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Comparison Study Between Airfoil to Enhancement the Wind Turbine Power

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Abstract:

The increasing demand for sustainable energy has heightened the need for efficient and cost-effective renewable energy systems. Among these, small-scale wind turbines offer a practical solution for decentralized energy generation, particularly in rural, agricultural, and residential settings. This thesis presents the aerodynamic design, optimization, and performance analysis of a 3-kW horizontal-axis wind turbine blade using four different airfoils: NACA 6409, NACA 4412, S818, and Eppler 387.

The study begins with a comparative analysis of the selected airfoils using XFOIL to evaluate key aerodynamic parameters, including lift and drag coefficients and the lift-to-drag ratio. The NACA 6409 airfoil give the highest performance, at an angle of attack of 6°, indicating its potential for maximizing energy extraction. The blade geometry was then designed and optimized using QBlade software, which incorporates Blade Element Momentum (BEM) theory and is integrated with XFOIL for precise airfoil modeling. Simulations were conducted to evaluate the power coefficient and output power across a range of tip speed ratios (TSR). Results showed that the NACA 6409-based blade achieved the highest power coefficient of 0.52 and a maximum power output of 3,200 W at a TSR of 7, outperforming the other airfoils.

الملخص:

أدى الطلب المتزايد على الطاقة المستدامة إلى ازدياد الحاجة إلى أنظمة طاقة متجددة فعّالة ومنخفضة التكلفة. ومن بين هذه الأنظمة، تُقدّم توربينات الرياح صغيرة الحجم حلاً عمليًا لتوليد الطاقة اللامركزية، لا سيما في المناطق الريفية والزراعية والسكنية. تُقدّم هذه الأطروحة التصميم الديناميكي الهوائي، والتحسين، وتحليل الأداء لشفرة توربين رياح أفقي المحور بقدرة 3 كيلوواط، باستخدام أربعة أجنحة هوائية مختلفة: NACA 6409، وNACA 4412، وS818، وEppler 387.

تبدأ الدراسة بتحليل مقارن للأجنحة الهوائية المختارة باستخدام تقنية XFOIL لتقييم المعايير الديناميكية الهوائية الرئيسية، بما في ذلك معاملات الرفع والسحب ونسبة الرفع إلى السحب. يُقدّم جناح NACA 6409 أعلى أداء، بزاوية هجوم تبلغ 6 درجات، مما يُشير إلى قدرته على تعظيم استخراج الطاقة. تم بعد ذلك تصميم وتحسين هندسة الشفرة باستخدام برنامج QBlade، الذي يدمج نظرية زخم عنصر الشفرة (BEM)، ويُدمج مع XFOIL لنمذجة دقيقة للجناح. أُجريت عمليات محاكاة لتقييم معامل القدرة وقوة الخرج عبر مجموعة من نسب سرعة الطرف (TSR). أظهرت النتائج أن الشفرة القائمة على NACA 6409 حققت أعلى معامل قدرة (0.52) وأقصى قدرة خرج (3200 واط) عند نسبة سرعة طرفية (TSR) قدرها 7، متفوقةً بذلك على الأجنحة الأخرى.

الإهــــــــــــداء

أهدي هذا العمل إلى روح والدي العزيز، الذي غادر جسده الدنيا، لكن حكمته ونصائحه لا تزال ترشدني في مسيرتي .
إلى من كان سندي في الحياة رغم غيابه الجسدي، فإن روحه تملأ قلبي طمأنينة وسلاما .
و الذي علّمني أن الطموح لا حدود له، وأن العلم هو النور الذي ينير دروبنا
إلى والدتي الحبيبة، التي كانت لي أماً وأباً، ولم تبخل عليّ يوماً بحبها وحنانها ودعواتها الصادقة .
إلى أخي و أخواتي و عائلتي العزيزة، وكل من كان لي عوناً وسنداً في مسيرتي الأكاديمية، أهدي إليكم ثمرة جهدي وكفاحي .
إلى زميلتي "وردة سعد الله" و"جهاد مود"، اللتين كانتا دعماً كبيراً لي في هذه الرحلة.
وإلى كل من آمن بي ووقف إلى جانبي، أهدي ثمرة جهدي وإخلاصي، مع خالص الشكر والتقدير**.**

BARIR –Djihad

الاهداء

الحَمدُ لله حُبّا وشُكراً وامتنانا على البدء والختام،الحمد لله الذي ما سلكنا البدايات الا بتيسيره ومابلغنا النهايات الا بتوفيقه وماحققنا الغايات الابفضله

"وكان فضل الله عليا عظيما"

إلى أول حبٍّ لا يُنسى، إلى من علّمني كيف لا أنحني إلا لله

يا من تعبت ولم تطلب مقابلًا، إلى من يراني طفلة في الثالثة من عمرها وانا صاحبة الثالثة والعشرون عاما, إلى سندي وقوتي وملاذي بعد الله

فخري واعتزازي .... إلى أبي

إلى من كانت أول نبض في حياتي، وأول وطن احتواني، إلى من منحتني حبًا لا يُقاس، ودفئًا لا يُنسى، إلى التي حملتني بقلبها قبل أن تحملني بين يديها, إلى من كانت اليد التي أمسكت بي في أول الطريق، والقلب الذي ظلّ يدعو لي حتى النهاية ,

وصاحبة الفضل الأول بعد الله .... إلى أمي

إلى وحيدي ورفيق دربي وسندي في هذه الحياة, إلى من كان وجوده طمأنينة لقلبي ودعمه نورا لطريقي ,في كل مرحلة من مشواري

الى الظل الذي لايغيب............... أخي

لاتي جمعتنا الحياة في منزل واحد، لكن قلبًا واحدًا ,أنتم الحكاية التي لا تنتهي، والضحكة التي تملأ كل زاوية في قلبي، إلى

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إلى المؤنسات الغاليات............... أخواتي وابنة اختى

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بِسْمِ اللَّهِ الرَّحْمَٰنِ الرَّحِيمِ

(وَآخِرُ دَعْوَاهُمْ أَنِ الْحَمْدُ لِلَّهِ رَبِّ الْعَالَمِينَ)

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And ALLAH is the Bestower of success.

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Symbols

c	chord length.
F_L	lift force.
F_D	drag force.
F_N	normal force.
F_T	tangential force.
F_G	gravitational force.
F_C	centrifugal force.
R	length of the blade (look stress ratio)
U_0	the wind velocity.
U_{rel}	relative wind velocity.
U_{ref}	reference wind velocity.
Cl	Lift coefficient.
Cd	Drag coefficient.
Cn	coefficients of normal force.
Ct	coefficients of tangential force.

Greek symbols

θ	twist angle.
α	angle of attack.
Φ	inflow angle.
ρ	air density.
Ω	rotational speed of the blade. [rpm]
ω.	angular velocity of blade rotation.
η	efficiency.
λ_{design}	tip speed ratio.

Abbreviations

GWEC	Global Wind Energy Council
BEM	Blade Element Momentum
CFD	Computational Fluid Dynamics
HAWT	Horizontal Axis Wind Turbine
AEP	Annual Energy Production
WWEA	World Wind Energy Association

GENERAL INTRODUCTION

1 GENERAL INTRODUCTION

The demand for energy is increasing globally due to urban expansion and the increasing prevalence of heavy industries. Fossil energy is considered a non-renewable energy source, and therefore, renewable energy must be considered as an alternative. One of the most important renewable energy sources that cannot be ignored is wind energy, as its abundance makes it an important source of energy generation that can be exploited through wind turbines.

The widespread use of wind turbines around the world makes them a focus of study and development for optimal utilization of wind energy. Small wind turbines are the ideal option for meeting household needs for clean energy, and therefore, improving the power output is essential to maximize the benefits of these machines.

Optimizing wind turbines primarily depends on improving the aerodynamic geometry, which is primarily composed of the airfoil. Choosing the appropriate airfoil in designing small blades is of great importance in the external design of the blade, and therefore, this study will focus on selecting the appropriate airfoil to build an optimized blade.

In the first chapter of this study, we will discuss various definitions of wind turbines and their component parts, in addition to previous studies to enhance their work. We will also provide a historical overview of wind turbine blades and their various modern uses. At the end of this chapter, we will provide definitions and models of the various airfoils used in wind turbine blade design.

In the second chapter of this study, we will discuss in detail the aerodynamics of wind turbines. We will also explain the most important aerodynamic equations for calculating power, lift, and drag, and we will explain in detail the blade element momentum theory, which we will use in this work to optimize the blade.

Chapter three addresses the aerodynamic performance analysis of wind turbines. In this study, we will analyze a 3-kW horizontal-axis wind turbine with a rotor diameter of 4 meters using the QBlade program, using various airfoils: the NACA 4412, the NACA 6409, the S818, and the Eppler 387. This will evaluate the aerodynamic performance and select the appropriate airfoil for the blade design.

Chapter I:

Generality About Wind Turbines

1. INTRODUCTION:

Wind turbines harness the kinetic energy of the wind and convert it into mechanical energy, which is then transformed into electricity for practical use.

Currently, wind energy contributes approximately 10% of the global energy supply, and its significance in the renewable energy sector is expected to grow as its potential becomes increasingly recognized. Maximizing the efficiency of wind turbines is essential for maintaining competitiveness with other energy technologies. This optimization involves selecting the appropriate turbine orientation whether horizontal or vertical as well as choosing suitable materials. The materials used should be durable, cost-effective, and ideally recyclable to ensure that the environmental and economic advantages of wind power are not compromised.

In this chapter, we will explore wind turbines, their types, airfoils, materials, and the advantages and disadvantages associated with them to provide a clearer understanding of our study.

2 BIBLIOGRAPHICSEARCH

Yossri Widad et al. [1]

This work presented a CFD investigation of airfoil and rotor's diameter size effects on the aerodynamic performance of small-scale wind turbines encapsulating complementary 2D and 3D analyses. In this research effort, an airfoil performance analysis was performed and showed that NACA 4412 resulted in a larger lift over drag ratio. Then, the 3D analysis showed that when considering a three-bladed turbine**.**

Ning et al. [2]

This work establishes a comprehensive optimization system to improve the power performance of a three-bladed high-solidity VAWT at a moderate TSR. The system is highly adaptive featuring the combination of 3D CFD simulation, Multi-Island GA and auto operation. Besides, the airfoil is studied as part of a three-bladed VAWT rather than as a single isolated body**.**

Janiga et al. [3]

This work investigates the aerodynamic performance of a monoplane Wells turbine consisting of symmetric airfoils, using numerical simulations. Due to the potential importance of the airfoil shape, an aggressive mathematical optimization procedure has been carried out considering simultaneously twenty-two free parameters (coordinates of eleven geometrical points employed to characterize the shape).

Andrew and Barrett [4]

The objective of this research was to develop and compare various airfoil precomputation parameterization and analysis techniques for aero structural optimization of wind turbine blades. The airfoils along the blade were added as optimization design variables through precomputation parameterization methods using thickness-to-chord ratios and blended airfoil family factors.

S. Mohamed et al. *[5]*

The present investigation has highlighted the advantages of using slotted airfoil blade in Darrius type VAWT. The performance of slotted airfoil turbine was examined using CFD tools. Initially, the slot concept was applied to static NACA0018 airfoil at different angles of attack to verify its advantages on flow separation at high angles of attack. Thus, the slot geometrical parameters were optimized based on static behavior results. Thereafter, the selected slotted airfoil configuration was applied to the Darrius rotor. The effect of the slot was investigated from different perspectives.

Hashem and Mohamed. [6]

Darrius turbine the lift-type vertical axis wind turbines (VAWTs) has the merit of working at low wind speed, but is has the demerit of low aerodynamic performance when compared with the ones with horizontal-axis. The present work aimed to enhance the aerodynamic performance of the Darrius turbine (H-rotor) through finding out the best blade airfoil and the most efficient configuration of a wind-lens.

Ben Rezk and Bouklouf. [7]

The purpose of this thesis is to study small wind turbines and the feasibility of installing them in the Ouargla region. The study involves describing the aerodynamic theories related to horizontal-axis wind turbines and presenting a scientific approach to analyzing the airflow around the blade in order to optimize its size and achieve the optimal blade design for a 5-kW wind turbine in the Ouargla region.

Baci et al. [8]

In this study, two different methods were adopted to analyze wind turbines and compare them in order to determine the simplest and most accurate approach. Using the Blade Element Momentum (BEM) theory and Computational Fluid Dynamics (CFD), the blade of a 10-kW wind turbine was analyzed to calculate the power coefficient, torque coefficient, and power output. According to the results obtained, it was found that the BEM theory is simpler and easier to use, relying on a 2D blade element. On the other hand, CFD relies on 3D simulations, which makes it more accurate in describing the studied model.

Guettatfi. [9]

The study presented in this thesis aims to provide a summary of the aerodynamic force calculations based on the thesis "Dynamic Study and Optimization of Wind Turbine Blades," in order to optimize the energy performance of the wind turbine, with the goal of maximizing the captured wind energy while reducing structural issues. This optimization is likely to reduce the costs associated with electricity production.

Diab Hamza et al. [10]

The aim of this thesis is to model and simulate wind turbines to improve the performance and aerodynamic shape to improve the power output of wind turbines.

3 HISTORICAL DEVELOPMENT:

Wind turbines harness the kinetic energy of the wind and convert it into mechanical energy, which is then transformed into electricity for practical use.

Currently, wind energy contributes approximately 10% of the global electricity supply, and its significance in the renewable energy sector is expected to grow as its potential becomes increasingly recognized. Maximizing the efficiency of wind turbines is essential for maintaining competitiveness with other energy technologies. This optimization involves selecting the appropriate turbine configuration—whether horizontal-axis or vertical-axis—as well as choosing suitable materials. The materials used should be durable, cost-effective, and ideally recyclable to ensure that the environmental and economic benefits of wind power are not compromised [11] .

In this chapter, we will explore wind turbines, their types, airfoils, materials, and the advantages and disadvantages associated with them to provide a clearer understanding of our study [12] .

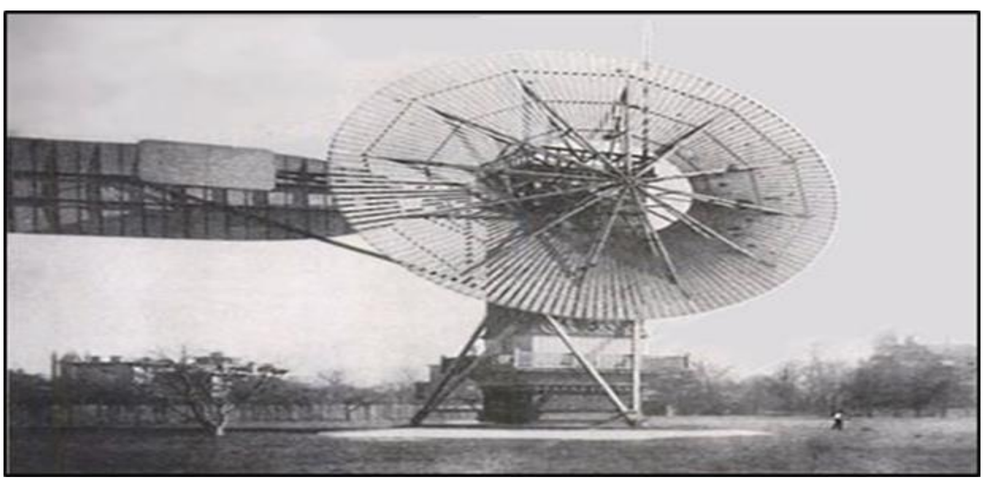


Figure I. 1 Charles Brush wind turbine US- 1888 [12]

These applications began to decline in the 19th century due to technological advancements in Europe during the Industrial Revolution. Efforts were later renewed to develop wind energy, and the Western world resumed investing in wind resources—this time for electricity generation. Research and development budgets for wind energy surged in the early 1980s in countries such as Germany, the

United States, Spain, and Denmark. After a period of trial and error, it was discovered that the optimal strategy was to gradually increase wind turbine capacity while establishing subsidized markets to create a solid industrial foundation for the sector's growth.

In addition to investments in wind energy, some nations introduced incentive policies to accelerate wind power adoption. These successful measures had a significant impact on certain countries, leading to the establishment of a robust wind energy industry [13] .

4 DEFINITION OF WIND ENERGY:

A wind turbine, sometimes referred to as a wind generator, is a device that converts a portion of the wind's kinetic energy into mechanical energy. This mechanical energy is transmitted through a shaft and then converted into electrical energy by a generator.

