OPTIMIZATION OF TURBINE BLADE PITCH ANGLE OF A HOMEBUILT TURBINE FOR MAXIMUM POWER OUTPUT

SAMMY GUTU MUGO

A thesis submitted to the School of Engineering and Built Environment in partial fulfillment of the requirements for the degree of Master of Science in Industrial Engineering and Management of Masinde Muliro University of Science and Technology

November, 2024

DECLARATION

This thesis is my original work and has not been presented for a degree in any other University or any other award.

………………………………… …………………………

Sammy Gutu Mugo Date

SEI/G/02/06

CERTIFICATION

The undersigned certify that they have read and hereby recommend for acceptance of Masinde Muliro University of Science and Technology a thesis entitled: ***Optimization of Turbine Blade Pitch Angle of a Home-built Wind Turbine for Maximum Power Output.***

………………………………………… ……………………….

Dr. Barasa H. Masinde, PhD **D**ate
Department of Mechanical and Industrial Engineering
Masinde Muliro University of Science and Technology

………………………………………… ……………………….

Dr. Peter T. Cherop, PhD **D**ate
Department of Mechanical and Industrial Engineering
Masinde Muliro University of Science and Technology

COPYRIGHT

DEDICATION

To my loving wife Gladys Mugo, and my two sons Elvis Mugo and Joseph Mugo

ACKNOWLEDGEMENTS

Firstly, I would like to express my gratitude to the Almighty God for his guidance and mercy throughout my academic career. Secondly, I would like to express my gratitude to my supervisors, Drs. Barasa Masinde and Peter Cherop, for their support and guidance; your constructive criticism and suggestions enabled me to produce quality work.

Lastly, I would like to express my gratitude to the late Prof. C K W Ndiema for his mentorship and support throughout my course work. Lastly, I would like to thank my friends and colleagues for their assistance and support throughout this project. Lastly, I would like to express my eternal gratitude to my entire family and friends for their encouragement and support during my time of study.

ABSTRACT

The increasing demand for renewable energy sources has led to a growing interest in wind energy as a viable and sustainable option. Home built wind turbines offer a cost effective and accessible way for individuals and small communities to generate their own electricity. However, optimizing the performance of these turbines is crucial to maximize their power output and ensure their efficiency and reliability Wind energy greatly reduces the world's dependence on fossil fuels (oil and natural gas) and is environmentally friendly. One of the most cost-effective alternatives of energy sources is wind power. This study used a horizontal axis wind turbine to investigate the optimal blade pitch angle that can give maximum electrical output. Specific areas of studies will be to identify the various pitch angles, then validate the pitch angels for the maximum power produced by the turbine. A proportional integral derivative pitch controller was used to establish blade pitch angles. Wind speeds of 3, 4, 5 and 6 m/s were run at every pitch angle respectively, and a maximum electrical power output was 1124.7W at a blade pitch angle of 16.8^0 when a wind speed of 6 m/s was used. Every wind speed had was run for 100 seconds. A simulation, using Visual Basic 6 software, was done at the respective blade pitch angles, and a wind speed of 6 m/s. The electricity produced was recorded. The simulated electrical power produced yielded a relationship that predicted the electrical power output with a coefficient of determination (R^2) of 0.9752; this shows a very close agreement with actual electric output values. It is recommended that a similar study be conducted to investigate maximum power output for vertical wind turbines.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF PLATES

LIST OF ABBREVIATIONS AND ACRONYMS

c_t	Torsion coefficient
v_t	Wind speed (m/s)
ω_t	Rational speed (rad/s)
t_o	Optimum torque
v_o	Optimum wind speed (m/s)
a	Rotor swept area [m^2]
c_p	Power coefficient
r	Maximum rotor radius (m)
p_{aero}	Aerodynamic power [W]
t_{rot}	Torsional rotation at the turbine's rotor [nm]
t_a	Aerodynamic torque [Nm]
t_g	Torque generator [Nm]
t_{aux}	Torque auxiliary [Nm]
j_g	Generator inertia [kg/m^2]
j_t	Rotor inertia [kg/m^2]
γ	Aerodynamic damping coefficient [n.m.s/rad]
c_{op}	Optimum power coefficient
b_t	Friction coefficient of turbine
ω_{rot}	Angular speed of rotor
η	Efficiency
λ	Tip speed ratio
λo	Optimal tip speed ratio
ρ	Air density (kg/m^3)
θ	Pitch angle blade (°)
u	Hellman coefficient

CHAPTER ONE: INTRODUCTION

1.1. Background

Wind, like sunlight, moonlight, and rain, is an essential component of our daily lives. Life on Earth depends heavily on the wind. In 2018, the global community was urged by the Global Crisis Summit to look for new and renewable energy sources to replace traditional energy sources. Petrusevska (2022) distinguished and categorized wind energy as a form of renewable energy. In 2010, global wind turbine installation reached 30%, with a total capacity of 160 GW, led by the United States with 39 GW, followed by Germany and China with 26 GW (Dimitrov, 2010). For centuries, humanity has harnessed the energy of the wind through the ingenious construction of windmills, crafted from materials such as wood, cloth, and stone, primarily to facilitate the pumping of water or the grinding of corn. In the 19th century, the antiquated designs, characterized by their substantial size, weight, and inefficiency, were supplanted by fossil fuel engines and the establishment of a nationally distributed power network. An enhanced comprehension of aerodynamics, coupled with significant advancements in materials—especially polymers—has facilitated the resurgence of wind energy extraction during the latter half of the 20th century. Devices harnessing wind power are currently employed to generate electricity, commonly referred to as wind turbines. The alignment of the shaft and the axis of rotation serves as the primary criterion for categorizing wind turbines.

Wind power is an environmentally benign and sustainable energy source (T Ming et al., 2016). It significantly reduces the world's reliance on oil and natural gas while not damaging the environment (X Zhang et al., 2015). This study looked into the optimal wind turbine pitch angle for maximum electrical power generation. The design parameters were selected and adjusted for Kenya's specific environmental circumstances.

The way the air responds to varying pressures across the globe is known as wind. Wind is the flow of air that equalizes these differing pressures. This phenomenon is explained by the second rule of thermodynamics, which states that every system strives for the largest entropy possible (Bergman, 2011; Eastop & McConkey, 1994).

Air pressure is often higher at the equator than it is at the poles. The warmer temperatures in the tropical areas are the primary cause of this. Different wind speeds can be caused by a variety of factors, such as the sun, clouds, temperature, humidity, and topography. These criteria dictate that winds in the northern hemisphere should originate from the south. But the wind from the south blows east because of coriolis force (Liu et al., 2019). According to Burton et al. (2011), the Coriolis force is the inertia acting on moving objects within a rotating frame of reference relative to an inertial frame.

Small horizontal-axis wind turbines (SHAWTs) must be installed in areas with limited wind resources. According to Culotta et al. (2015), SHAWTs are defined as those that produce a voltage of less than 1000V AC or 1500V DC and have a swept area of less than 200m2. A cut-in wind speed of 4 m/s is another characteristic of SHAWTs (Clarke and Eng, 2018; El Zein, 2019). According to Davis et al. (2023), at a height of 10 meters above the earth, the average wind speed over 50% of the planet is 6.04 meters per second. Buildings, trees, and mountains all stand at this height and obstruct the wind's ability to flow freely. Due to these characteristics, the wind speed is reduced and turbulence increases, rising two to three times the height of the obstruction and two to ten times the frontal contact section (Martón et al., 2021; Martón Lluch et al., 2019).

