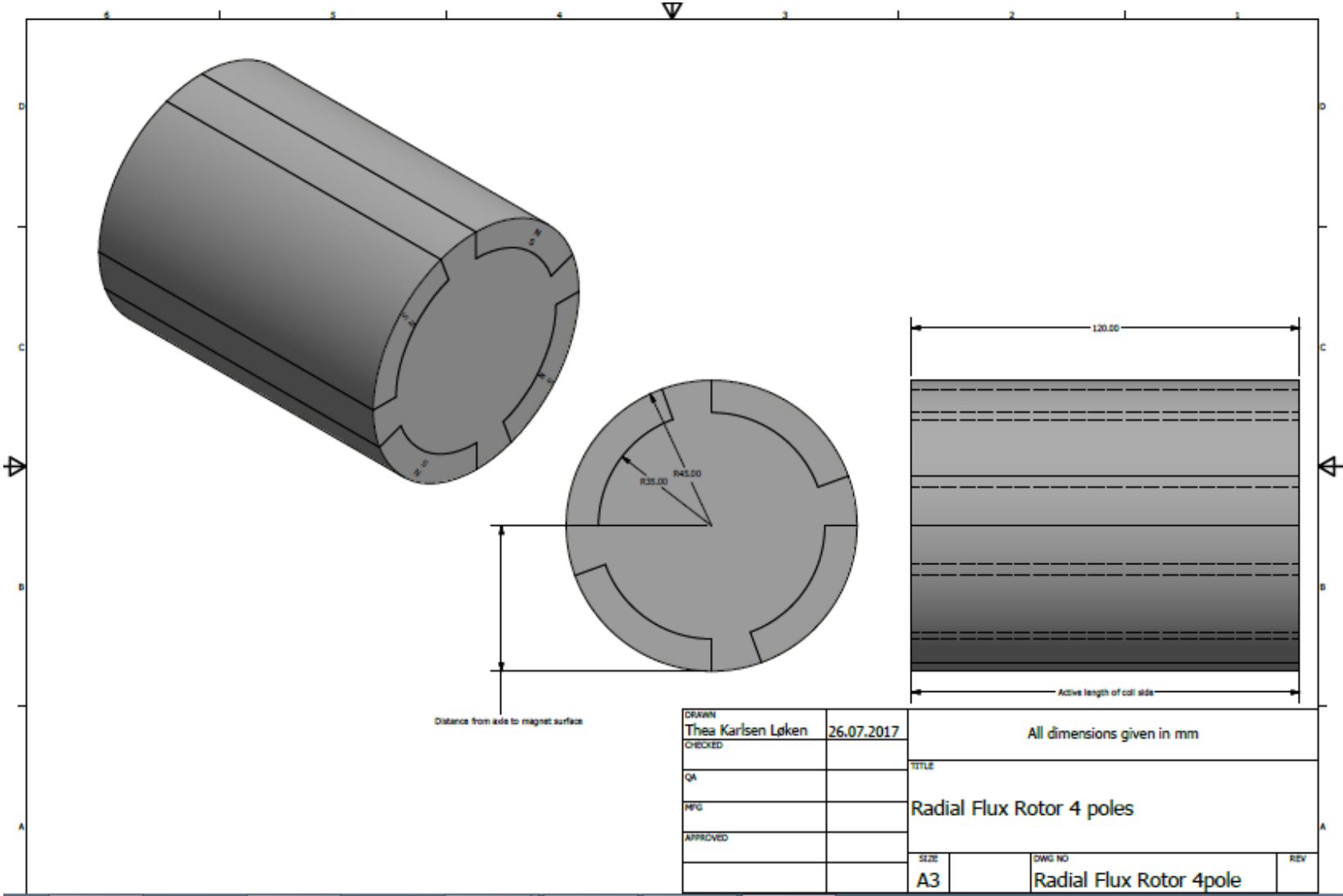


Figure 44- Generator Rotor Plan (NTNU, 2017)