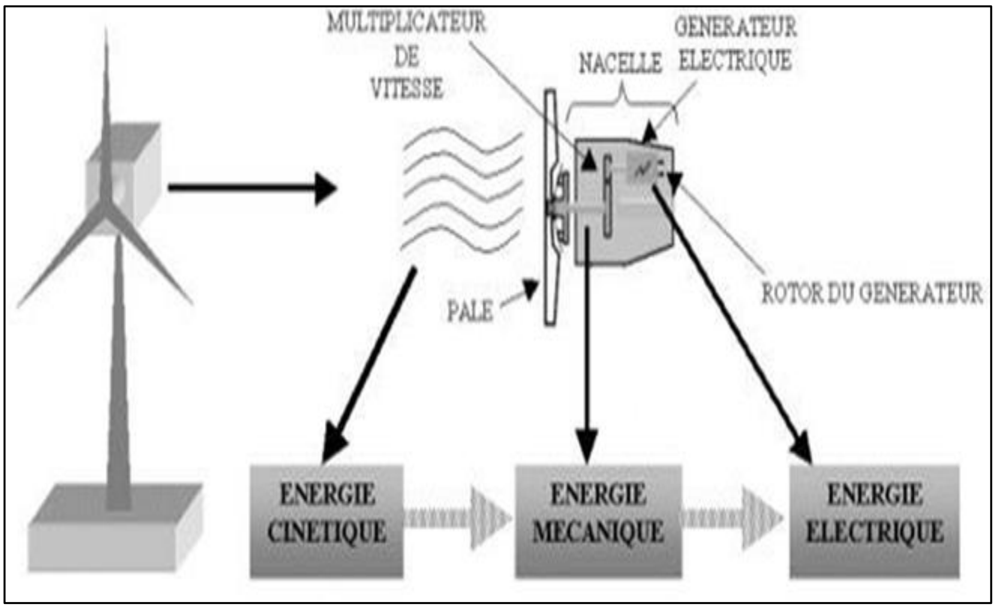


Figure I. 2 Conversion of wind kinetic energy [14]

Wind power is a renewable energy source that is geographically widespread and is considered an alternative solution for electricity production. It is especially crucial in winter when the average wind speed is higher. Moreover, it is an energy source that produces no atmospheric emissions or radioactive waste. However, it is unpredictable over time, and harnessing it remains fairly complex, requiring tall towers and large blades (up to 60 meters for multi-megawatt wind turbines) in open areas to avoid turbulence effects [14].

The materials required to manufacture various components (notably the nacelle, tower blades, and gearbox) must be technologically advanced and are therefore expensive. Wind power is one of the emerging means of decentralized electricity production, offering a viable alternative to nuclear power, though not intended to replace it (as the scale of energy production is significantly lower).

Wind farms can be built on land, but increasingly, they are also being developed offshore, where wind conditions are more consistent.

Figure I. 3 turbine Wind foundation

Figure I. 4 Inside mechanical components of the nacelle

5 WIND TURBINE TYPES:

Wind turbines can be classified into two main types, vertical-axis wind turbines (VAWTs) and horizontal-axis wind turbines (HAWTs).

Figure I. 5 Vertical Axis Wind Turbine (VAWT)

Figure I. 6 Horizontal Axis Wind Turbine (HAWT)

5.1 Horizontal wind turbine types:

These wind turbines have their axis of rotation horizontal to the ground and almost aligned with the wind direction. The majority of wind turbines on the market belong to this category. Although they often require a yaw mechanism to orient the blades, they offer higher aerodynamic efficiency Moreover, they start up autonomously [15] .

Figure I. 7 Horizontal Axis Wind Turbines (HAWT)

Depending on the relative position of the rotor to the wind direction, horizontal-axis wind turbines can be classified into two types.

5.1.1 up-wind turbine

The main drawback of this design is that the blades need to be strong, rigid, and spaced far apart to prevent collisions with the tower during strong winds. Additionally, these rotors require a yaw system to withstand the wind. This design is used in the majority of wind turbines.

5.1.2 down-wind turbine:

In a downwind turbine, the rotor is positioned on the flow side of the tower. One advantage of this design is that the rotor naturally aligns with the wind direction without requiring a yaw system. Additionally, since there is no risk of the blades colliding with the tower, they can be designed to be more flexible compared to upwind configurations. This flexibility helps reduce stress on the tower during high wind speeds, allowing for lighter blade construction. However, the main drawback is that as the blades pass through the wind shadow behind the tower, the wind flow becomes unstable. Consequently, power output may decrease when the rotor moves behind the tower, a challenge that becomes more significant in large-scale turbines.

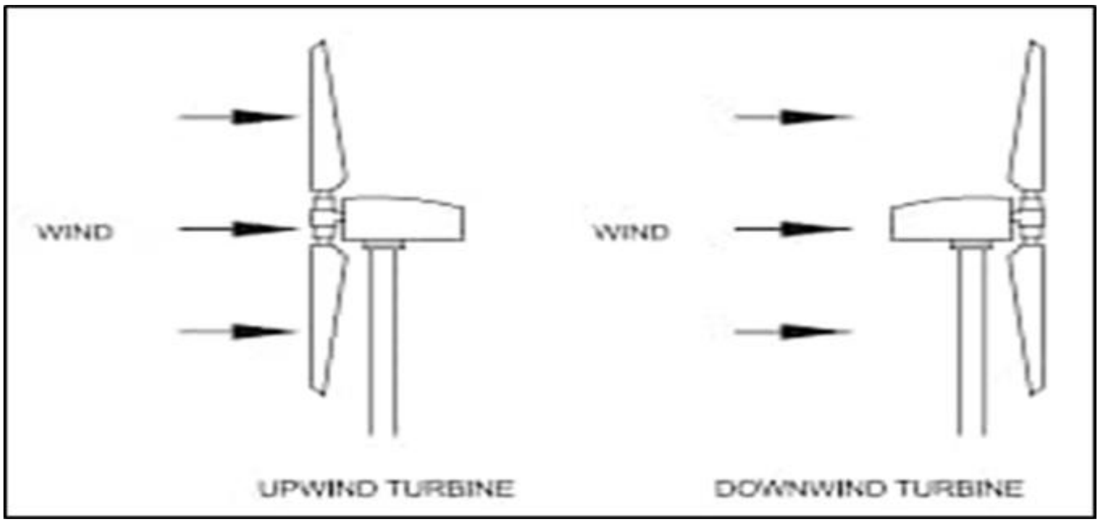


Figure I. 8 Down-wind and Up-wind of wind turbine

5.1.3 Main components of a horizontal-axis wind turbine

The main components of a wind turbine are the rotor, the drive train system, the generator, the blade and nacelle steering system, the tower and foundation, and the control systems (figure I.7) [16] .

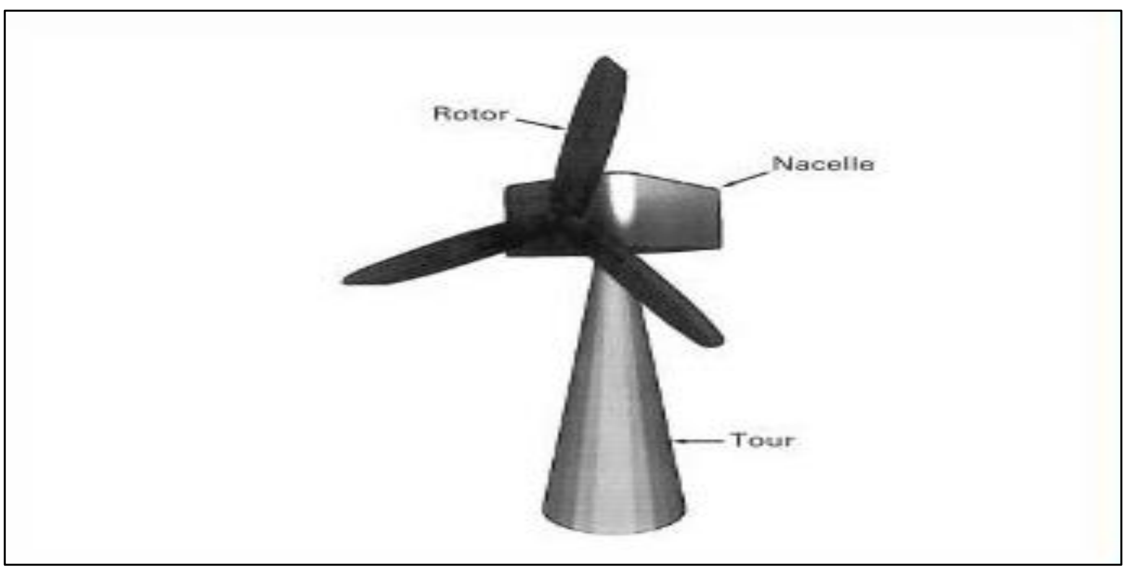


Figure I. 9 Components of a wind turbine

- The rotor consists of a hub and the turbine blades.
- The drivetrain comprises a low-speed shaft, a gearbox, and a high-speed shaft connected to the generator.
- The drivetrain also includes support bearings, couplings, and mechanical brakes. In some cases, the generator is directly connected to the rotor, eliminating the need for a gearbox.
- The nacelle is the enclosure that protects the drivetrain and generator from harsh weather conditions.
- The yaw system keeps the rotor shaft aligned with the wind. It is controlled by an automatic system that includes a sensor to detect wind direction and uses electric motors to rotate the nacelle so that it faces the wind.
- The control system consists of sensors, mechanical controllers, electrical circuits, computers, hydraulic pumps and valves, and actuators (motors, pistons, etc.).
- The control system is crucial for the operation of the wind turbine and electricity generation, so a reliable controller is necessary for efficient functioning.

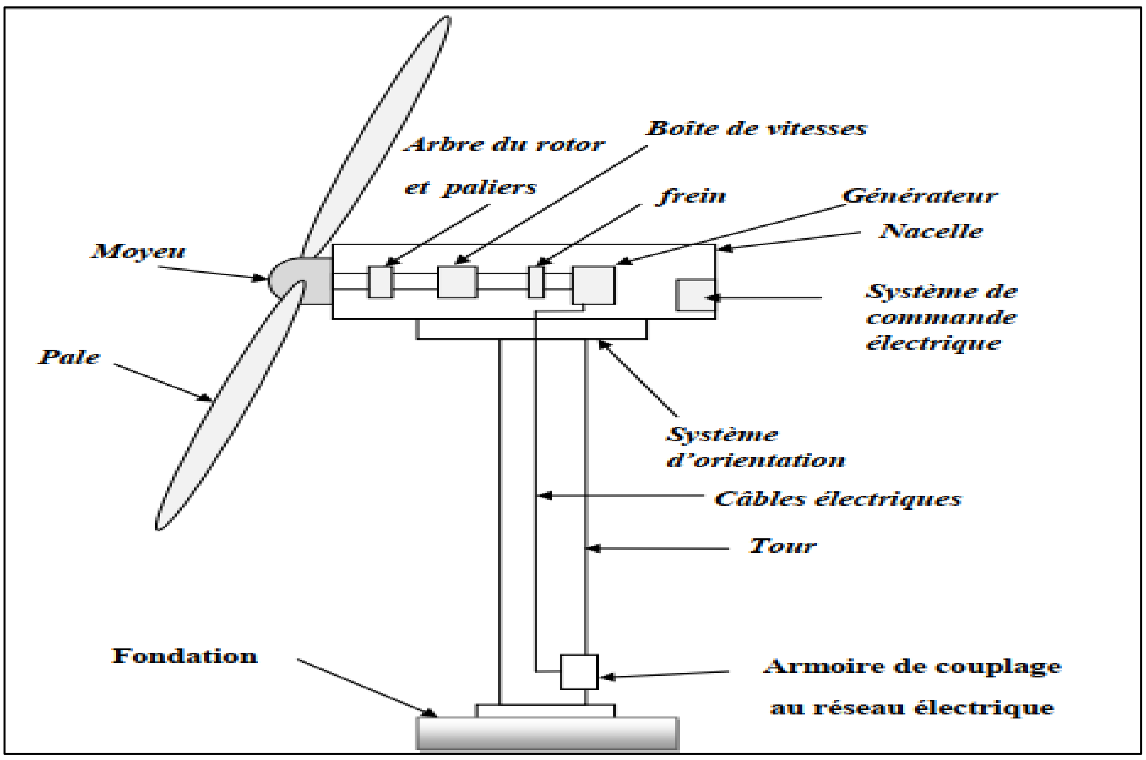


Figure I. 10 Wind turbine components [11]

5.1.4 Vertical axis wind turbines (VAWT):

These turbines have a rotor shaft and blades that rotate perpendicular to the ground, eliminating the need for orientation adjustments to follow the wind direction. The gearbox and generator can be positioned near the ground, making maintenance easier. Additionally, they can be installed in locations such as rooftops. However, a major drawback of these designs is that they generate very little energy.

5.1.4.1 Darrieus wind turbines:

The Darrieus turbine is a type of vertical-axis wind turbine named after the French inventor Georges Darrieus. It features an airfoil design that harnesses wind lift forces, similar to airplane wings. However, this vertical model does not self-start and requires a motor to reach a sufficient speed before generating significant torque. While efficient, it experiences high torque ripple and cyclical stress on the tower, reducing its reliability. Using three or more

blades help minimize torque ripple by increasing rotor solidity. Modern Darrieus turbines no longer rely on guy wires for support; instead, they incorporate an external superstructure connected to the top bearing.

Figure I. 11 Darrieus turbine by guy-wire.

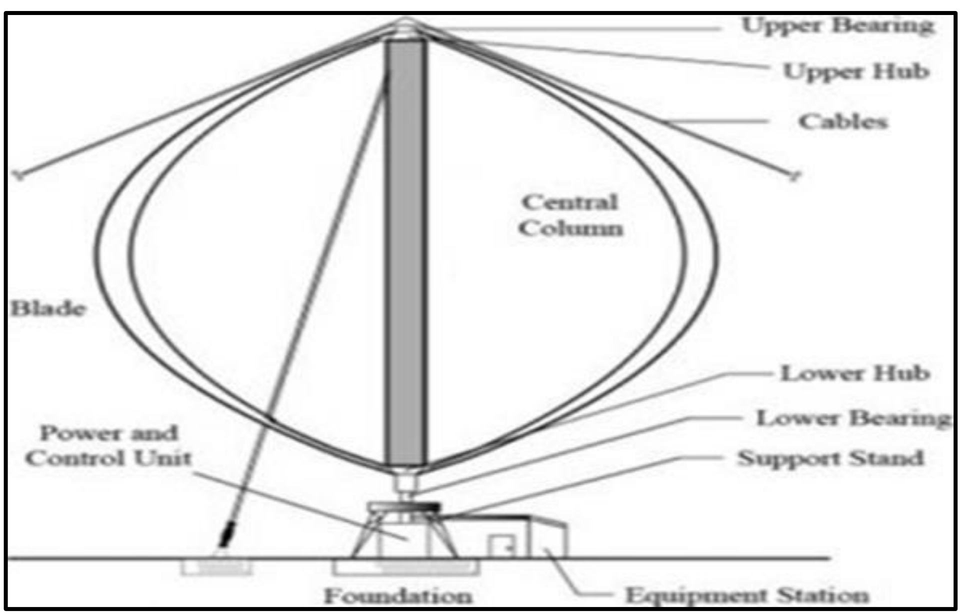


Figure I. 12 Darrieus turbine schematic.

5.1.4.2 Giro mill wind turbine

This type of turbine, also known as an H-rotor or H-bar, features straight vertical blades instead of the curved blades used in the traditional Darrieus design. These blades are connected to the central tower using horizontal supports.

Figure I. 13 Giro mill wind turbine

5.1.4.3 Savonius wind turbine:

Savonius turbines operate based on drag force. These turbines have an "S" shape when viewed from above (Figure 1.3). As they interact with the wind, the difference in drag forces enables them to rotate. However, their efficiency is lower compared to other types of wind turbines [7].