1.2. Problem Statement

From the analysis of gaps in literature, most commercialized wind turbines are designed to operate efficiently at certain wind speeds; often-offshore wind speeds or wind speeds on elevated ground. This has prompted wind turbine designers to incorporate turbine kick-in and cut-off mechanism that ensure the blades do not operate at low wind speed. It is expensive and not feasible to implement such operational envelope for small wind turbines. Most wind turbines, however, are fitted with automatic pitch changing mechanisms to try and cover lower wind speeds, and are applicable to huge commercial turbines. This research aimed at filling this gap by systematically studying the relationship between the blade pitch angle and the power output in home-built wind turbines, and identifying the optimal pitch angle that maximizes power output. The aim of this study was to therefore to answer the key questions of systematically identifying the optimal pitch angle for max power output for a home built wind turbine.

1.3 Objectives

1.3.1 Broad objective

The broad objective was to optimize the blade pitch angle for a home-built wind turbine that would give maximum electrical power output.

1.3.2 Specific objectives

1. To establish possible blade pitch angles of a wind turbine.
2. To determine the optimal blade pitch angle for maximum electric power output.
3. To validate the blade pitch angle and electrical power output.

1.4 Research Questions

1. How can various blade pitch angles be established?

2. Can an optimum pitch angle be determined for maximum electric power production?
3. Can a relationship be established between the blade pitch angle and the electric power output?

1.5 Justification

A home-based wind turbine can be used in homes to generate power for domestic use. wind energy is a clean source of fuel, which means it does not produce environmental emissions of greenhouse gases (Kalyani *et al.*, 2015).

Wind energy is sustainable and reliable. This means as long as the sun rises and heats the earth surface and the earth will rotate, the movement of heating the earth surface and the earth rotation generate wind (Kazimierczuk, 2019; Mukulo *et al.*, 2014; Takase *et al.*, 2021).

Wind energy is cost effective; materials used to fabricate a domestic wind turbine were readily and cheaply available thus making power cheaper by four to six cents per kilowatt-hour as compared to the electricity from the grid (Council, 2017; Kanyako and Baker, 2021; Rajesh Karki and Roy Billinton, 2004).

Over the past few years, there has been a 35% annual average growth in the use of wind energy worldwide. The main wind energy investors are from Europe, China, the United States, Germany, and India. The demand for solutions to combat global warming, combined with technological advancements and economies of scale, has made wind energy the most likely alternative to replace nuclear and fossil fuels (Long et al., 2023; Tingzhen Ming et al., 2016; Saidur et al., 2010).

An optimal pitch angle allows the blades to capture wind energy efficiency and convert it into mechanical power maximizing the turbine output. Incorrect pitch angles can lead to inefficiencies, reduced power generation and increase mechanical stress resulting in higher maintenance cost and shorter turbine life span. Furthermore this study contributed knowledge in the field of renewable energy, especially wind energy.

1.6 Scope and Limitations

This study concentrated on small horizontal axis wind turbines. they have blades that are shaped aerodynamically to allow the wind to flow over and under the blade; thereby creating different pressures on the top and bottom causing a force that pushes the blade upward and a drag that slows down the blade (Burton *et al.*, 2011).

The main constraint was extraneous. It is impossible to effectively control natural variables such as wind speed and humidity. Other limitations included lack of accurate equipment for measuring the speed of wind, difficulties in calibrating equipment to ascertain their precision because there were no benchmarks, the high cost of leasing the equipment for research.

1.7 Conceptual Framework

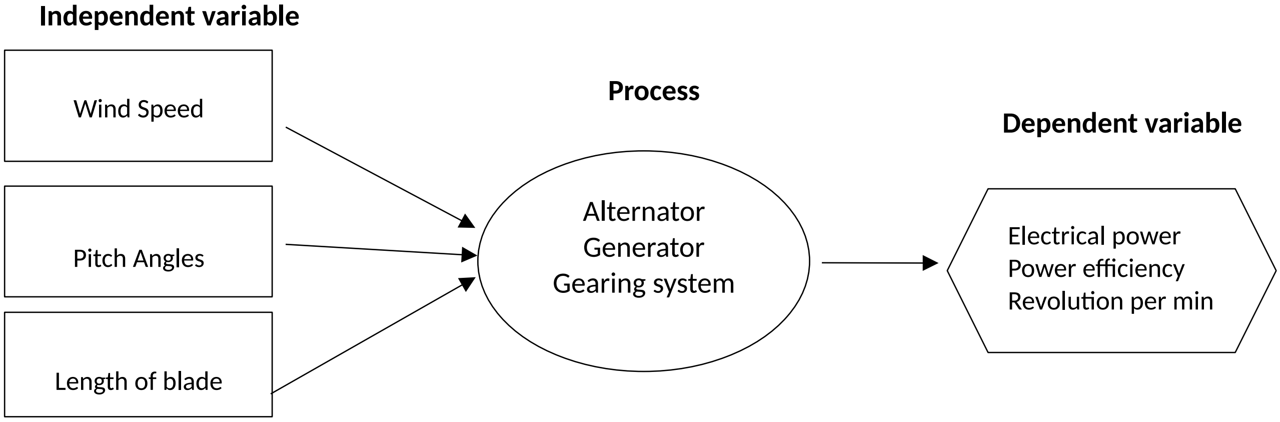

Figure 1. 1: Conceptual Framework

CHAPTER TWO: LITERATURE REVIEW

2.1 Introduction

One environmentally beneficial energy source is wind power. There is no soil, water, or air pollution produced by wind turbines. There will be no release of dangerous gases into the air, unlike fossil fuels. It is these fossil fuels that are responsible for the greenhouse effect and the warming of the planet (Mathew, 2022; Todorov and Vukov, 2010). According to some estimates, one 750 kW wind turbine keeps as much carbon dioxide from going into the air as 500 acres of forest could soak up. (Long *et al.*, 2023; Sherman, 2007). Wind power is a form of renewable energy. Wind is the primary source of energy; it is accessible everywhere and provides no cost. Outside, one can perceive the forces of the wind by standing, walking against the wind, or riding a bicycle. The force of a strong wind is demonstrated by the objects it moves. Recent years have witnessed an increase in interest in wind energy power systems due to the economic and environmental benefits associated with fuel savings (Tingzhen Ming et al., 2016; Senjyu et al., 2007). Wind energy will never require importation. The anticipated lifespan of oil and natural gas reserves is around sixty years (Sijmons and Van Dorst, 2012). 88% of the world's electricity is currently derived from fossil fuels, whereas coal reserves can endure for around 200 years (Jacobson et al., 2017).

Our predecessors were among the first to see the immense potential of wind energy.

Throughout antiquity, wind was utilized for a multitude of reasons. Wind power to utilize for sailing ships. This occurred because powerful winds would blow from the coast to the sea and occasionally the winds would blow from the sea to the coast. The first sail ship was by the Egyptians. it was built in 1500 B.C. and it initially sailed in the Nile river (Jacobson et al., 2017) (Jacobson et al., 2017) .

Plate 2.1: Egyptian ship (Tremblay, 1975)

The first ship having a horizontal rotation axis was constructed in Europe during the 12th century. In ancient times, wind was used to power windmills. Grain grinding was accomplished using windmills. Grain grinding was extremely difficult prior to the development of windmills (Tremblay, 1975). With the creation of the wind, people no longer had to work as long for their daily food, allowing them to devote more time to other household activities such as handcrafting or gardening.