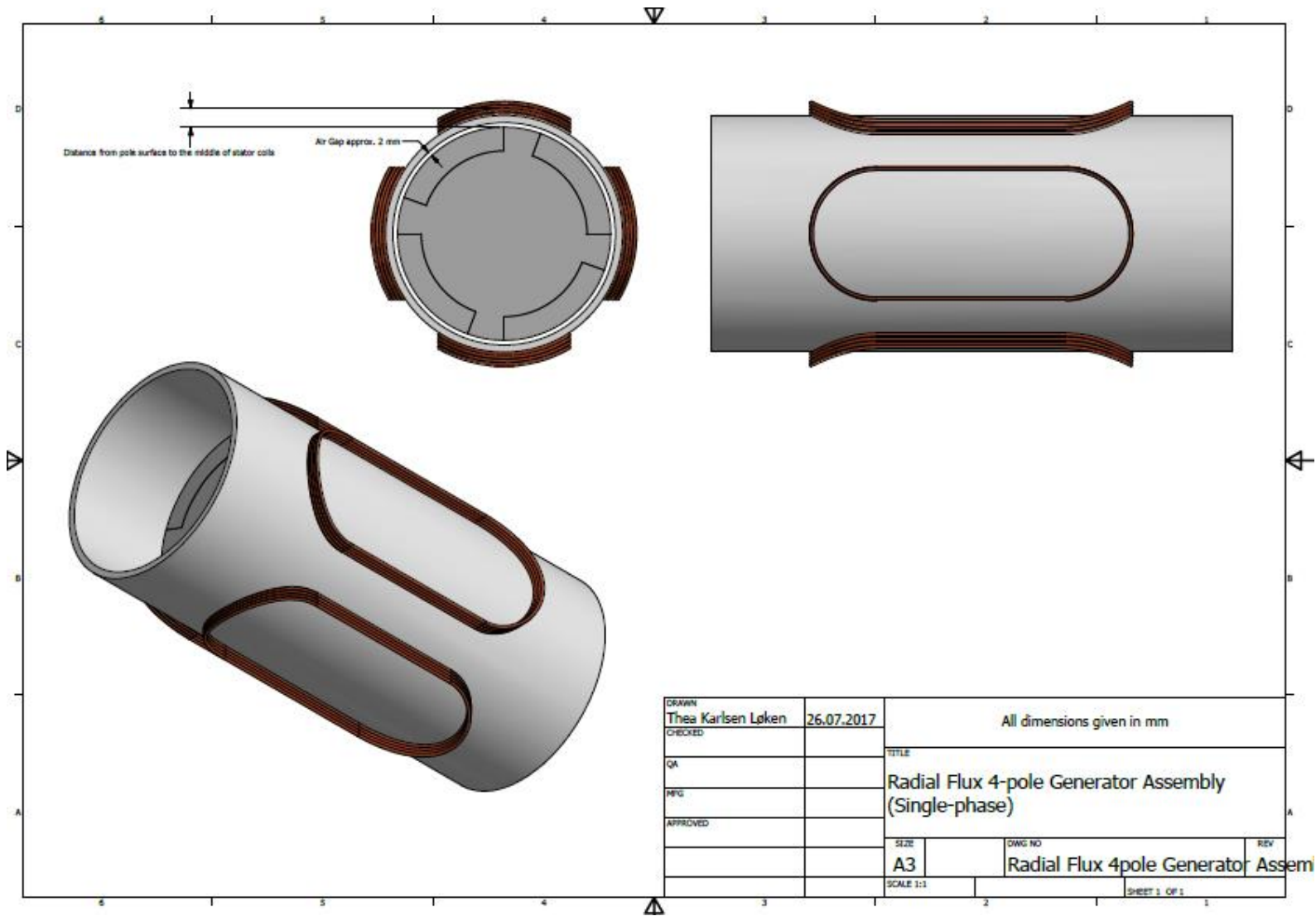


Figure 455- Generator Stator Plan (NTNU, 2017)