Figure I. 14 Savonius wind turbine

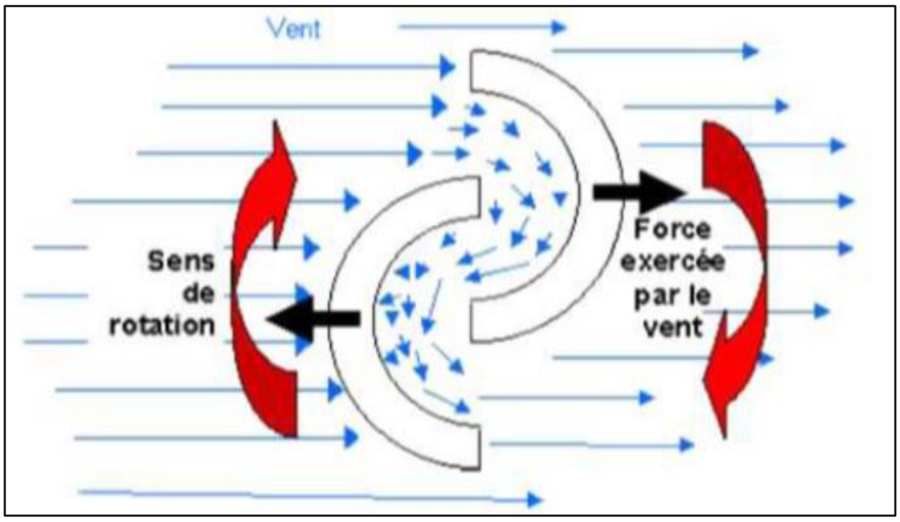


Figure I. 15 Rotor de Savonius turbine

6 MATERIALS AND PROPERTIES OF WIND TURBINE BLADES:

6.1 Materials Used in Wind Turbine Blades:

E-glass fibers and polyester resins are the most commonly used fiber and matrix materials. The fiber volume fraction (FVF) in the resin significantly influences the composite's strength, depending on the manufacturing process. When the fiber content exceeds a certain level, the mechanical properties begin to deteriorate due to insufficient resin to transfer the load to the fibers. Traditional hand layup techniques typically achieve an FVF of around 30-35%, whereas advanced methods like SCRIMP and vacuum infusion using prepregs can achieve FVF levels of up to 70% [17] .

6.1.1 Polyester resin:

Polyester resin possesses good thermal properties, as it can withstand high temperatures (compared to other resins) up to 260°C. However, it undergoes spontaneous decomposition at approximately 300°C, even in the absence of oxygen. Additionally, it exhibits excellent electrical resistance, as well as chemical resistance to solvents, acids, and salts. It is also resistant to wear and environmental effects. Moreover, it is a cost-effective material, but it is characterized by weakness and brittleness. this makes it ideal for small wind turbine blades. On the other hand, other resins compete fiercely in the production of larger wind turbine blades.

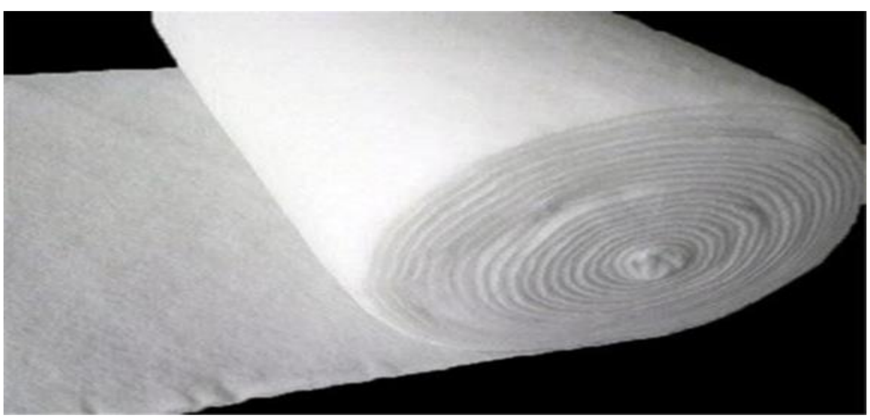


Figure I. 16 Synthetic Polyester Fibers

6.1.2 aramid

Aramid is a synthetic fiber composed of a long-chain synthetic polyamide, with at least 85% of its amide (-NH-CO-) linkages directly attached to two aromatic rings. Aramid fibers are characterized by low flammability, high strength, and a high modulus of elasticity. However, most aramid fibers are affected by ultraviolet (UV) radiation, which alters their natural color and weakens their strength when exposed for prolonged periods. Aramid fibers have been used in protective clothing, ropes, and belts for safety applications, as well as for protection against projectiles and missiles, and in wind turbine blades.

Figure I. 17 Synthetic Aramid Fibers

6.1.3 Carbon fiber:

Carbon fiber, a high-modulus reinforcement material, was initially preceded by boron fibers. The replacement of boron with carbon fiber has led to a reduction in its cost. While carbon fiber has the same tensile strength as glass fiber, its modulus can be up to five times higher. The primary advantage of reinforcement is to increase the stiffness of the structure [15] .

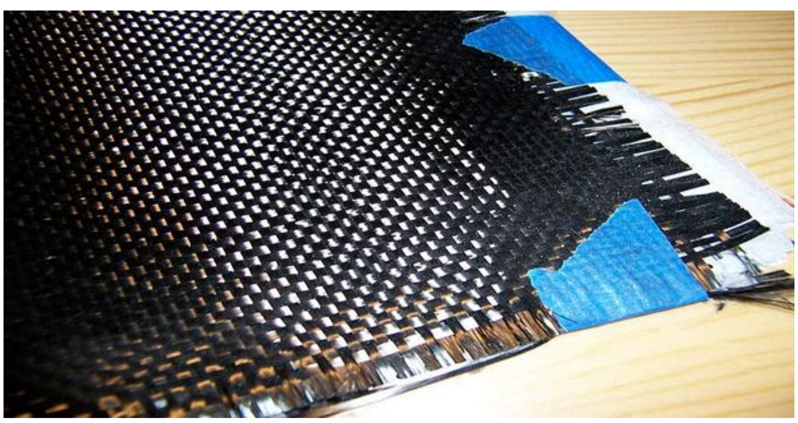


Figure I. 18 carbon fiber material

6.2 Elastic Properties of Materials:

Modern wind turbine blades are three-dimensional structures made from various materials, where the elastic properties and thermo-physical constants, such as the thermal expansion coefficient, play a crucial role in determining blade damage. Consequently, the stress field is affected by the elastic characteristics of the materials. For isotropic materials, the key elastic properties include Young's modulus (E) and Poisson's ratio. In contrast, orthotropic materials, such as composite laminates with aligned continuous fibers, exhibit different elastic properties in different directions [18] .

7 Wind turbine blade airfoils:

Airfoil families have been used to construct wind turbine blades. In HAWT, NASA LS, NACA 44xx, and NACA 63-xxx were commonly used. Roughness effects caused by leading- edge contamination, on the other hand, degrade their performance [19]. The NACA four-digit airfoil series was developed geometrically using analytical equations that define the camber (curvature) of the mean line (geometric centerline) of the airfoil section, as well as the thickness distribution along its length. In contrast, the six-digit airfoil series is considered to be more theoretical than purely geometrical, and modifying these designs by incorporating specific variables makes them more complex.

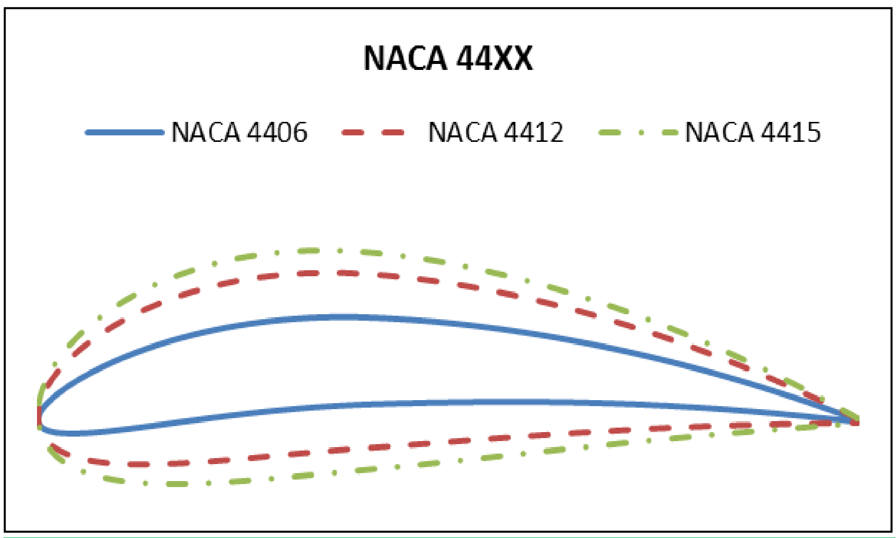


Figure I. 19 NACA4415&NACA4412&NAKA4406 Airfoils.[19]

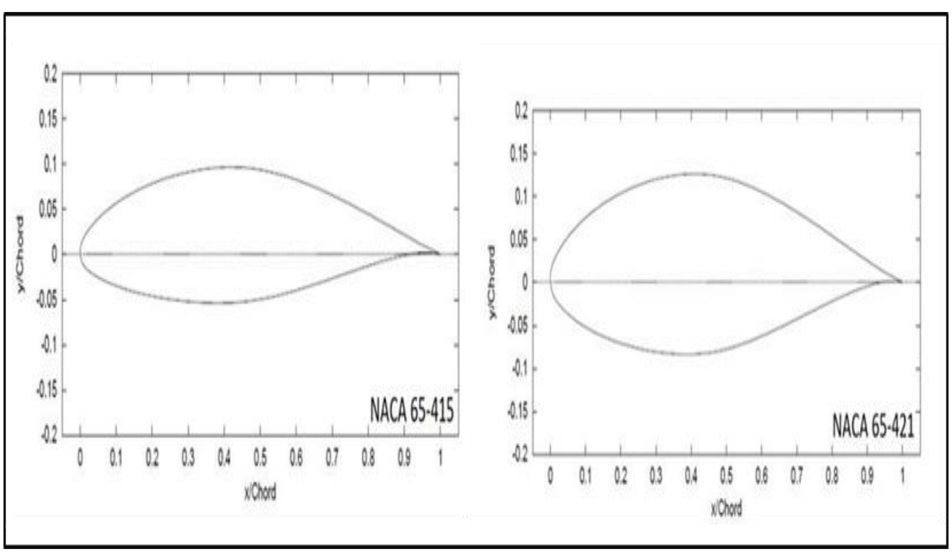


Figure I. 20 NACA65-415 &NACA65-421 Airfoils [19].

With the assistance of Tangler and Somers, the National Renewable Energy Laboratory (NREL) successfully addressed energy losses when it began developing different series of airfoils for wind turbines in the 1980s. Using the Eppler airfoil design and analysis program, NREL created nine airfoil families tailored for various rotor diameters. The primary performance requirement for these airfoil families is to maximize the lift coefficient while remaining largely unaffected by surface roughness effects. According to, NREL airfoil families have contributed to increased annual energy production in various types of wind turbine blades [19] .

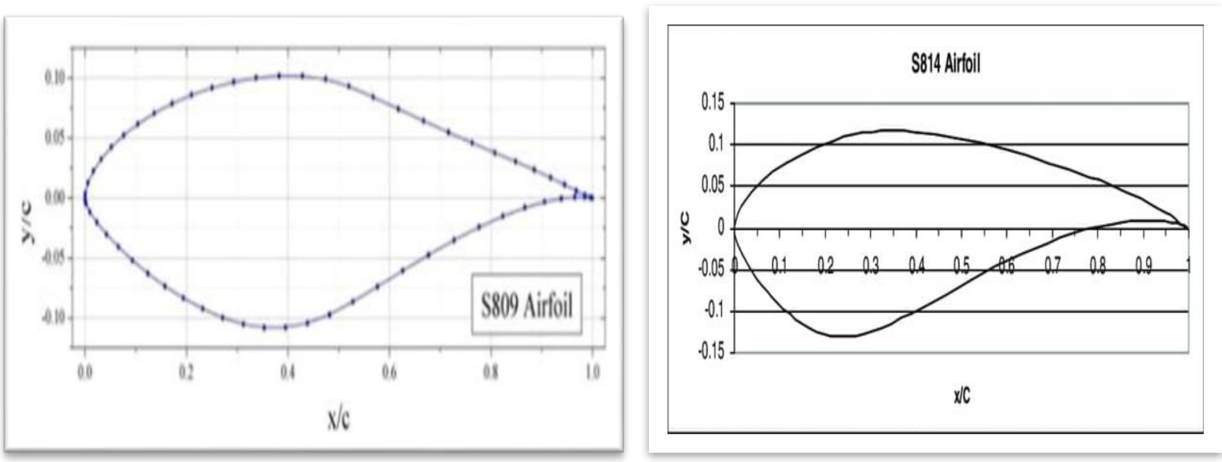


Figure I. 21 S814 &S809 NREL Airfoils [12].

In the mid-1990s, RISO developed three airfoil families Riso-A1, Riso-P, and Riso-B1 designed for rotor sizes ranging from 600 kW to megawatt-scale turbines. The Riso-A series was created using a direct numerical optimization algorithm based on a B-spline representation of the airfoil shape. This approach proved to be insensitive to leading-edge roughness in the RISO airfoil series, as noted in [12].

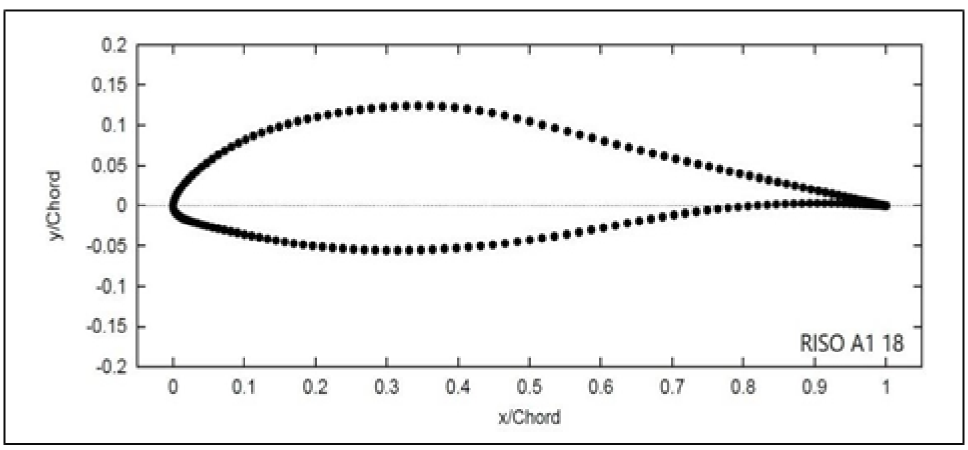


Figure I. 22 A1-18RISOAirfoils [19]

Delft University of Technology developed the DU airfoils (DUT), with a maximum relative thickness ranging from 15% to 40% of the chord. The initial designs were created using the XFOIL code. Since 1995, the airfoils have been designed using the RFOIL program, a modified version of

XFOIL with improved predictions around the maximum lift coefficient and the ability to account for rotational effects on airfoil

properties. The effects of Gurney flaps, trailing edge wedges, vortex generators (VG), and trip wires on the aerodynamic characteristics of various DU airfoils have been measured and documented. Additionally, a relationship has been established between the leading-edge thickness of the airfoil and the angle of attack concerning leading-edge separation.

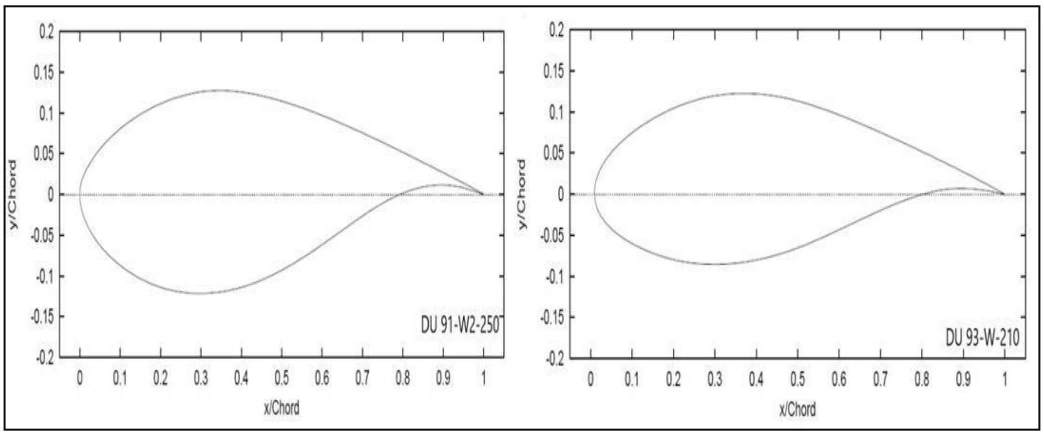


Figure I. 23 DU91-W2-250 andDU93-W-210Airfoils [19]

8 Wind turbines applications

Wind turbines have a wide range of applications, from small-scale uses for local energy supply to large-scale implementations as primary sources of renewable energy. Here are some key applications:

- **Electricity Generation for National Grids:**

Wind farms are widely used to supply power to national electricity grids, both onshore and offshore.