Philo of Byzantium created the watermill in the third century B.C. using the windmill concept, which advanced humankind (Burton et al., 2011). In addition to milling grain, windmills were also utilized for drilling, sawing, and pumping.

In 3000 B.C., the Egyptians developed and sailed boats using wind power for the first time (Burton et al., 2011). The first windmill was constructed in Persia, or modern-day

Iran, around 900 A.D. Throughout Europe, windmills were being utilized for grain grinding and water pumping by 1100 (Schöbel-Rutschmann, 2008). Eventually, windmills were changed to cut lumber (Riziotis et al., 2004). Charles F. Bush invented the first wind turbine in Ohio in 1888, and it produced electricity. In 1891, Danish inventor Poul la Cour invented the modern wind turbine (Burton et al., 2011).

Plate 2.2: Windmills in the Netherlands

Adopted from Sherman (2007)

2.2 Types of wind turbines

Wind turbines are divided into two main categories. Vertical turbines can be horizontal or vertical. Every class has its own variations, benefits, and drawbacks. The following is the outline.

2.2.1 Vertical axis wind turbines

The primary feature of vertical axis wind turbines, or VAWTs, is a rotor shaft oriented perpendicular to the direction of the wind.

Plate 2.3: VAWTs in a building rooftop

Adopted from Sherman (2007)

The primary benefit of this kind of turbine, according to Kumar et al. (2018), is that it does not need to be oriented into the direction of the wind. In regions where the wind is erratic, this kind of wind turbine is appropriate. In order to reduce weight on the tower and facilitate maintenance, the generator and the other parts are positioned close to the ground. When a wind turbine is installed on a rooftop, the wind is directed over the roof by the building, which doubles the wind speed, bringing the wind turbine close to maximum wind energy and lowest wind turbulence. The fact that a yawing system is not required is an additional benefit (Bhutta et al., 2012). It starts at a substantially slower pace than a wind turbine that is horizontal (Ragheb, 2011). VAWTs depend more on whether there is any wind at all than on the direction of the wind (Johari et al., 2018; Pope et al., 2010). It is possible to construct VAWTs near the ground (Möllerström et al., 2019).

Howell et al. (2010) noted that VAWTs can be extremely unstable, making it impossible to place them on towers; as a result, the only options available to them are to mount them close to the ground or on a rooftop. They are situated at lower altitudes than HAWTs, thus they produce less energy (R. Kumar et al., 2018). Extremely turbulent wind can create vibrations and noise at low altitudes, which can harm turbine components and reduce their lifespan (Kinzel et al., 2012). They are unstable and require a lot of upkeep (Tjiu et al., 2015). Because of theft, they also pose a security risk.

2.2.2 Horizontal axis wind turbines

Horizontal axis wind turbines (HAWTs) account for the majority of wind turbines produced worldwide (Hansen and Butterfield, 1993). Their design is akin to a windmill's; their propeller-like blades create a rotor that revolves around a horizontal axis (Johari et al., 2018).

Plate 2.4: Classic HAWTs wind turbine with three blades

Adopted from Jacobson *et al.* (2017)

The primary drawback of HAWTs is the requirement to construct a sturdy tower in order to support the component weight (Rehman et al., 2018). This wind turbine's height can degrade the surrounding area, and the locals frequently object about it. Turbulence-induced wear and structural failure are problems for downwind kinds (Sørensen, 2016). In order to prevent the turbine from turning under strong winds, HAWT needs a brake system in addition to a mechanism to orient the rotor (Lignarolo et al., 2014). The cost of installation and shipping is high. It may account for up to 20% of the cost of the materials and equipment.

However, it is possible to capture power from greater winds by positioning the rotor near the top of the tower (Xu and Sankar, 2000). The available power increases by 34% and the wind speed by 20% for every 10 meters of height gain (Burton et al., 2011). According to Sørensen (2016), HAWT turbines are highly efficient due to the fact that they obtain electricity from the entire blade revolution. Optimal blade angle of attack is determined by varying the pitch angle of the blade (Chavero-Navarrete et al., 2019). They are powerful and generate more energy (R. Kumar et al., 2018).

Although fiberglass is the most common material used to make wind turbine blades, steel or wood can also be used. The blade is referred to as an airfoil because of its similar form to that of an airplane. The aerodynamic design of the blades allows wind to pass over and under them, resulting in differential pressures at the top and bottom that provide lift. The blade is forced upward by this force. The force that slows the blade down is called drag. The blade is pushed downward by this force (Burton et al., 2011).

Certain wind turbines can have their blade pitch angle changed to increase their energy output. According to studies, the most variable energy will be produced at a blade angle of 8° and a wind speed of roughly 13 miles per hour (mph) (Chavero-Navarrete et al., 2019). The study found that further investigation is necessary to determine the maximum power production and the relationship between power output and wind speed. Additionally, it was mentioned that the wind will not always blow at 13 mph. Wind turbines may adjust the angle of their blades to suit the surrounding conditions, as demonstrated by Liu et al. (2019). The blade angle at 15° is another angle that studies have discovered to be effective (Savino et al., 2017). This indicates that opinions regarding which angle yields the most energy are divided. Research has indicated that the wind turbine's energy output is contingent upon both its position and the speed of the wind at that specific area (Karthikeyan et al., 2015).

2.3 Wind turbine evaluations

It was evident which sort of wind turbine to use after reading the explanation of the several varieties above. The parameters utilized to narrow down to the type of wind turbine used in this study were identified by Chian et al. (2018) in a comparative analysis. The requirements include affordability and high efficiency, design flexibility, information accessibility, resilience to the environment, and ease of manufacturing.

Table 2.1: Summary of different models of wind turbines

Wind turbine type	Main characteristics
HAWT	o High efficiency o Most used.
Darrieus	o High robust o Good efficiency
Savonius	o Simple design o Small-scale applications
Giromill	o Cheap o Simple design o Only suitable for small power requirements

Source: Chian *et al.* (2018)

Table 2.2: Decision-table with the evaluation criteria

Item	HAWTs	VAWTs
Efficiency	4	3
Global cost of installation and transportation	2	4
Flexibility of the design	4	1
Ease of manufacture	4	3
Cost of materials	3	3
Weather resistance	4	1
Total	21	15

Source: Chian *et al.* (2018)

2.3.1Axial stream around the wind turbine

Burton et al. (2011) describe the wind turbine blade calculation approach in Plate 2.5 below; this method is utilized for both the analysis of current machines and the design of new ones. The design technique can be accomplished by utilizing blade element momentum theory, together with a spreadsheet and the lift and drag curves specific to the chosen airfoil. Based on the study shown in Table 1, it was concluded that the HAWT wind turbine design was the most suitable choice for the project.

As seen in Table 2.2, the HAWT performed better than the VAWT in nearly every category. The versatility of the design is the main benefit of utilizing a horizontal axis wind turbine. The models used in VAWTs are extremely accurate and do not permit significant changes.