- **Powering Remote Areas:**

Wind turbines are used in areas where extending power grids is challenging, such as islands, deserts, and mountainous regions.

- **Hybrid Energy Systems:**

Wind turbines are integrated with other renewable energy sources, such as solar power, in hybrid systems to provide a stable energy supply.

- **Industrial and Commercial Applications:**

Large companies utilize wind turbines to power their facilities and reduce dependence on the main power grid.

- **Agricultural Uses:**

Small wind turbines are used for irrigation systems, water pumping, and energy supply for remote farms.

- **Research and Development Projects:**

Wind turbines are employed in research to improve airfoil designs, enhance efficiency, reduce noise, and optimize performance under different conditions.

- **Water Desalination:**

Wind turbines can be integrated with desalination systems to provide clean energy for water desalination processes in coastal and arid regions.

9 CONCLUSION:

Wind power could be the ideal solution to meet our energy needs, as it has immense potential and is easy to manage. Simply building a turbine allows for free energy generation. As long as the wind blows, it can be harnessed to produce electricity. Currently, wind power accounts for only a small portion of total electricity production. However, it is a fully renewable energy source and does not produce greenhouse gases, unlike coal. Many believe that it may soon become the primary source of energy. Although wind turbines may cause some complaints due to noise and pose risks to wildlife, they remain a promising option that could be the solution we seek for the future of energy.

Chapter II:

Aerodynamic Of Wind Turbine Blade

1 INTRODUCTION:

Aerodynamics plays a crucial role in the design and performance optimization of wind turbines, directly influencing the efficiency of converting wind kinetic energy into mechanical and electrical energy. Wind turbine blades rely on the principles of lift and drag to maximize the utilization of available wind energy.

Their shapes are aerodynamically optimized, often inspired by aircraft wings, to reduce resistance and enhance lift force. Several factors affect the aerodynamic performance of turbine blades, including the angle of attack, aspect ratio, camber, and the characteristics of the surrounding airflow.

Additionally, the choice of materials and modern technologies, such as biomimetic designs and winglet improvements, contribute to enhancing turbine efficiency and sustainability.

By studying the aerodynamics of wind turbine blades, their performance can be improved, leading to higher energy output. This, in turn, strengthens the viability of wind power as a renewable and clean energy source for electricity generation.

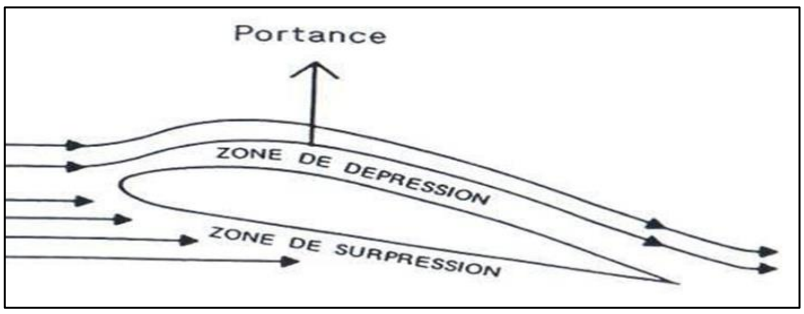


Figure II. 1 Airflow around the airfoil

The wind is first converted into mechanical energy in the shaft and then into electrical energy in the generator. The available energy is maximized if the wind speed could theoretically be reduced to zero.

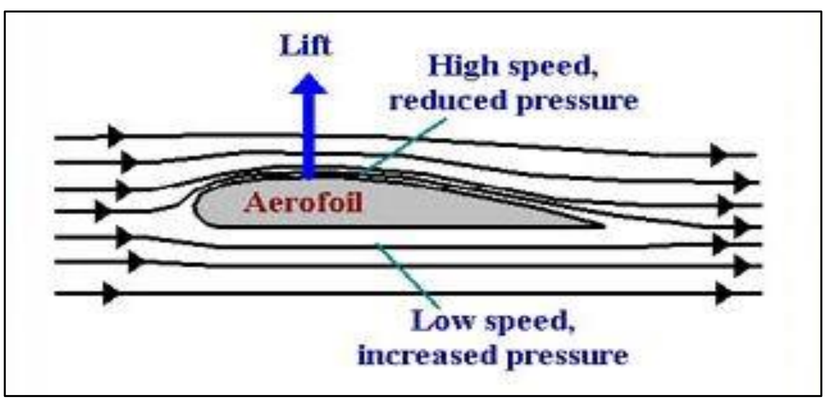


Figure II. 2 Airflow around the airfoil

The wind is first converted into mechanical energy in the shaft and then into electrical energy in the generator. The available energy is maximized if the wind speed could theoretically be reduced to zero.

$$P_{max} = \frac{1}{2}\dot{m}V^2 = \frac{1}{2}\rho A V^3 \quad \text{II.1}$$

Where P_{max} is the wind power of the moving air mass (W), $\dot{m}$ is the mass flow rate (kg/s), V is the wind speed (m/s), $\boldsymbol{\rho}$ is the Air density (kg/m^3), and A is the swept area (m^2)

2 wind turbine blade aerodynamics 2D

The aerodynamics of wind turbine blades in two dimensions involves studying the airflow around the blades and its effect on force generation, particularly in horizontal or vertical axis wind turbines. To simplify understanding, aerodynamics can be divided into several key points:

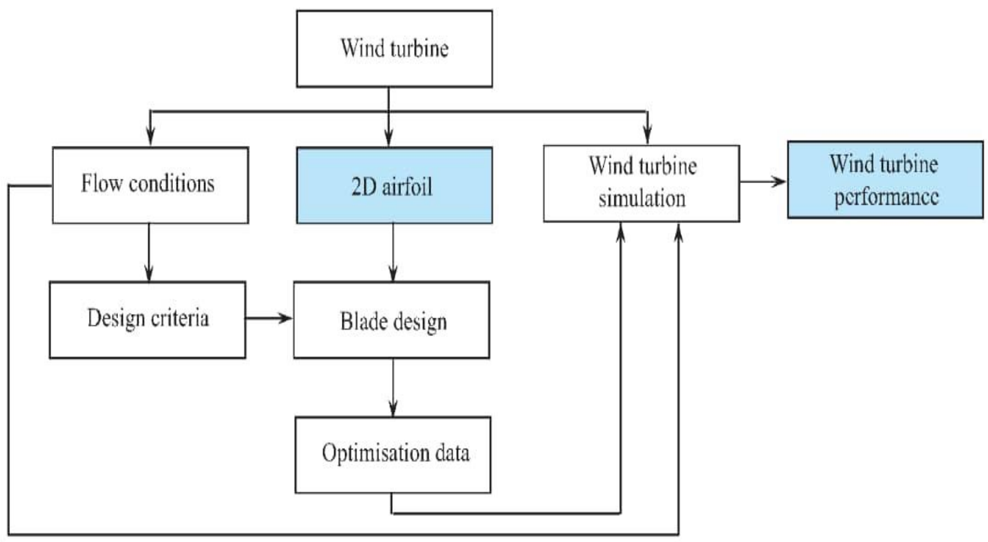


Figure II. 3 Flow chart diagram of the modelling of wind turbine.

3 CHARACTERISTIC AND PARAMETERS:

3.1 Power coefficient and moment coefficient:

The Coefficient of Performance (C_p) represents the amount of energy the turbine can convert from the wind. It corresponds to the aerodynamic efficiency of the turbine, the relationship between the energy available in the wind and the energy generated by the rotor [20] .

$$C_p = \frac{P_{turbine}}{P_{wind}} = \frac{P_{turbine}}{\frac{1}{2}\rho A V_1^3} \quad \text{II.2}$$

Numerically, the Betz limit for a horizontal-axis wind turbine (HAWT) is 27/16, which equals 59.3%.

To fully explain the forces, the moment M about a point in the airfoil must also be known. This point is frequently seen on the leading edge's c/4 chord line. When the airfoil in Figure II tends to turn, the moment is positive. A moment coefficient is defined as: 2 clockwise (nose up) and a moment coefficient is defined as:

$$C_m = = \frac{M}{\frac{1}{2}\rho V_\alpha^2 C^2} \quad \text{II.3}$$

3.2 Trust coefficient:

The thrust is the force in the streamwise direction resulting from the pressure drop over the rotor.

$$T = \Delta p. A \quad \text{II.4}$$

Where $A = \pi. R^2$ is the area of the rotor and Δp Is the pressure drops over the rotor.

The thrust coefficient is another important dimensionless number in wind turbine aero dynamics; it is defined as:

$$C_T = \frac{T}{\frac{1}{2}\rho A V^2} \quad \text{II.5}$$

3.3 Tip-Speed Ratio:

The specific speed of the turbine represents the speed of an ideal turbine, defined as the ratio of the blade speed to the nominal wind speed.

$$\lambda = \frac{\omega R}{V} \quad \text{II.6}$$

Where**:**

ω: is the rotor rotational speed (rad/s).

R: is the rotor radius (m).

V: is the nominal wind speed (m/s).

ωR:is the peripheral linear speed of the blade (m/s).

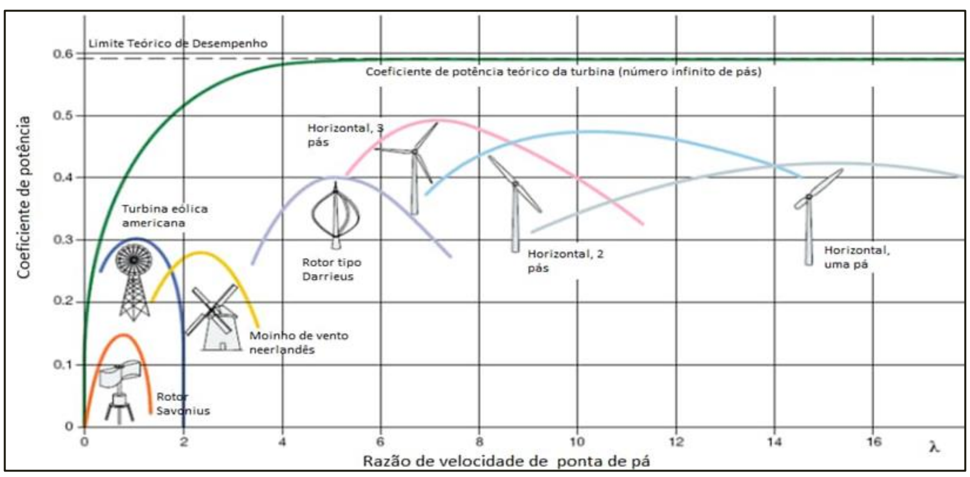


Figure II. 4 Power factor for different types of wind turbines [21].

Its operation does not exceed 60% of the maximum value (0.59) due to the different successive returns of the conversion chain, frictional losses in the rotating parts, etc [22].

We note in Figure II.4 that the best aerodynamic efficiency is for horizontal-rotating wind turbines, which are said to be fast and likely have a higher return than other versions, which explains their dominance of the current machine market [21].

We can also note the effect of the number of blades on aerodynamic efficiency.

3.4 Lift and Drag Coefficients:

The wind turbines blades generate a lift force due to their shape like airplane wings. This force is a net result of low pressures in the more curved side and high pressure in the other side of airfoil.

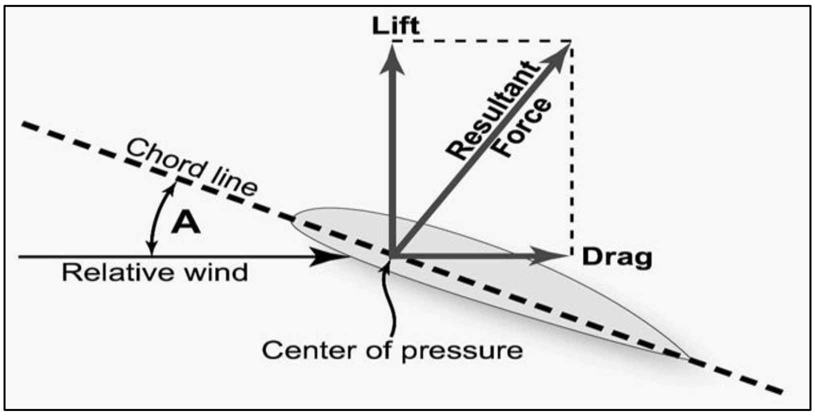


Figure II. 5 Pressure distribution on the wing

The lift force is always perpendicular to the airflow direction and increases as the blade aligns more closely with the wind. However, at a very large angle of attack, the lift force drops to zero, indicating the existence of an optimal angle of attack for maximum lift.

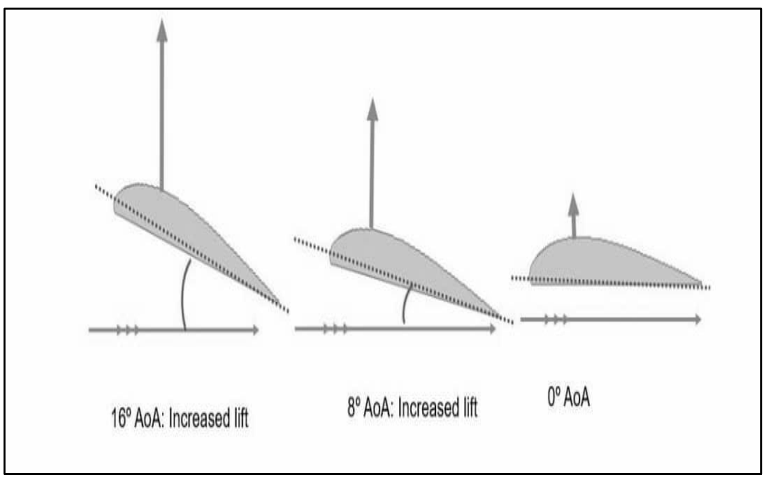


Figure II. 6 Lift forces at low, medium and high angels of attack

3.4.1 Lift Coefficients

$$C_l = \frac{L}{\frac{1}{2}\rho A V^2} \qquad \text{II.7}$$

Where L is Lift force, ρ is the Air density, and A is the Airfoil reference area

3.4.2 Drag Coefficients:

$$C_d = \frac{D}{\frac{1}{2}\rho A V^2} \qquad \text{II.8}$$

Where W is the relative wind as experienced by the blades. This speed is done by the relation below:

$$\vec{W} = \vec{V} - \vec{U} \quad \text{II.9}$$

$\vec{W}$: Relative wind: The velocity that actually acts on the airfoil section of the blade.

$\vec{V}$: Free-stream wind speed: The true wind velocity approaching the wind turbine.

$\vec{U}$: Tangential (rotational) speed: The velocity of the blade section due to its rotation around the hub (i.e., the motion added by the turbine's rotation).

This equation expresses the difference between the actual wind speed (relative to the ground) and the blade's rotational speed, resulting in the relative velocity at which the air meets the blade. This relative velocity determines the angle of attack and the lift and drag forces acting on the blade.

4 THE APPLIDE FORCE ON THE BLADE

We can distinguish between three forces acting on the blade profile represented in Figure (II.6).

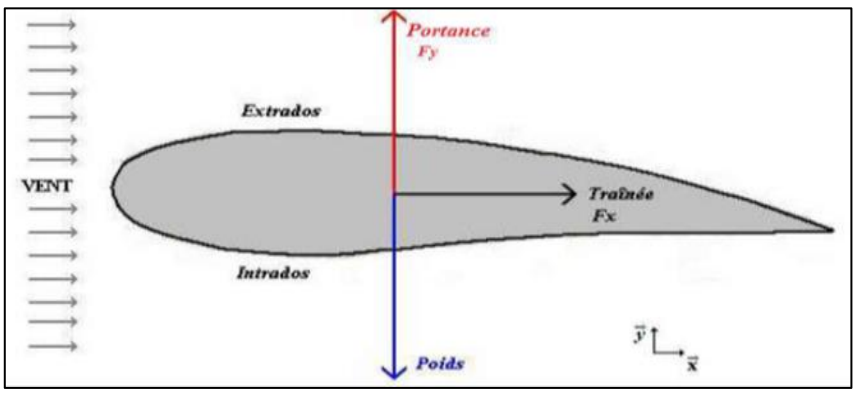


Figure II. 7 Forces acting on the blade [23]

4.1 Gravity force (weight):

This force that pushes the wing down is given by the following expression

$$F_g = mg \quad \text{II.10}$$

Where F_g is Gravitational force (N), m is the mass of the object (kg), and g is the acceleration due to gravity, and its value is (9.81 m/s²).

4.2 lifting force:

This force is perpendicular to the wing relative to the airflow, resulting from aerodynamic dynamics, and it is what keeps the aircraft in the air. It is given by the following equation:

$$F_y = \frac{1}{2} C_y S V_\infty^2 \quad \text{II.11}$$

C_y: is the lift coefficient which depends on both the Reynolds number, Mach number, blade profile shape and twist angle.

4.3 Pull force:

This force represents the resistance of a wing to movement through the air, as it moves in the opposite direction and increases with the speed of the moving body. It is defined by the following formula.

$$F_x = \frac{1}{2} C_x S V_\infty^2 \quad \text{II.12}$$

Where C_x:The drag coefficient depends on the Reynolds number, Mach number, blade profile shape and angle of incidence.

5 BEM theory and the momentum of the blade element:

is an analytical method used to evaluate the performance of wind turbine blades by combining momentum theory with blade element theory. The approach involves dividing the turbine blade into several cross-sectional elements and analyzing each section individually using the aerodynamic forces generated by the airfoil. These forces are then combined with the overall momentum analysis to determine the distribution of torque and power along the blade.

5.1 Momentum Theory Definition:

Momentum Theory is a simplified physical model used to analyze the performance of wind turbines, where the turbine is represented as an ideal actuator disk that influences the airflow. The theory is based on the application of the conservation laws of mass, linear momentum, and energy over a control volume through which air flows from the upstream to the downstream. Its main objective is to calculate the thrust force and the power generated from the interaction between the turbine and the airflow.

5.1.1 Linear Momentum

Linear Momentum is defined as the product of an object's mass and its velocity.

$$P = m.V \quad \text{II.13}$$

P: is the linear momentum (kg m/s).

m: is the mass of the object (kg).

v: is the velocity of the object (m/s).

5.1.2 Angular momentum:

is a physical quantity that describes the extent of an object's rotation around a point or an axis. It is an important concept in rigid body mechanics and rotational physics, and it is commonly denoted by the letter L.

$$L = I.\omega \quad \text{II.14}$$

L: Is the angular momentum (kg.$m^2.s^{-1}$).

I: Is the moment of inertia of the body about the axis of rotation (kg.m^2).

ω: Is angular velocity (rad/s).

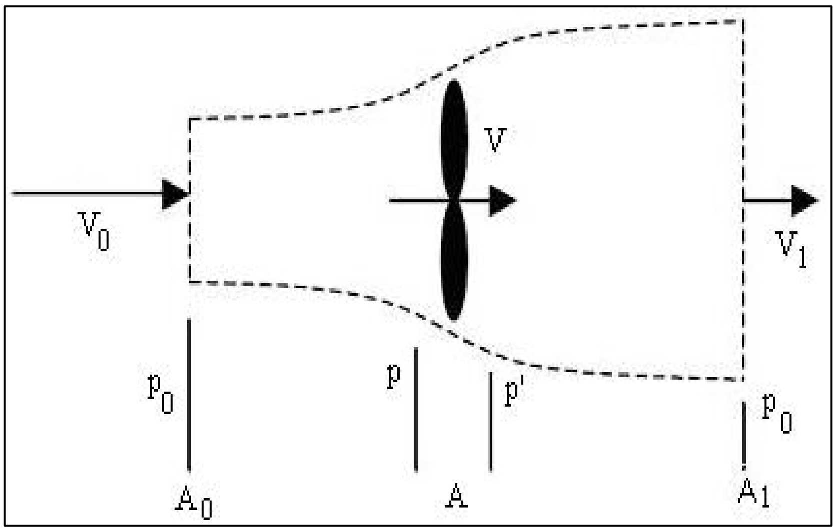


Figure II. 8 Axial Airflow

5.2 Blade Element Theory

This theory is based on dividing the blade element into several sections, and then calculating the lift and drag forces (Cd and Cl) for each section resulting from the airflow around each blade element.

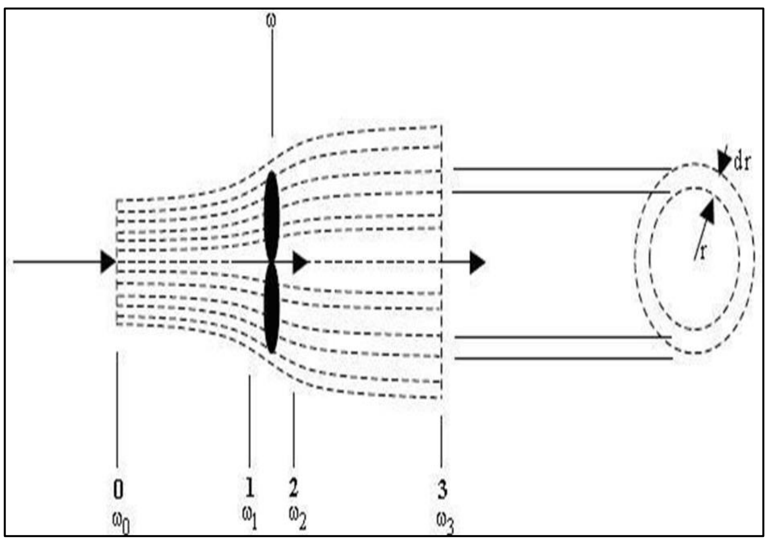


Figure II. 9 Airflow through an annular element

5.3 The axial and tangential induction factors:

5.3.1 Determination of velocities at the blade:

The axial velocity at the blade is given by flown equation:

$$V_a = V_\infty \, (1 - a) \qquad \text{II.15}$$

And the relative rotational velocity is given by:

$$V_t = \omega \, r \, (1 - \acute{a}) \qquad \text{II.16}$$

The relative velocity on the blade wright by:

$$Vrel = \sqrt{[V_\infty (1 - á)]^2 + [\omega r(1 - á)]^2} \tag{II.17}$$

5.4 Aerodynamic forces on the blade element:

Axial aerodynamic forces given by:

$$dF_N = \frac{1}{2} \rho V^2 rel\, cC_N\, dr \tag{II.18}$$

and tangential forces given by:

$$dF_T = \frac{1}{2} \rho V^2 rel\, cC_{NT}\, dr \tag{II.19}$$

5.5 Application of momentum theory:

From the axial thrust theory on a stream tube at radius r, it is:

$$dF\ momentum = 4\pi r \rho V_\infty^2 (1\_ a)dr \tag{II.20}$$

We equate the aerodynamic force with the momentum force (including the adjustment for the number of blades B and the radial factor).

$$B.dF_N.r = 4\pi r \rho V_\infty^2 (1\_ a)dr \tag{II.21}$$

We compare and calculate, expressing B and C and r in the form of σ, and then simplify again:

$$a = \frac{1}{4sin^2\emptyset/(\sigma C_N)+1} \tag{II.22}$$

5.5.1 Torque from momentum:

Aerodynamic torque along the turbine is:

$$d\emptyset = 4\pi r^3 \rho V_\infty á(1\_ a)\omega dr \tag{II.23}$$

From the blade element, we obtain:

$$B.dF_T.r = 4\pi r^3 \rho V_\infty á(1\_ a)\omega dr \tag{II.24}$$

After equating both sides, we simplify and analyze to find:

$$á = \frac{1}{4sin\emptyset cos\emptyset/(\sigma C_T)\ \_1} \tag{II.25}$$

Where:

$$\sigma = \frac{CB}{2\pi r} \tag{II.26}$$

Where, c is the chord length, B is the number of blades and r is the disk radius.

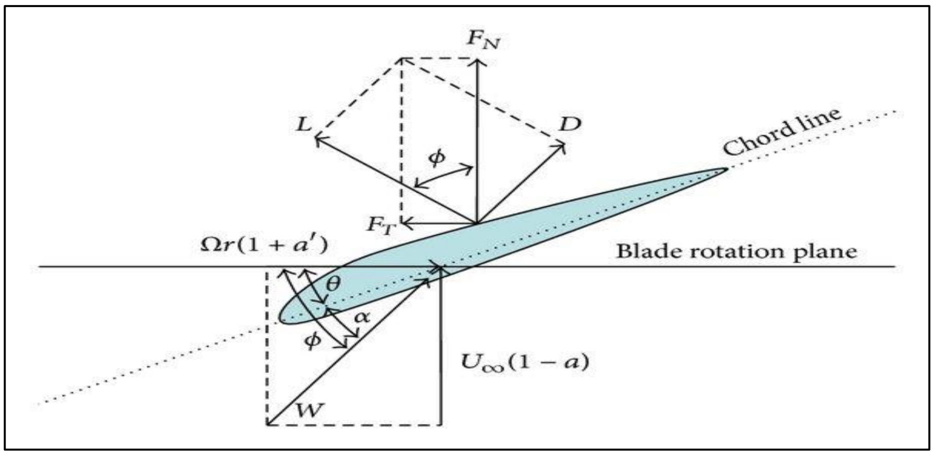


Figure II. 10 Velocity component in the rotor plane. [24]

5.6 Explanation of diagram:

This diagram represents the aerodynamic forces acting on an airfoil section of a wind turbine blade, based on the Blade Element Momentum (BEM) theory. Below is an explanation of the key elements in the diagram:

5.6.1 Variables and Velocities:

- The axial wind velocity after being affected by the axial induction factor
- The tangential velocity of the blade, where is the angular velocity, is the radius at the section, and is the tangential induction factor.
- The relative wind velocity acting on the airfoil, which is a combination of the above two velocities.

5.6.2 Important Angles:

- The angle of attack, which is the difference between the chord line and the relative wind velocity.
- The pitch angle of the blade.
- The angle of the relative wind velocity with respect to the plane of blade rotation.

5.6.3 Aerodynamic Forces Acting on the Blade:

- The lift force, which is perpendicular to the relative wind velocity.
- The drag force, which is parallel to the relative wind velocity.
- The normal component of the aerodynamic forces, resulting from the projection of both and.
- The tangential component of the aerodynamic forces, which contributes to the rotational torque on the blade.

5.6.4 Relationship Between Forces and Velocities:

- The lift force and the torque generated by the tangential force drive the turbine rotation.
- The drag force negatively affects performance and should be minimized by optimizing airfoil design.

6 Wind turbine blade aerodynamics 3d:

The aerodynamics of wind turbine blades in three dimensions play a crucial role in performance efficiency and optimizing energy extraction from the wind. This aerodynamics differ from two-dimensional analysis due to effects such as tip effects, unsteady losses, and variations in the angle of attack along the blade.

6.1 Key Factors in Three-Dimensional Aerodynamics:

6.1.1 Tip Effects:

- At the blade tip, vortex formation leads to energy loss due to pressure drop.
- This effect can be mitigated by designing winglets or improving the blade's aspect ratio**.**

6.1.2 Spanwise Variations:

- The angle of attack and relative wind speed vary along the blade span.
- Blades are designed with a gradual twist to achieve optimal lift and drag distribution.

6.2 Flow Separation and Stall Effects:

At high angles of attack, boundary layer separation occurs, reducing turbine efficiency. Techniques such as winglets or flow control mechanisms are used to delay separation and enhance performance.

6.2.1 Spanwise Vortices:

- Vortices form along the blade, affecting pressure distribution and lift force.
- Optimized winglet designs help minimize these effects and improve flow stability.

6.2.2 Reynolds Number Effects:

- The Reynolds number varies along the blade due to changes in relative velocity, influencing the transition between laminar and turbulent flow.

7 BLADE SHAPE DESIGN FOR OPTIMUM ROTOR

When designing an ideal rotor, the effect of wake rotation is considered in the design process. The blade shape optimization for an ideal rotor takes into account wake rotation, while neglecting drag (C_d = 0) and tip losses (F = 1). The power coefficient depends on the inflow angle, ø, and can be determined using the following equation:

$$C_P = \frac{8}{\lambda^2} \int_{\lambda h}^{\lambda} \sin^2 \emptyset \, (\cos\emptyset - \lambda_r \sin\emptyset) \qquad \text{II.27}$$

$$(sin\emptyset + \lambda_r \, cos\emptyset)[1 - (C_d / C_l) \, cos\emptyset](\lambda_r)^2 d\lambda_r$$

The partial derivative of the integral expression for the power coefficient is taken, and the derivative is then set equal to zero.

$$\frac{\partial}{\partial\emptyset}[sin^2(cos\emptyset - \lambda_r\, sin\emptyset)(sin\emptyset + \lambda_r cos\emptyset] = 0 \quad \text{II.28}$$

The local tip speed ratio, inflow angle, and chord length of the blade section can be calculated as follows:

$$\lambda_r = sin\emptyset \frac{2cos\emptyset+1}{[(1-cos\emptyset)(2cos\emptyset+1)]} \quad \text{II.29}$$

$$\emptyset = (\frac{2}{3}\tan^{-1}(\frac{1}{\lambda_r}) \quad \text{II.30}$$

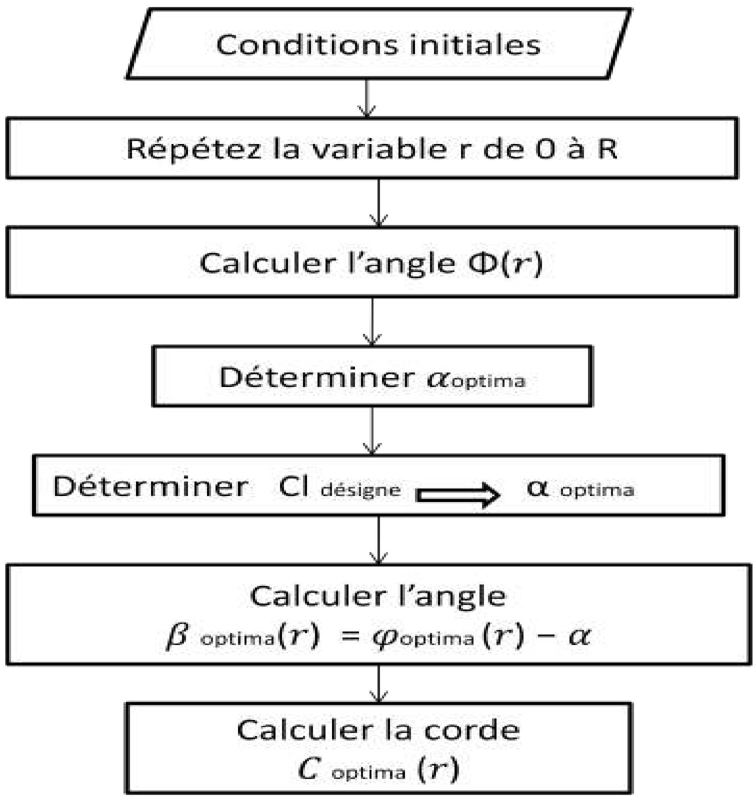


Figure II. 11 Flowchart for Determining the Optimal blade shape.

8 CONCLUSION:

In this chapter, we explored the impact of aerodynamics on the design and performance improvement of wind turbines, as well as the various forces acting on the turbine blades and the mathematical equations associated with each force.

Chapter III:

Results and discussion

1 INTRODUCTION:

In this chapter, we used the QBlade software to predict the aerodynamic performance of a horizontal-axis wind turbine with a rated power of 3 kW and a rotor diameter of 4 meters, using the NACA- 4412 airfoil and NACA- 6409 and airfoil S-818 airfoil and Eppler-387 airfoil.

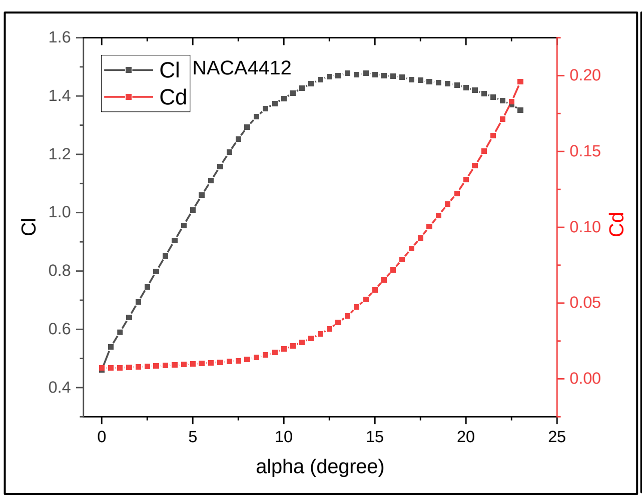
QBlade It is a free engineering software used for designing wind turbine blades and analyzing their performance under various operating conditions. It relies on accurate physical models to simulate turbine behavior and improve its efficiency. is used for designing the turbine and analyzing and optimizing its aerodynamic performance. QBlade simulates wind turbines based on the Blade Element Momentum (BEM) theory and is integrated with XFOIL for airfoil design and analysis. Finally, the results obtained from QBlade are compared with the power coefficient versus tip speed ratio, and drag and lift coefficients as well as lift-to-drag ratio versus angle of attack.