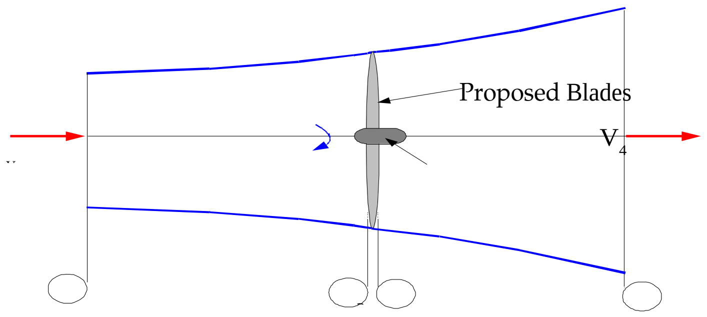

Figure 2. 1: Axial stream around a wind turbine

Adopted from Burton *et al.* (2011)

Figure 2.1 displays the dispersion of wind patterns. It provides us with information on both the average wind speed and the frequency at which various wind speeds occur. Wind pattern is significant because it was used to calculate the ideal rotor motor diameter, wind turbine generator profiles to get the desired power, and the greatest feasible relationship between turbine costs and captured wind (Karthikeyan et al., 2015). The wind's direction is another crucial factor regarding the wind turbine. This is crucial since the wind is influenced by the topography and other natural elements. When developing a wind park with multiple turbines, shadowing is an important factor to take into account (Zou et al., 2020). Because the turbine removes energy from the wind, the wind moves more slowly behind a turbine than in front of one. Additionally revolving is the air behind the turbine. For a turbine to operate efficiently, it is therefore not a good idea to place one turbine behind another. Consequently, the wind turbine's placement is crucial. When the wind is blowing from this main direction, the turbines should be placed in a wind park where they can be exposed to the least amount of shadowing.

Because the turbine removes energy from the wind, the wind moves more slowly behind a turbine than in front of one. Additionally revolving is the air behind the turbine. For a turbine to operate efficiently, it is therefore not a good idea to place one turbine behind another. Consequently, the wind turbine's placement is crucial. When the wind is blowing

from this main direction, the turbines should be placed in a wind park where they can be exposed to the least amount of shadowing.

2.3.2 Weibull curve

The most popular mathematical representation of the distribution of the various wind speeds is a Weibull curve (Elmahdy, 2015).

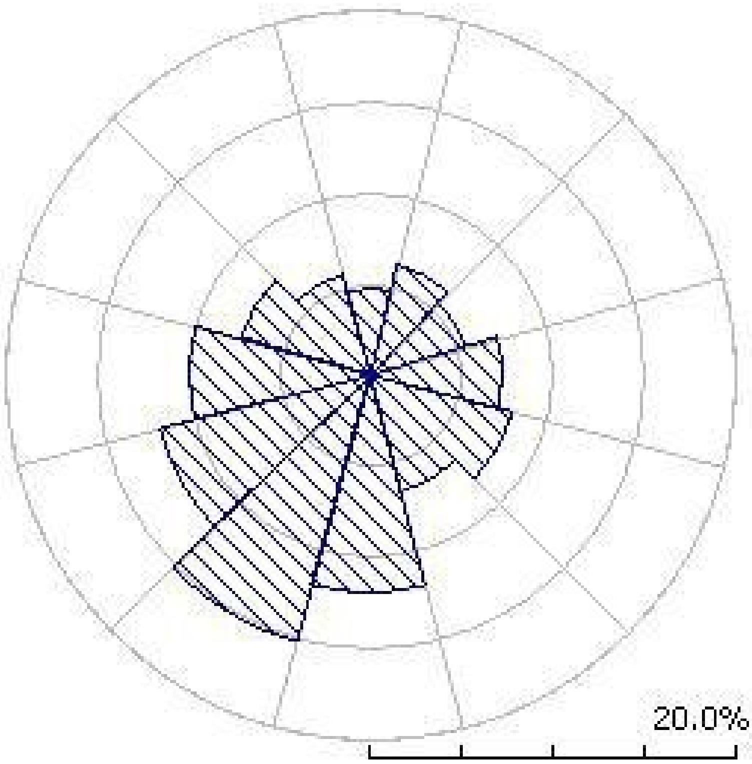

Figure 2. 2: Distribution of the wind direction

Adopted from Biegel *et al.* (2011)

Ernst Hjalmar Waloddi Weibull is honored in the curve, which depicts the pattern of wind distribution. When characterizing the drop out ratio over a wind turbine's lifetime using the distribution of wind power, the Weibull curve is employed (Pedrosa et al., 2020). Knowing the location's shape factor (k) and average wind speed (a) is necessary to calculate the likelihood of a given wind speed (Kohout, 2022). The wind speed variability is described by the form factor, k, which is comparable to the terrain's roughness. This is often different from consistent wind speeds observed on an open sea from varying wind speeds found in mountainous areas. According to Hadiana et al. (2017)'s study, the wind data collected at the research site facilitated the design of a low-cost, user-friendly 500W wind turbine that can be utilized in places without grid power. The Kinangop area, where the majority of the population lacks access to the national grid for electricity, was a good fit for the concept.

Table 2.3: Average wind speed

Place/ station	Country	Wind speed
Alger-port	Algeria	6.68
Bahrain-Airport	Bahrain	5.14
Hurghada	Egypt	8.23
Cairo-Airport	Egypt	7.20
Aqaba	Jordan	5.14
Homs	Libya	8.23
Alhoceima	Morocco	6.17
Tanger-Airport	Morocco	5.65
Tetouan	Morocco	5.14
Walvisbay-Airport	Namibia	6.68
Dakar	Senegal	4.62
Mtwara	Tanzania	6.17
Dar es salaam	Tanzania	5.14
Bizerte	Tunisia	6.17
Kelibia	Tunisia	5.14
	Average	6.10

Source: Chian *et al.* (2018)

CHAPTER THREE: MATERIALS AND METHODS

3.1 Introduction

In this study, power was produced using an existing model of a horizontal axis micro wind turbine. The turbine's parameters are displayed in Table 3.1 below:

The wind turbine operated effectively under the above conditions and specifications. The material used to make the blade was fiberglass, the pole was made of a hollow steel rod, the turbine consisted of an alternator, and the tail wing was made of cardboard laminated with fiberglass. All these materials were affordable and readily available. The setup was done in Kinangop area, where there was no access to electricity from the power grid. the wind speed/ velocity was between on average 3m/s, 4m/s, 5m/s and 6m/s as per the meteorological department as shown in Table A1.1. An alternator was used to generate current. The alternator was connected to a battery. The battery converted the alternating current (AC) to direct current (DC).

3.2. Materials

Plate 3.2 show the main components of a horizontal axis wind turbine.

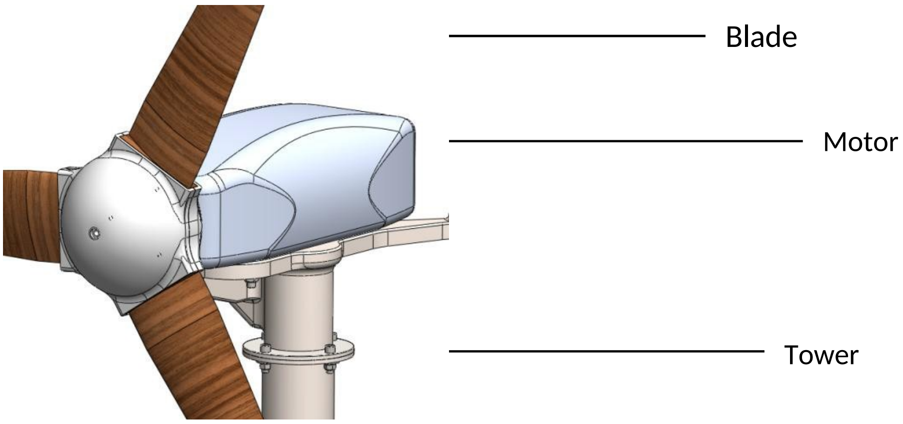

Plate 3. 1: Main components of the wind turbine.

3.3 Equipment

Table 3. 1: Wind turbine specifications

Item	Value	Item	Value
Rated power at 5m/s	500 W	Generator type	Plda50.pma
Blade diameter	1 m	Power rating	0.5 kW
Hub height	10 m	Voltage rating	14/28 V
Swept area of blade	0.785 m^2	Ampere rating	1.79/3,57 A
Rotor speed	20-500 rpm	Torque	< 0.15 Nm
Tower type	Tubular	Power efficiency	> 65%

The wind turbine comprises of the following parts:

Wind turbine blades

A rotor has three blades attached to it, and a motor shaft connects the rotor to the alternator. The wind causes the blades to revolve. The primary shaft that is attached to the rotor is rotated by the blades. The rotor generates power as it turns.

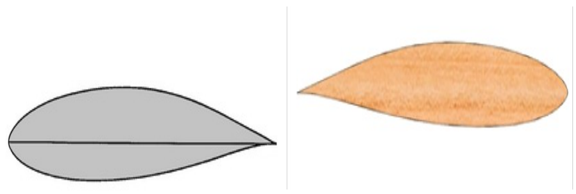

Plate 3. 2: Wind turbine blades size and profiles (Biegel et al., 2011)

i. Nacelle/ gear housing/alternator

   The nacelle/ gear housing carries the gear box which is connected to the main shaft, and the transmission axle which is connected to the alternator.

ii. Tower

The pole/ tower supported the nacelle. The pole was elevated to 6m height. The pole supported the whole housing of the blades, nacelle and the alternator.

iii. Voltmeter

The voltmeter was used to measure the output voltage from the turbine and also from the battery.

Plate 3. 3: Voltmeter.

iv. Anemometers are weather instruments that measure wind direction and speed. The wind's direction and speed were determined using the anemometer. It was positioned adjacent to the wind turbine and used to determine the wind's direction and speed. .

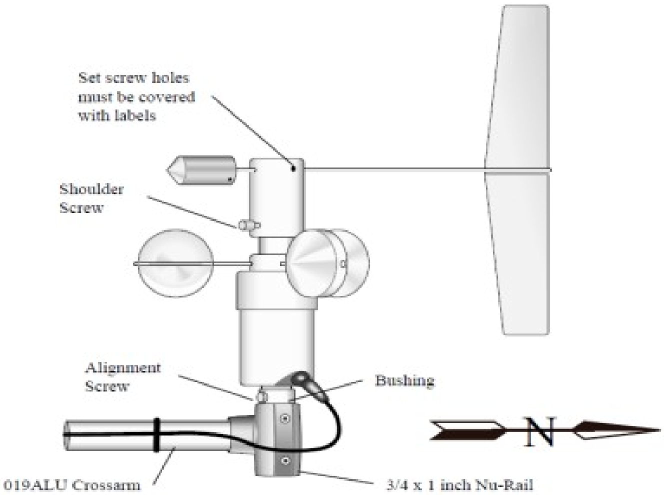

Plate 3. 4: Anemometer.

Adopted from Burton *et al.* (2011)

v. Ammeter: this device was used to gauge how much current the turbine was producing.

Plate 3. 5: Ammeter.

vi. Ohmmeter: it was used to measure output resistance from the alternator and the battery.

Plate 3. 6: Ohmmeter.

3.4 Site Study

The project was done in Kinangop area, Nyandarua County. the average speed of wind in this location is 6.2 m/s according to Porté-Agel *et al.* (2011). However, at the time of this study, the average wind speed was 6.3 m/s in the south-west direction. The area did not have tall buildings that would obstruct wind flow. The sky was clear and with an average temperature of 22^{0}C. Geographical coordinates for Kinangop are 37^0 40’ E, 36^0 42’ N.

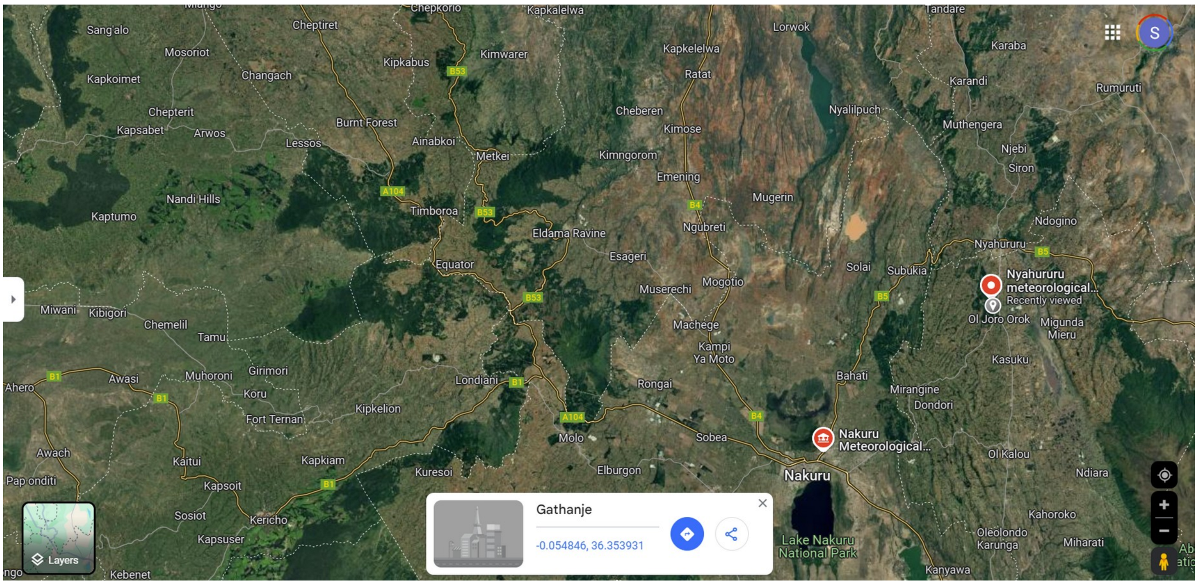

Figure 3. 1: Study site map

3.5 Experimental Set up

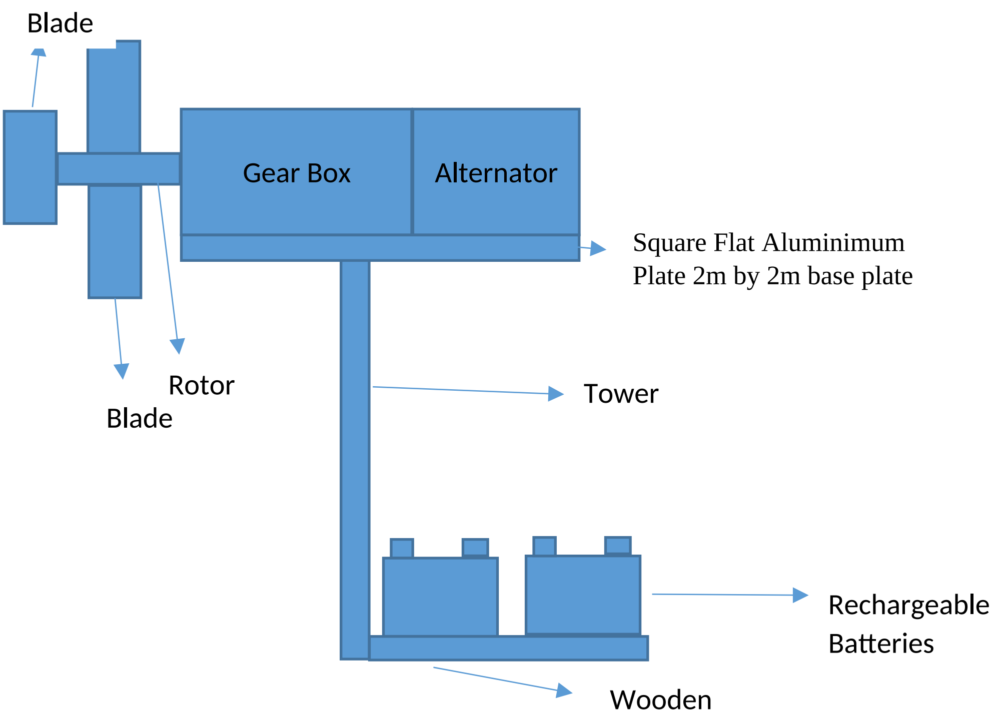

Figure 3. 2: Wind turbine assembly.