2 Airfoil for small wind turbine analyses:

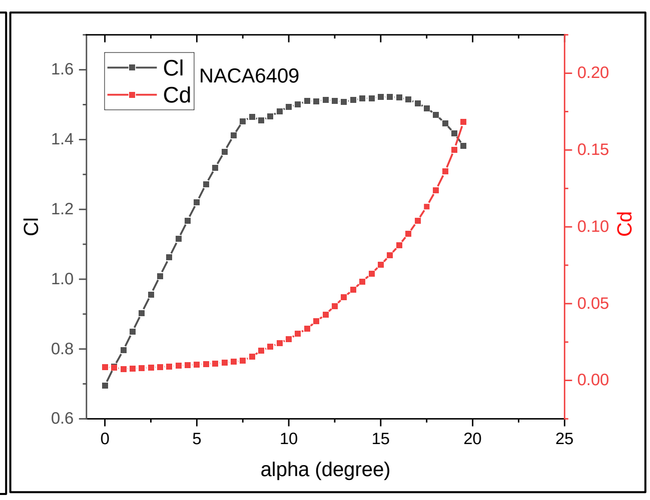
In this important step, we will analyze several types of airfoils commonly used in small wind turbines, including (E 387, NACA4412, NACA6409, and S818), to improve the design and aerodynamic shape, as well as improve the extracted power.

2.1 Lift and drag coefficient analyses:

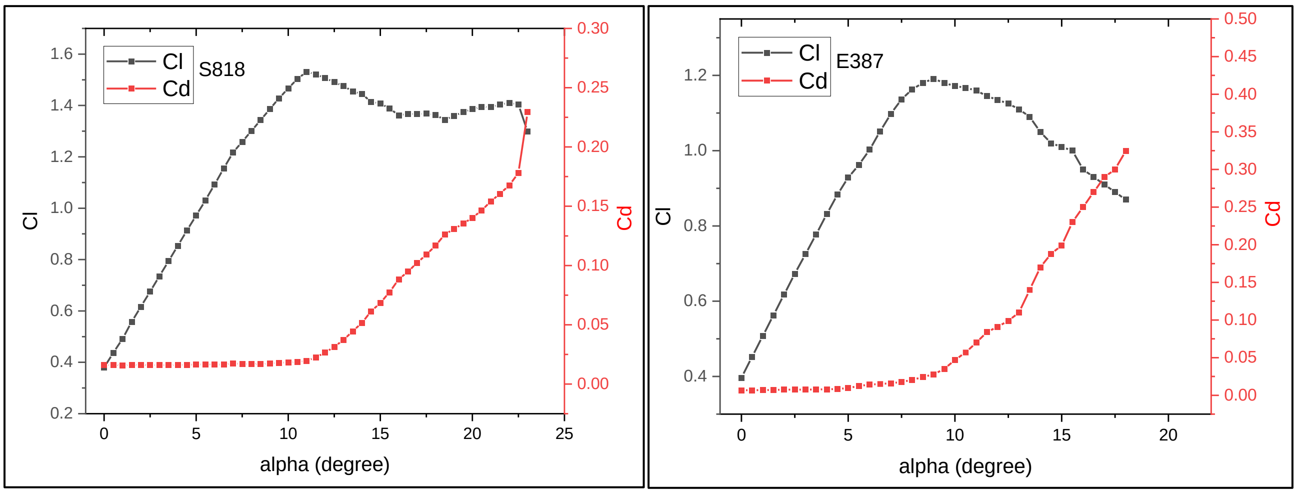
There are several criteria by which the appropriate airfoil can be selected, perhaps the best of which is the lift-to-drag ratio. In this work, we will use the XFoil program to calculate the lift and drag coefficients and calculate the ratio between them to select the best one. The results can be showed in the figures below.



(a)

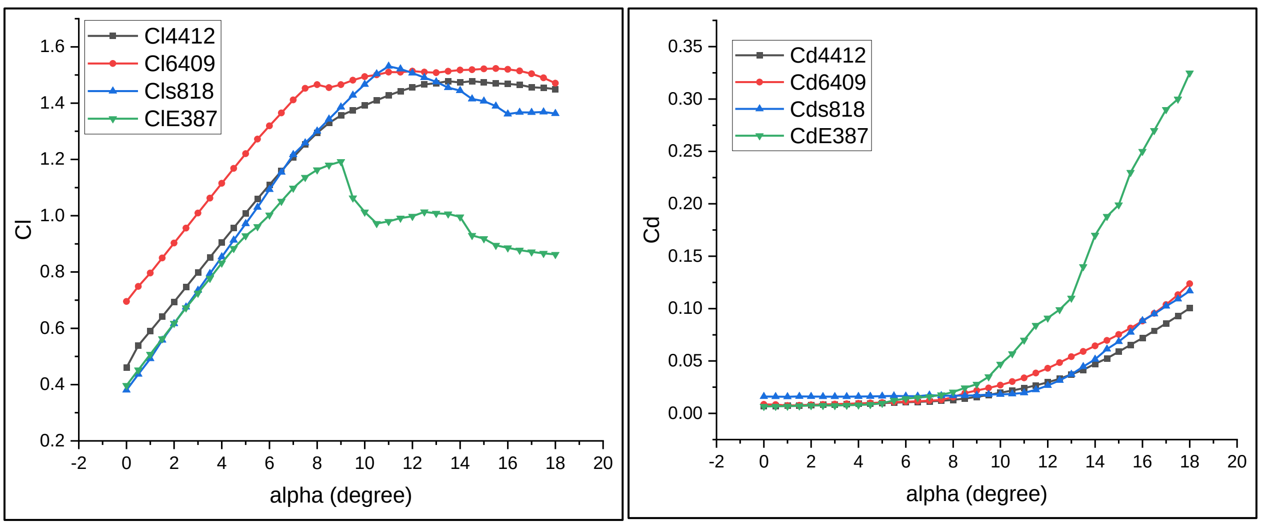


(b)



(c) (d)

Figure III. 1 Cl, and Cd for a) NACA4412, b) NACA6409, c) S818, and d) E387 airfoils



(a) (b)

Figure III. 2 comparison between a) Cl, and b) Cd for the different airfoil

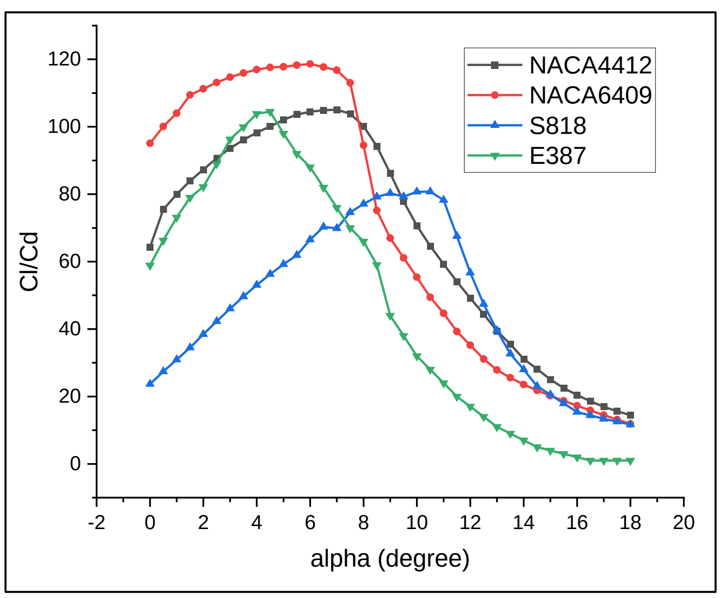


Figure III. 3 comparison between Cl/ Cd for the different airfoil

By analyzing the obtained results, it is clear that the lift coefficient and drag coefficient values are similar. When comparing the lift-to-drag ratio, we note that the best result was achieved by NACA6409, which provided the highest value among the ratios, followed by NACA4412 in second place.

3 Wind Turbine Analysis:

At this stage, we will design the wind turbine blade according to different models in terms of shape, by changing the external aerodynamic shape of the blade by changing the airfoil according to different models specific to small wind turbines. Table 1 shows the various configurations for a 3-kW blade after optimization.

Table III. 1 3kW wind turbine blade radius, chord, and twist distribution

Section	Radius (m)	Chord length(m)	Twist angle (deg)
1	0,00	0.06	0
2	0,01	0.06	0
3	0,20	0. 25	14
4	0,40	0.22	12.5
5	0.60	0.19	11
6	0.80	0.16	9.5
7	1.00	0.14	08
8	1.20	0.12	6.5
9	1.40	0.10	05
10	1,60	0.,08	04
11	1.80	0.06	03
12	2.00	0.05	02

3.1 Design blade by airfoil Eppler 387:

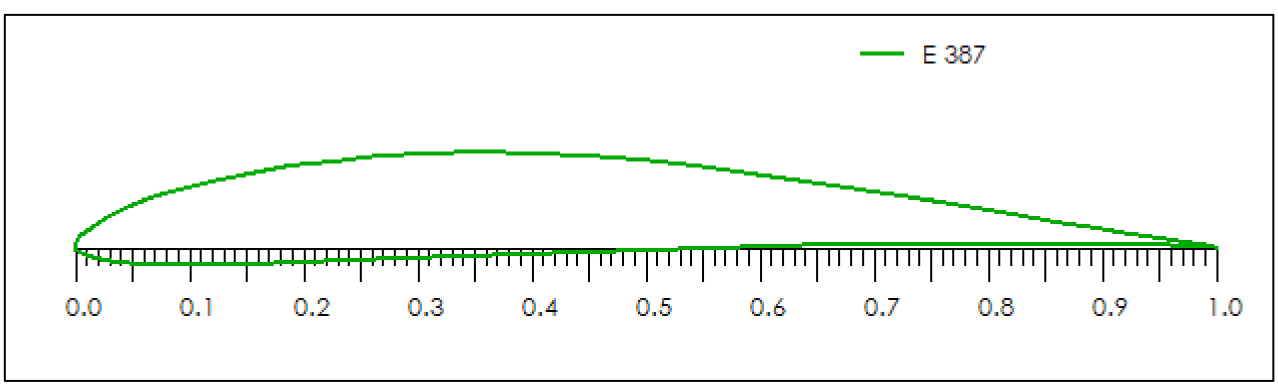


Figure III. 4 The cross-sectional shape of the wing: Eppler 387

Table III. 2 blade shape of E-387 airfoil section segment

Section	Radius (m)	Airfoil
1	0,00	Circle
2	0,01	Circle
3	0,20	E-387
4	0,40	E-387
5	0.60	E-387
6	0.80	E-387
7	1.00	E-387
8	1.20	E-387
9	1.40	E-387
10	1,60	E-387
11	1.80	E-387
12	2.00	E-387

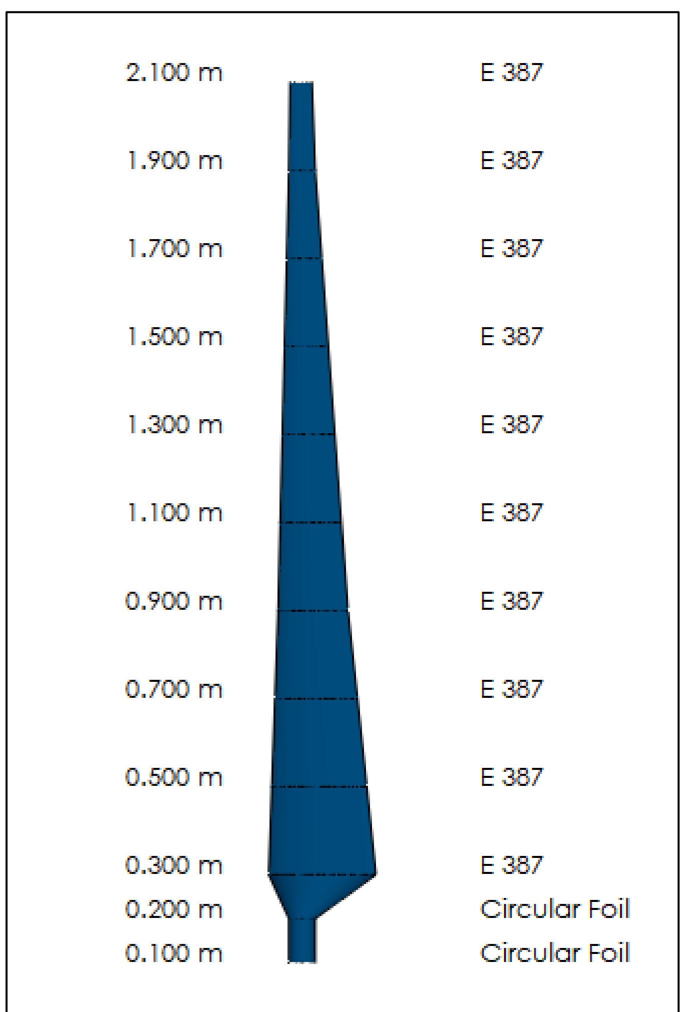


Figure III. 5 wind turbine designed with the Eppler 387 airfoil.

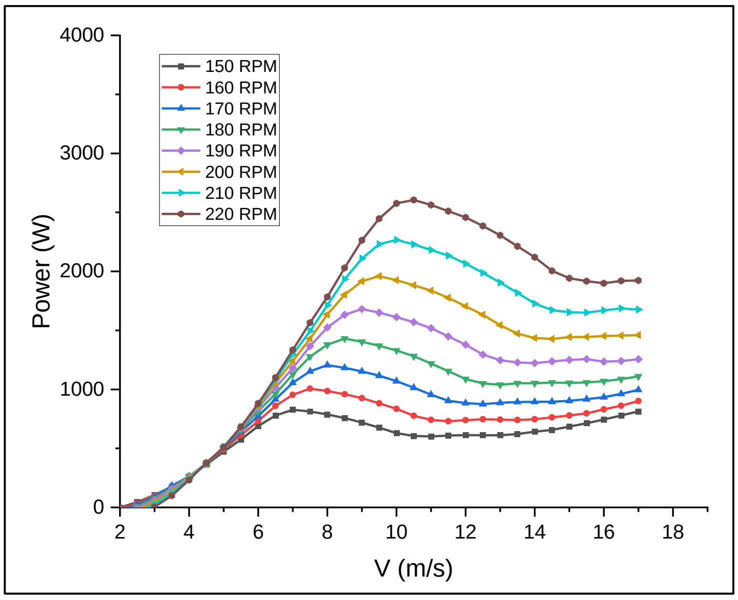
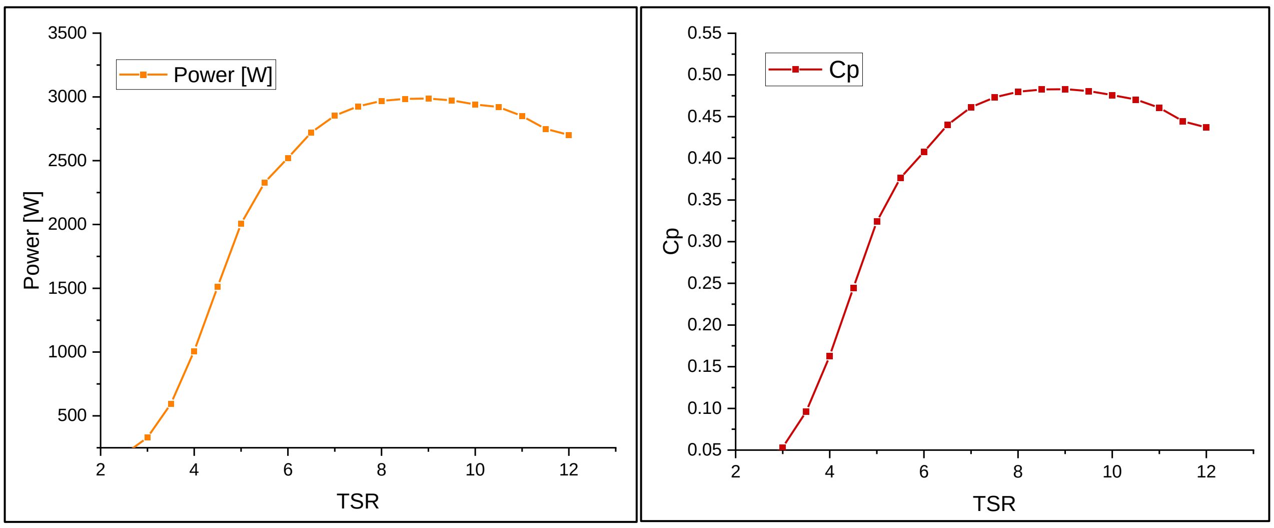


Figure III. 6 wind turbine power at different rotation speed for E387 airfoil



(a) (b)

Figure III. 7 wind turbine a) power, b) Cp with TSR for E387 airfoil

3.2 Designed blade by NACA 4412 airfoil:

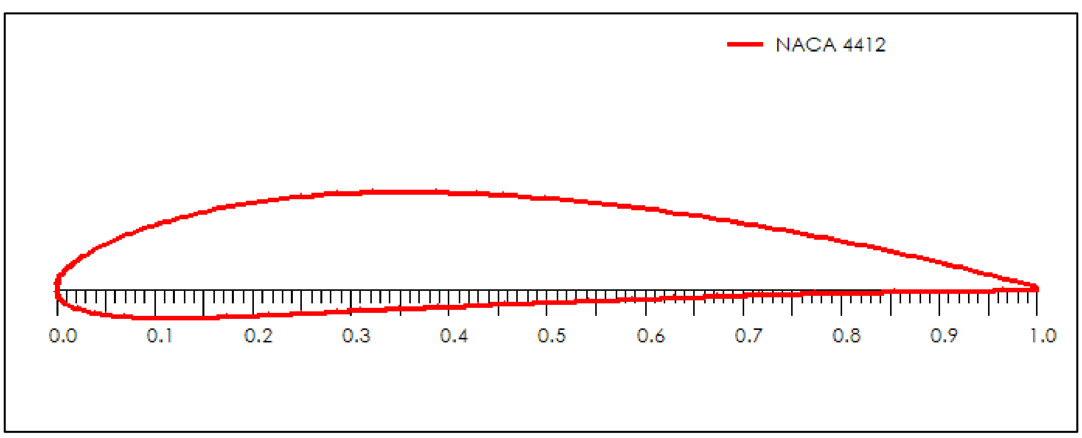


Figure III. 8 The cross-sectional shape of the wing: NACA 6409

Table III. 3 blade shape of NACA4412 airfoil section segment

Section	Position(m)	Airfoil
1	0,00	Circle
2	0,01	Circle
3	0,20	NACA 4412
4	0,40	NACA 4412
5	0.60	NACA 4412
6	0.80	NACA 4412
7	1.00	NACA 4412
8	1.20	NACA 4412
9	1.40	NACA 4412
10	1,60	NACA 4412
11	1.80	NACA 4412
12	2.00	NACA 4412

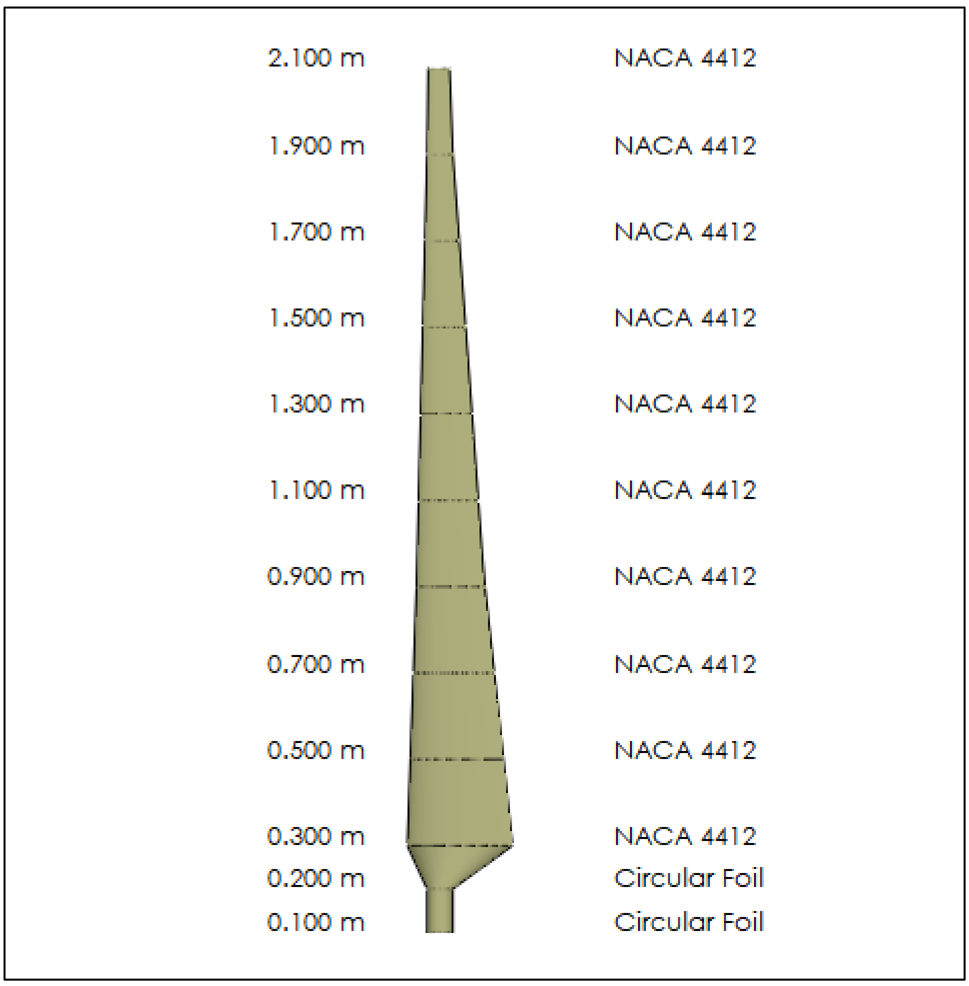


Figure III. 9 wind turbine designed with the NACA 4412 airfoil.

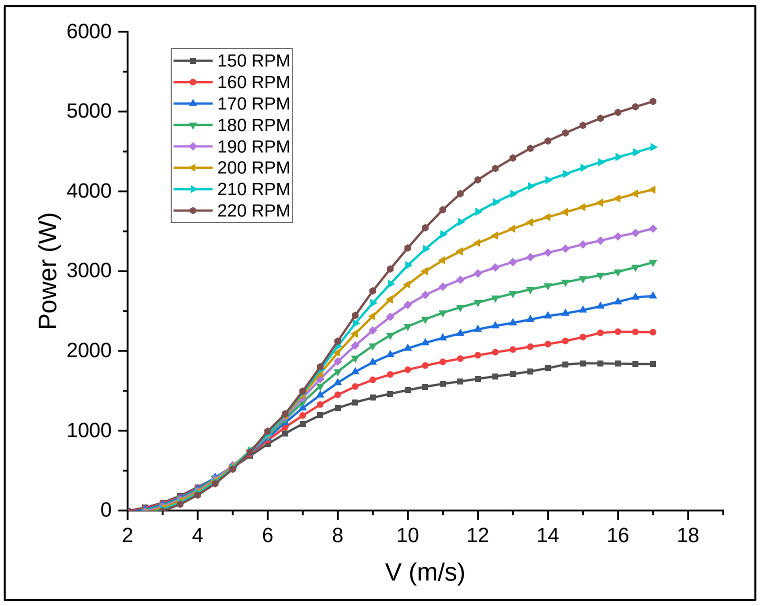
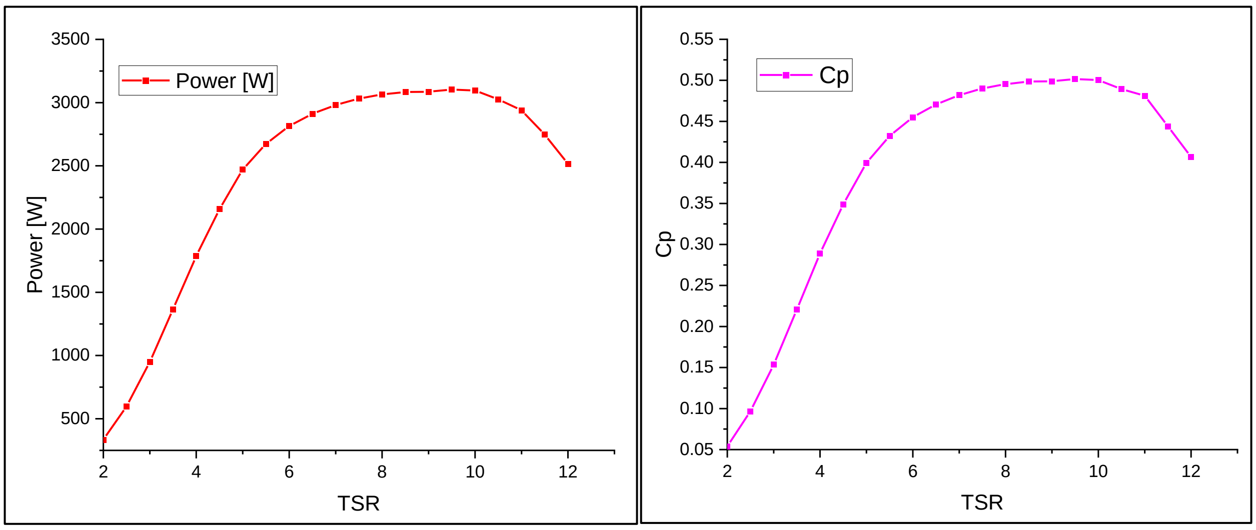


Figure III. 10 wind turbine power at different rotation speed NACA4412



(a) (b)

Figure III. 11 wind turbine a) power, b) Cp with TSR for NACA4412 airfoil

3.3 Designed blade by NACA 6409 airfoil:

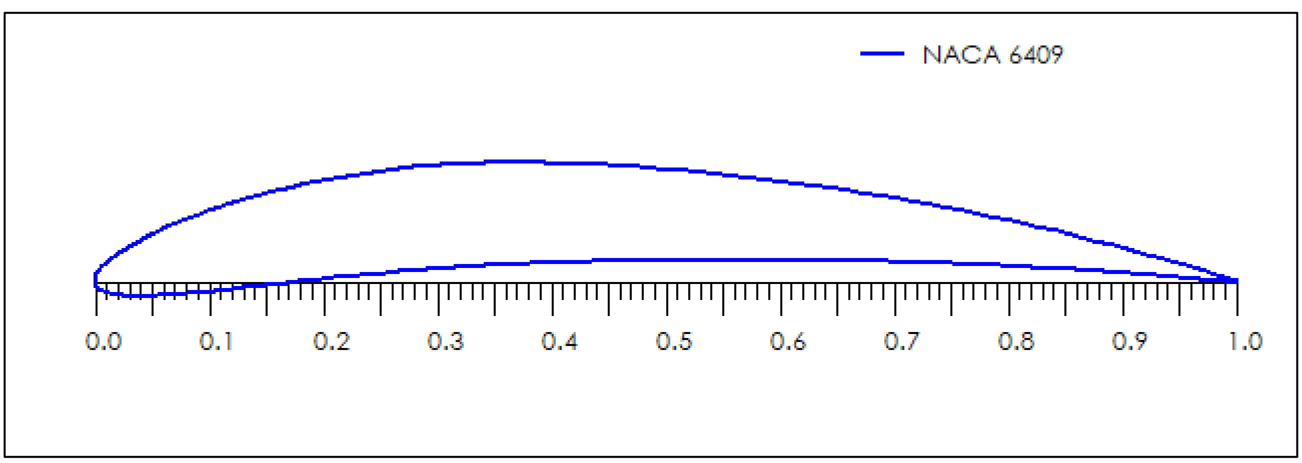


Figure III. 12 The cross-sectional shape of the wing NACA 6409

Table III. 4 blade shape of NACA6409 airfoil section segment

Section	Position(m)	Airfoil
1	0,00	Circle
2	0,01	Circle
3	0,20	NACA 6409
4	0,40	NACA 6409
5	0.60	NACA 6409
6	0.80	NACA 6409
7	1.00	NACA 6409
8	1.20	NACA 6409
9	1.40	NACA 6409
10	1,60	NACA 6409
11	1.80	NACA 6409
12	2.00	NACA 6409