3.6 Experimental Procedure

The blades were casted with fiberglass and mounted into a mound the shape of a wind turbine. After 3 hours the mound was removed. Sharp edges were removed, and the blade was measured 2m and cut to the right length. Three holes were drilled on the blade and bolted to the shaft. The shaft was connected to the hub that was carrying the 3 blades. The alternator was then mounted to the housing and supported by the base plate. The housing was then screwed firmly the turbine tail (aluminium square plate) on the other end. The platform was then mounted to the tower. Using anemometer, the wind turbine was correctly positioned in the direction of the wind. The tower was installed into the ground firmly. Steel nails were used to secure the tower into the ground.

3.5 Methods

3.5.1 Specific objective one

To establish possible blade pitch angles of a wind turbine

i. The pitch angle controller software was based on proportional integral derivative (PID). The software was mounted onto the wind turbine set-up.

ii. An in-coming lowest wind speed of 3 m/s (herein called cut-in, c_{in}) was input into the software.

iii. An out-going maximum wind speed of 7 m/s (herein called cut-out, c_{out}) was input.

iv. The 3 m/s wind speed was run against the blades for 100 seconds.

v. A mathematical algorithm done by D. Kumar and Chatterjee (2016) in the software established the probable pitch angles.

Figure 3.2 shows a schematic diagram that explains the principle of working of a PID controller.

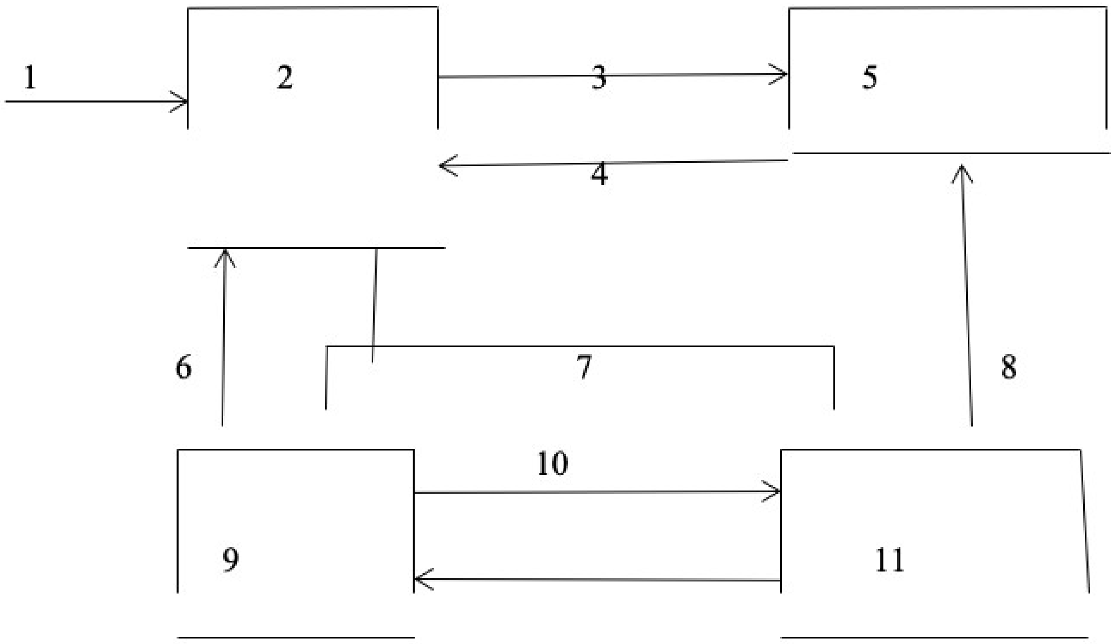

Figure 3. 3: Schematic diagram of a wind turbine coupled with a pitch angle controller.

Adopted from J. Zhang *et al.* (2008).

Key:

1. Wind speed
2. Wind turbine + generator.
3. Active power
4. Reactive power
5. Power converter
6. Blade pitch angle
7. Rotor speed
8. Power set point
9. Pitch angle controller.
10. Cross coupling
11. Speed controller.

Refer to figure 3.2 for the description.

The wind turbine's blades are driven by the force of the wind (1). 2. The power converter transforms the wind's kinetic energy into electrical energy by harnessing the movement of the blades, which in turn rotates the rotor connected to the generator (5). Active and reactive power are present between the generator and the power converter. A signal indicating the rotor speed is delivered to the PID controller and the speed controller (11) as the wind rotates the blades (9). A reaction through the cross coupling (10) activates the actuator in the PID controller that uses a mathematical algorithm to tilt the blades at a pitch angle (6).

3.5.2 Specific objective two

To determine the optimal pitch angle for maximum electric power output

i. The lowest pitch angle of 0.0^0 was set in the software to enable the blades to tilt at that angle when the wind blows.

ii. Wind speeds of 3, 4, 5, and 6 m/s were blown respectively against the blades for 100 seconds.

iii. The electrical power produced in every wind speed at a pitch angle of 0.0^0 was recorded.

iv. Steps 1, 2 and 3 were done for pitch angles of 5.6^0, 11.2^0, 16.8^0, 22.4^0, 28.0^0, 33.6^0, 39.2^0, 44.8^0, 50.4^0, 56.0^0, 61.6^0, 67.2^0, 72.8^0, 78.4^0, 84.0^0, and 89.6^0.

3.5.3 Specific objective three

To validate the blade pitch angle and electrical power output

i. Visual Basic 6 software was attached to the horizontal axis wind turbine (HAWT) to control and simulate blade pitch angle.

ii. The HAWT was run using a wind speed of 6 m/s for 100 seconds at every blade pitch angle to produce electric power.

iii. The measured data were presented in real time.

Note: Additionally, a recording data system based on Microsoft Office Excel linked with Visual Basic 6 was installed in the monitoring system.

CHAPTER FOUR: RESULTS AND DISCUSSION

In this chapter, the results are discussed exhaustively, and appropriate interpretations are made regarding the specific objectives of the research.