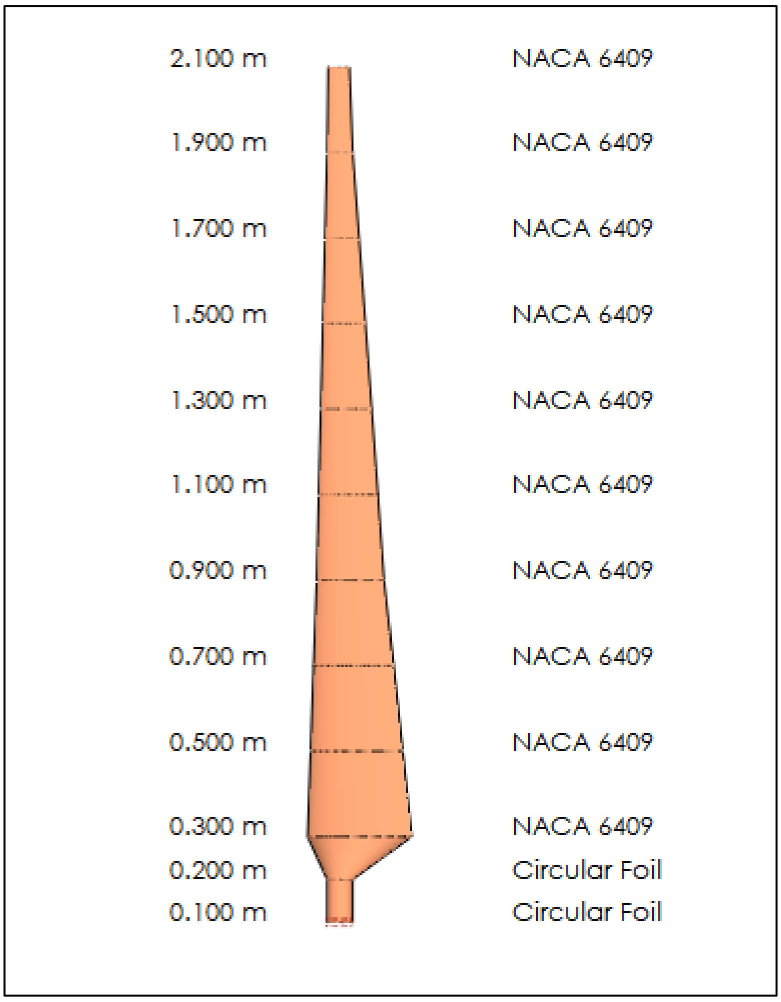


Figure III. 13 wind turbine designed with the NACA 6409 airfoil

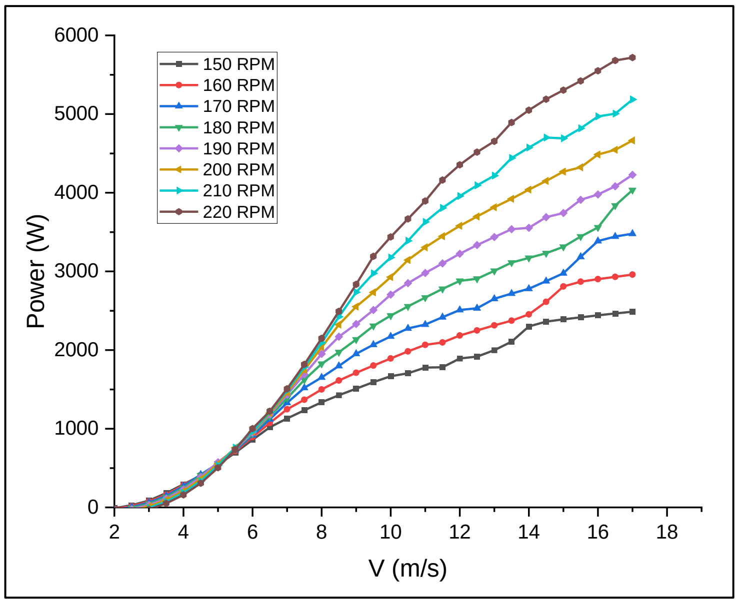


Figure III. 14 wind turbine power at different rotation speed for NACA6409

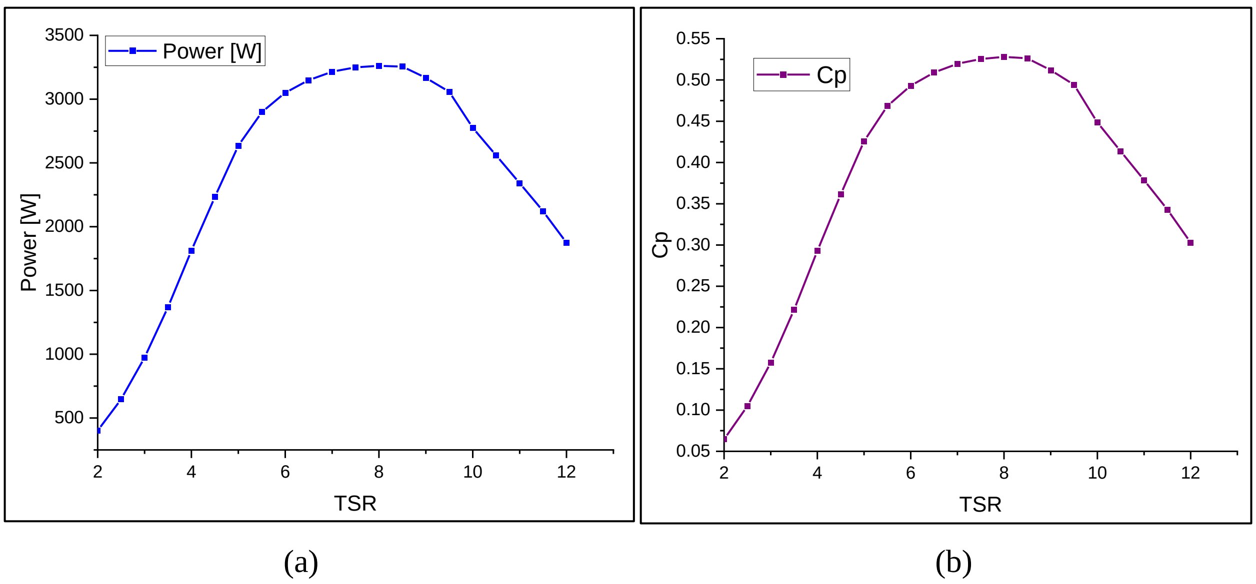


Figure III. 15 wind turbine a) power, b) Cp with TSR for NACA6409 airfoil

3.4 Designed blade by S-818 airfoil:

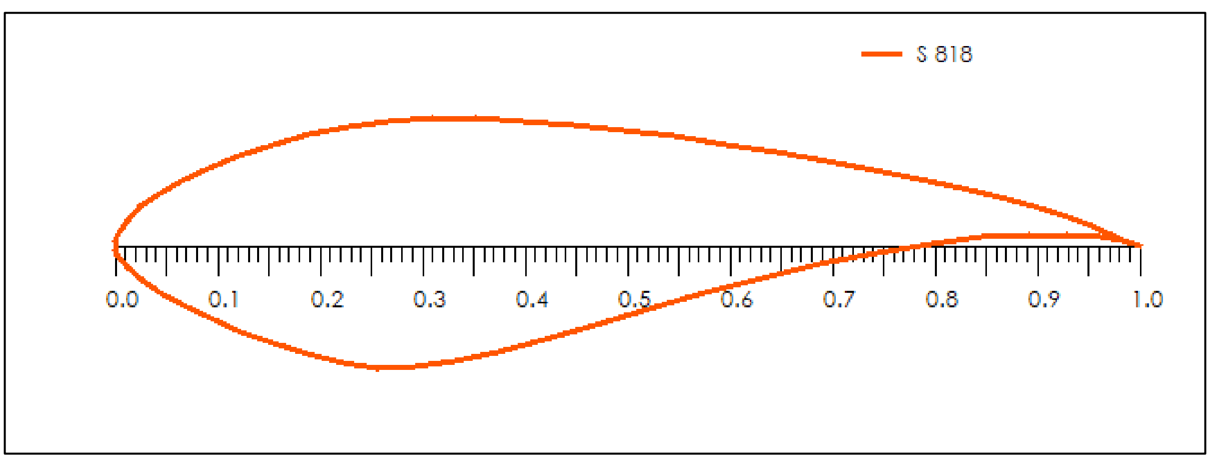


Figure III. 16 The cross-sectional shape of the airfoil S-818

Table III. 5 blade shape of S818 airfoil section segment

Section	Position(m)	Airfoil
1	0,00	Circle
2	0,01	Circle
3	0,20	S-818
4	0,40	S-818
5	0.60	S-818
6	0.80	S-818
7	1.00	S-818
8	1.20	S-818
9	1.40	S-818
10	1,60	S-818
11	1.80	S-818
12	2.00	S-818

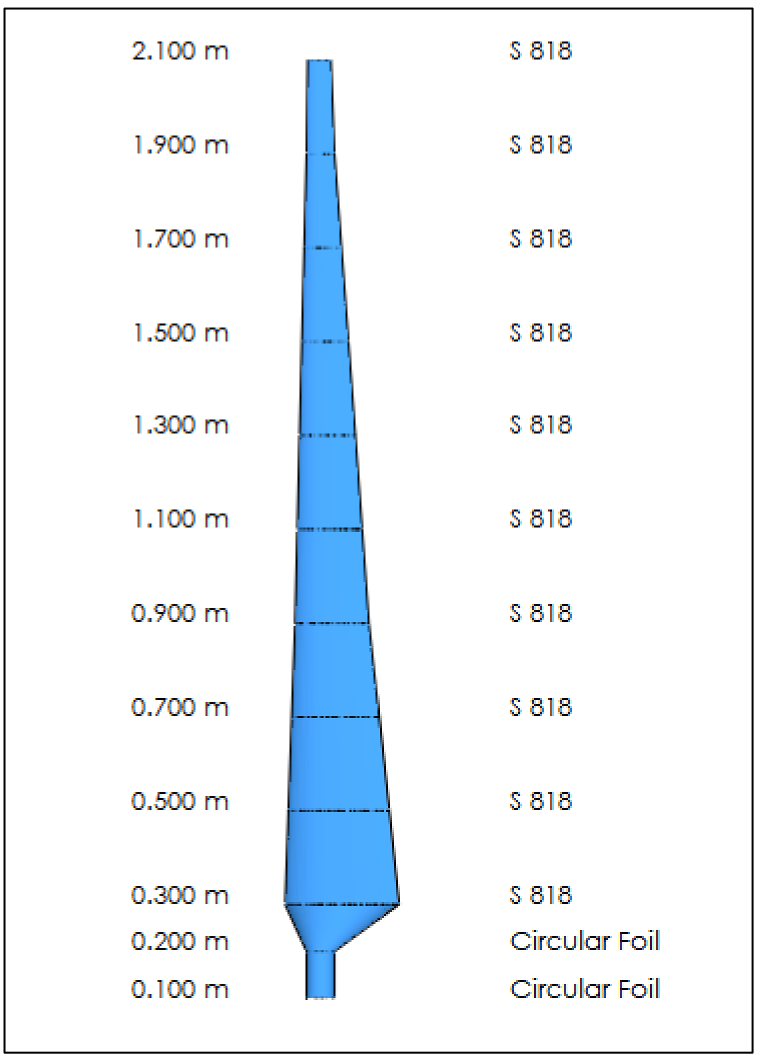


Figure III. 17 wind turbine designed with the S818 airfoil

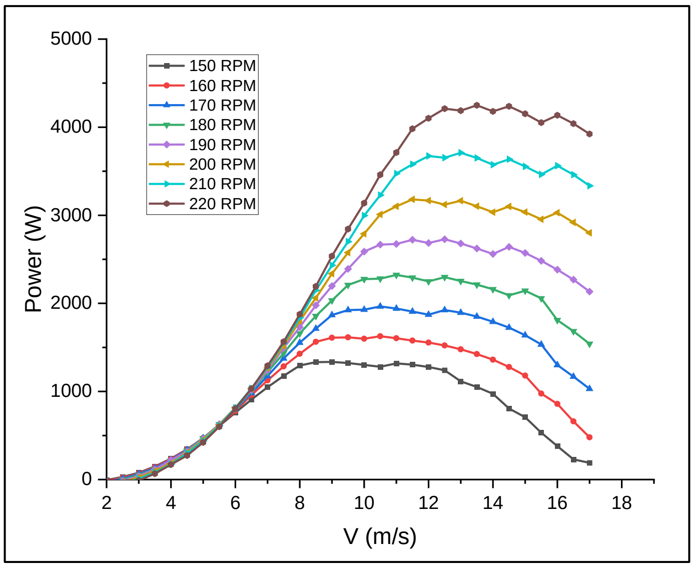
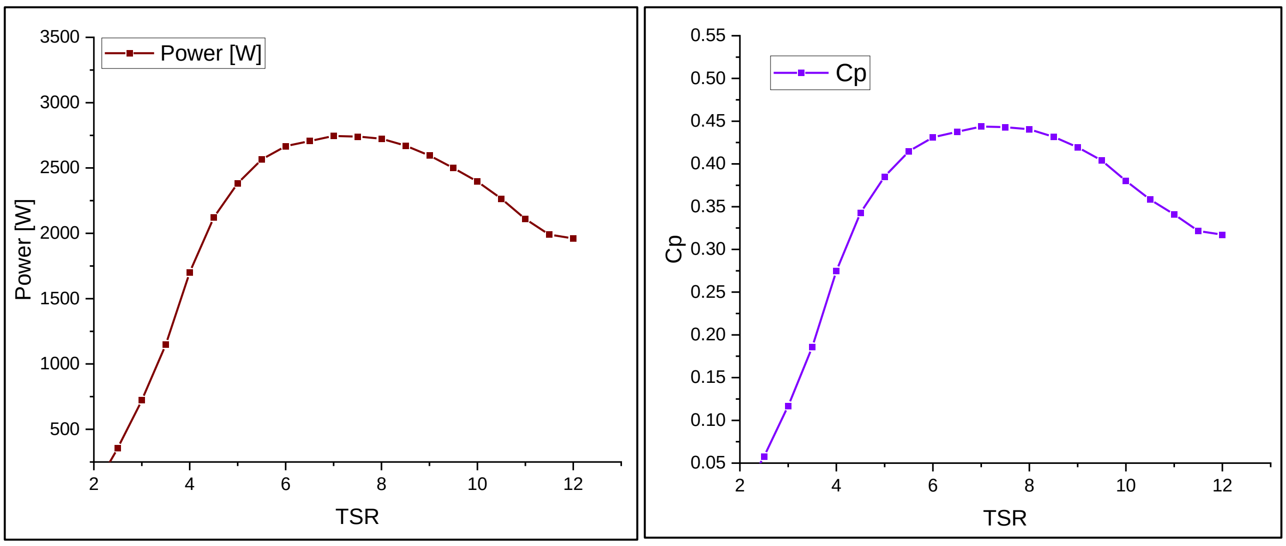


Figure III. 18 wind turbine power at different rotation speed for S818 airfoil



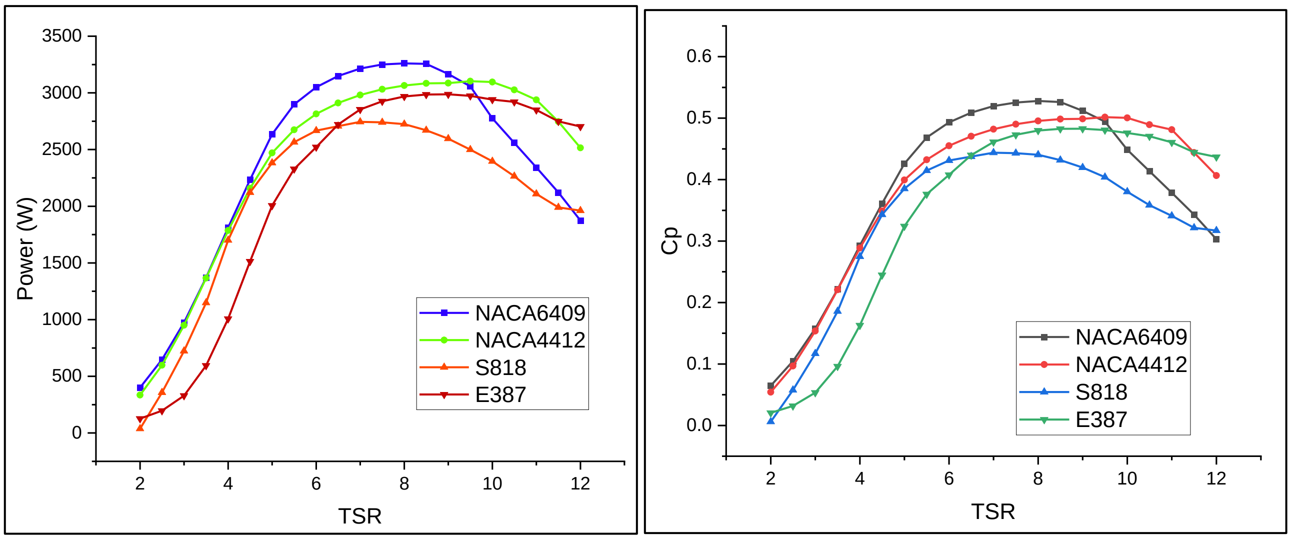
(a) (b)

Figure III. 19 wind turbine a) power, b) Cp with TSR for S818 airfoil

3.5 Comparison Between Different Design:

At this stage, we will compare different designs to determine the most efficient blade in terms of power coefficient or power output by collecting the power coefficient and power curves of the blades studied.

As can be seen from Figures III.20-(a) and (b), the airfoil significantly impacts the blade's power output, playing a key role in aerodynamic design. The results reveal that the best design was the NACA 6409 airfoil, which provided the highest power coefficient and the highest power. The NACA 4412 airfoil came in second, with a slightly lower power coefficient. As the graphs show, if the TSR is less than 5, the NACA 6409 airfoil closely matches the NACA 4412. If the TSR is between 4 and 5, the S818 airfoil also closely matches them.



(a) (b)

Figure III. 20 wind turbine a) power, b) Cp with TSR for all airfoil

4 CONCLUSION:

Based on the comparative analysis of the power coefficient (Cp) and the lift-to-drag ratio (Cl/Cd) for the four selected airfoils, it can be concluded that airfoil NACA6409 exhibits the highest efficiency for wind turbine blade design. This airfoil demonstrates superior aerodynamic performance over a broad range of angles of attack, which is crucial for maintaining stable and efficient energy conversion under varying wind conditions. Its favorable aerodynamic behavior suggests that it can contribute significantly to maximizing the power output and improving the overall performance of the wind turbine. Consequently, airfoil NACA6409 is a reliable and effective choice for modern wind energy systems, especially in environments characterized by fluctuating wind speeds and directions.

General Conclusion

GENERAL CONCLUSION:

The growing energy demand worldwide is driving us to seek alternatives and new energy sources. Renewable energy sources are an effective resource to meet energy needs. Wind is among the largest sources of renewable energy, as it is available everywhere and at all times. Harnessing wind energy with wind blades is of paramount importance, which is why we focused our work on one of the most important of these sources: small wind turbines, which are suitable for agricultural and domestic use. In this study, we optimized a 3-kW wind turbine blade by improving the aerodynamic shape. We selected four commonly used airfoils to construct the blade structure: the NACA 6409, NACA 4412, S818, and E387.

After analyzing the performance of the airfoils studied and comparing the various lift coefficients, drag coefficients, and lift-to-drag ratios, we found that the NACA 6409 airfoil was the best, yielding a value of Cl/Cd 120 at an angle of attack of 6 degrees. This was followed by the NACA 4412 airfoil with a value of Cl/Cd100 at an optimal angle of attack of 7 degrees, followed by the S818 airfoil and the E387.

A power analysis of wind turbine blades provides a clearer and better analysis for determining the appropriate airfoil for the design shape. Therefore, we designed the blade using the aforementioned airfoils to determine which one is most suitable for the blade design. The obtained power factor and blade output power results revealed that the best airfoil was the NACA 6409, which achieved a power coefficient of 0.52 and a maximum power of 3,200 W at TSR 7. The NACA 4412 airfoil achieved a power coefficient of 0.5 and a maximum power of 3,000 W at TSR 8. The S818 airfoil achieved a power coefficient of 0.45 and a maximum power of 2,700 W at TSR 6. The E387 airfoil achieved a power coefficient of 0.47 and a power of 3,000 W at TSR 8.5.

Finally, the study and improvement of wind turbines play a significant role in building the future of renewable energy, as they are a clean energy source. This study is therefore of utmost importance, as it enhances the field of research and improvement of small wind turbines, highlighting the improvement of a 3-kW blade that can be used to generate energy for homes and farms.

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