4.1 Effects of Blade Pitch Angle on Power Output.

The turbulent motion and variable speed of wind might hinder the optimal functioning of a wind turbine, potentially leading to its failure and severe repercussions (Ouyang et al., 2017). Measuring the angle at which the blade meets the wind helps in regulating the wind's impact on the rotor. This is why it is important to operate a wind turbine with adjustable speed (Menezes et al., 2018). Proportional integral derivative (PID) control is a recommended approach for adjusting the blade pitch angle of a wind turbine. The system operates by employing a mathematical algorithm that incorporates feedback from the regulated variable. This algorithm calculates the discrepancy between the desired and measured values (D. Kumar and Chatterjee, 2016). According to Noton (2014), the weights assigned to the integral time, derivative time, and proportional constant have an impact on the adjustment of the PID controller gains. The objective of fine-tuning optimal gains is to attain the desired control response. However, it is important to keep in mind that the appropriate response in a wind turbine with changing speeds depends on the extent to which the wind speed fluctuates. According to Chavero-Navarrete et al. (2019) and Sruthi et al. (2017), the fluctuation of wind speed can lead to instability in a PID controller.

The PID controller gave the following blade pitch angles: 0.0^0, 5.6^0, 11.2^0, 16.8^0, 22.4^0, 28.0^0, 33.6^0, 39.2^0, 44.8^0, 50.4^0, 56.0^0, 61.6^0, 67.2^0, 72.8^0, 78.4^0, 84.0^0, and 89.6^0. The mathematical method is based on an indirect power control (IPC) model and applies the maximum power point tracking (MPPT) system, which uses the optimal torque (Merabet et al., 2011). According to several studies (Abdullah et al., 2012; Ganjefar et al., 2014; Nasiri et al., 2014), this case involves controlling the generator's torque to reach an optimal torque (OT) reference curve. All of the studies that support the IPC model follow the same pattern: Bianchini et al. (2015), Molina and Mercado (2011), Neammanee et al. (2010), Schinas et al. (2007), and Muljadi and Butterfield (2001).

One further way to manage the pitch angle of a wind turbine so that it is less affected by wind speed is via a fuzzy logic controller (Xiao et al., 2015). After deciding whether the gains for the error are big, positive, or negative, the fuzzy logic controller (FLC) controls the desired pitch angle (Baburajan, 2018; Civelek et al., 2016). The controller's use of ANNs allows for the determination of the gain values (Kang et al., 2014). Alternatively, Taher et al. (2013) showed that, in "differential evolution," an optimization method can be used to update the PID gain values in reaction to changes in operating points.In order to change the proportional and integral gains of a proportional integral derivative controller, Behera et al. (2016) and Hodzic and Tai (2016) found that a "particle swarm" optimization method can be utilized. The PID parameters of the "flame-moth" optimization approach were the moth's position in a 3D search space, according to research by Ebrahim et al. (2018). Using an optimization strategy grounded in the classroom's teaching-learning paradigm, Chavero-Navarrete et al. (2019) calculated a PID controller's gains.

Each of these wind speed ranges requires a different controller modification, thus all of the above observations were taken to improve the control signal's response throughout those ranges. The fundamental problem with these approaches is the mechanical rotational speed of the pitch angle (Ouyang et al., 2017). D. Kumar and Chatterjee (2016) described a PID controller, but it was sufficient for the purpose of this study.

4.2 Identification of optimal Pitch angle for the Maximum Power output

The principle of working of a wind turbine is to capture kinetic energy from the wind, convert it into mechanical energy, and lastly avail it to the point of utilization. the theory behind this is outlined in the work done by Sudhamshu *et al.* (2016).

Table 5 shows the data that was recorded during this study. It involved the rotor rotational speed (ω) with wind speed (v) and pitch angle (β).

Table 4. 1: Rotational speed vs Pitch angle

Pitch angle (degrees)		Wind	speed	
	3m/s	4m/s	5m/s	6m/s
0	0	0	0	0
5.6	0	92	142	202
11.2	0	124	182	252
16.8	20	135	202	282
22.4	0	117	162	218
28.0	0	106	146	195
33.6	0	96	117	145
39.2	0	81	99	123
44.8	0	45	78	117
50.4	0	38	63	93
56.0	0	18	47	81
61.6	0	2	27	57
67.2	0	0	18	39
72.8	0	0	2	6
78.4	0	0	0	1
84.0	0	0	0	0
89.6	0	0	0	0

The corresponding graph given by excel is as shown in Figure 4.1

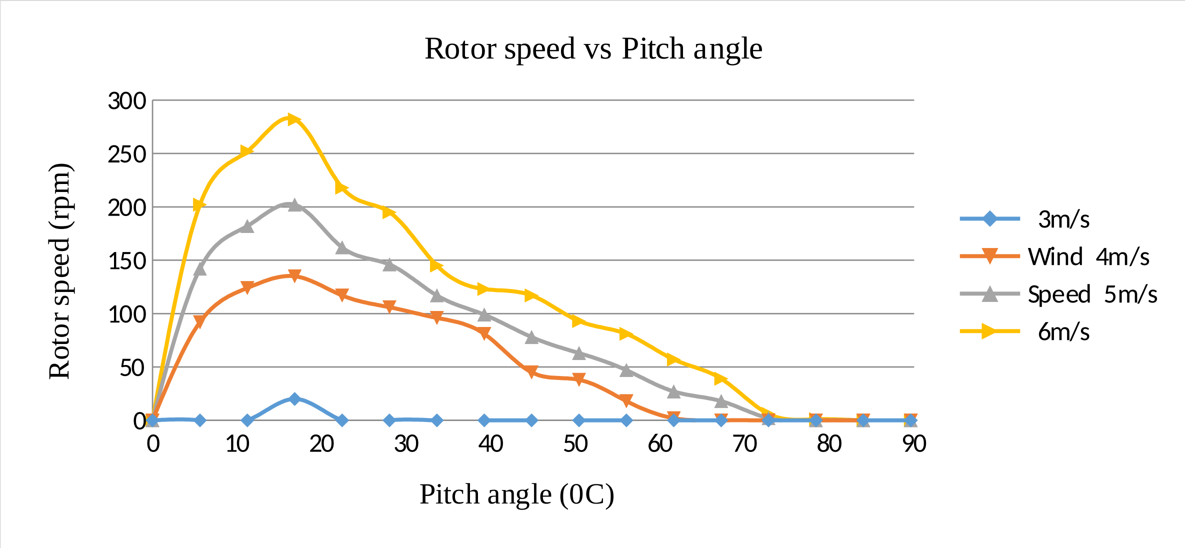

Figure 4. 1: Rotor speed vs Pitch angle

The rotor speed rose gradually as the pitch angle increased in all wind speed scenarios, peaking at a pitch angle of 16.80. After that, the rotor speed decreased to zero rpm for pitch angles of 22.40, 61.60, and 72.80 at wind speeds of 3 m/s, 4 m/s, 5 m/s, and 6 m/s, respectively. At 16.80 of the pitch angle, the swept area of blades in contact with the wind had the lowest drag force and produced the most torque (Merabet et al., 2011).

After achieving the highest rotor speed at a pitch angle of 16.8^0, the rotor speed declines steadily to zero. This behaviour is explained by the Weibull curve as articulated by Pedrosa *et al.* (2020), Kohout (2022), and Elmahdy (2015); that as the blade pitch angle increases above 16.8^0, the wind imparts a decreasing torque to the blades and hence the fall in rotor speed.

The site of this research (Kinangop area) has an average wind speed of 6 m/s. consequently, a further analysis is based on this wind speed. Table 4.2 shows the data collected on electricity generated for 100 seconds. the duration of 100 seconds was chosen as an average value because the steady wind speed varies between 90 seconds to 110 seconds (Biegel *et al.*, 2011).

Table 6 shows the data that collected with regard to the variation of the blade pitch angle versus the electric power generated.

Table 4. 2: Pitch angle vs Electric power output

Pitch angle (^0C)	Electric power output (W)
0.0	0.00
5.6	850.77
11.2	1008.09
16.8	1124.70
22.4	961.86
28.0	862.50
33.6	685.86
39.2	536.13
44.8	500.94
50.4	415.38
56.0	353.28
61.6	233.22
67.2	214.59
72.8	61.41
78.4	0.00
84.0	0.00
89.6	0.00

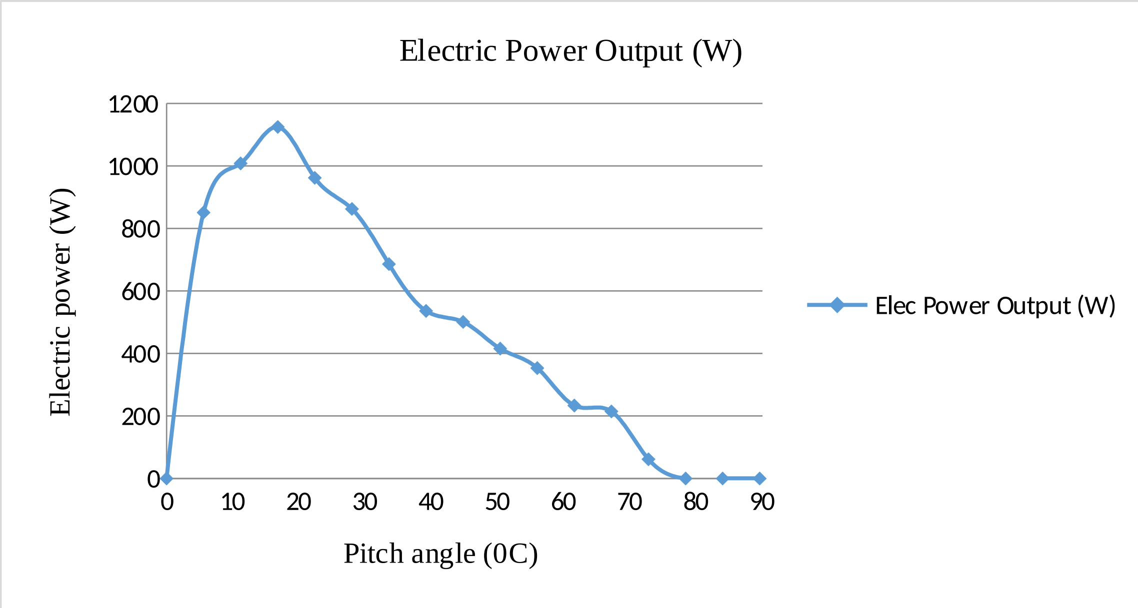

Figure 4. 2: Electric power output vs Pitch angle

Figure 4.2 shows a graphical representation of the data in Table 4.2

The wind power equation (4.1) as given by Eisa (2019) is as follows:

where:

P = Wind power (W)

c_p = Coefficient of power

= Density of air (kg/m^3)

A = Swept area of the rotor (m^2)

V = Wind speed (m/s)

The rotor speed increases with increasing wind speed. This suggests that when wind speed increases, so does the output of electric power. This is due to the fact that wind power is directly correlated with the wind speed cube (Chavero-Navarrete et al., 2021; Eisa, 2019; Zou et al., 2020). It was observed that the highest electric power output of 1124.7W was attained when the blade pitch angle was 16.8^0.

Another way of identifying the optimal pitch angle is to analyse the power conversion efficiency recorded by the power conversion unit (an alternator in this study) in the wind turbine assembly. Table 4.3 shows the data.

Table 4. 3: Power conversion efficiency

Pitch angle (^{0}c)	Power conversion efficiency (%)
0	0
5.6	24
11.2	27
16.8	31
22.4	28
28.0	25
33.6	21
39.2	19
44.8	15
50.4	14
56.0	12
61.6	10
67.2	7
72.8	6
78.4	4
84.0	0
89.6	0

A graphical presentation of the data in Table 4.3 is shown in Figure 4.3

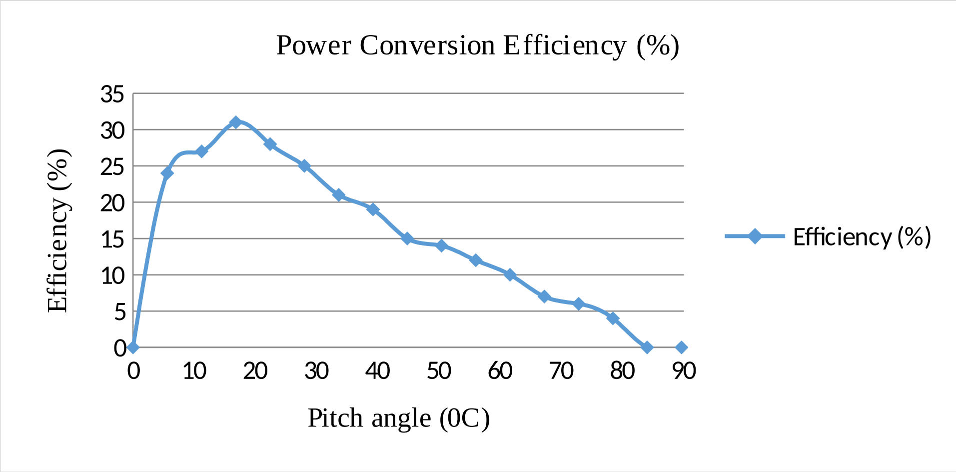

Figure 4. 3: Power conversion efficiency vs Pitch angle

A blade pitch angle of 16.80 resulted in a high-power conversion efficiency of 31%. Giordano et al. (2020) state that the wind turbine's performance is determined by the speed at which wind enters its rotor. However, since wind speed is measured at the rear of the turbine, where a lower value is typically found, achieving this quantity is seldom possible. The turbine's efficiency is defined as the ratio of the electrical power generated by a wind turbine to the aerodynamic power of the wind at the entrance of the rotor. The efficiency can be calculated by dividing the electrical energy generated by the wind energy during a specific time period. (Carullo *et al.*, 2021; El-Ahmar *et al.*, 2017). This low power conversion efficiency is attributed to the losses incurred in the transmission system from the rotor to the alternator (Chavero-Navarrete *et al.*, 2021).

4.3 Validation of the blade pitch angle and electrical power output

Simulation is the act of replicating a situation or process. To determine the connection between wind speed, pitch angle, and electric power production, wind turbine simulations were conducted. The wind speed that was utilized was 6 m/s. The study's location has an average wind speed of 6 m/s, thus that's the wind speed that was used

(Burton et al., 2011). This wind speed was used to determine all blade pitch angles. Table 8 displays results.

Table 4.4: Actual vs Simulated power output

Pitch angle (^{0}C)	Actual electric power output (w)	Simulated electric power output (w)
0.0	0.00	0.00
5.6	850.77	621.63
11.2	1008.09	809.95
16.8	1124.7	914.74
22.4	961.86	947.99
28.0	862.50	921.73
33.6	685.86	847.97
39.2	536.13	738.71
44.8	500.94	605.98
50.4	415.38	461.78
56.0	353.28	318.12
61.6	233.22	187.01
67.2	214.59	80.48
72.8	61.41	10.53
78.4	0.00	0.00
84.0	0.00	0.00
89.6	0.00	0.00

Figure 4.4 is a graphical representation of the data in Table 4.4.

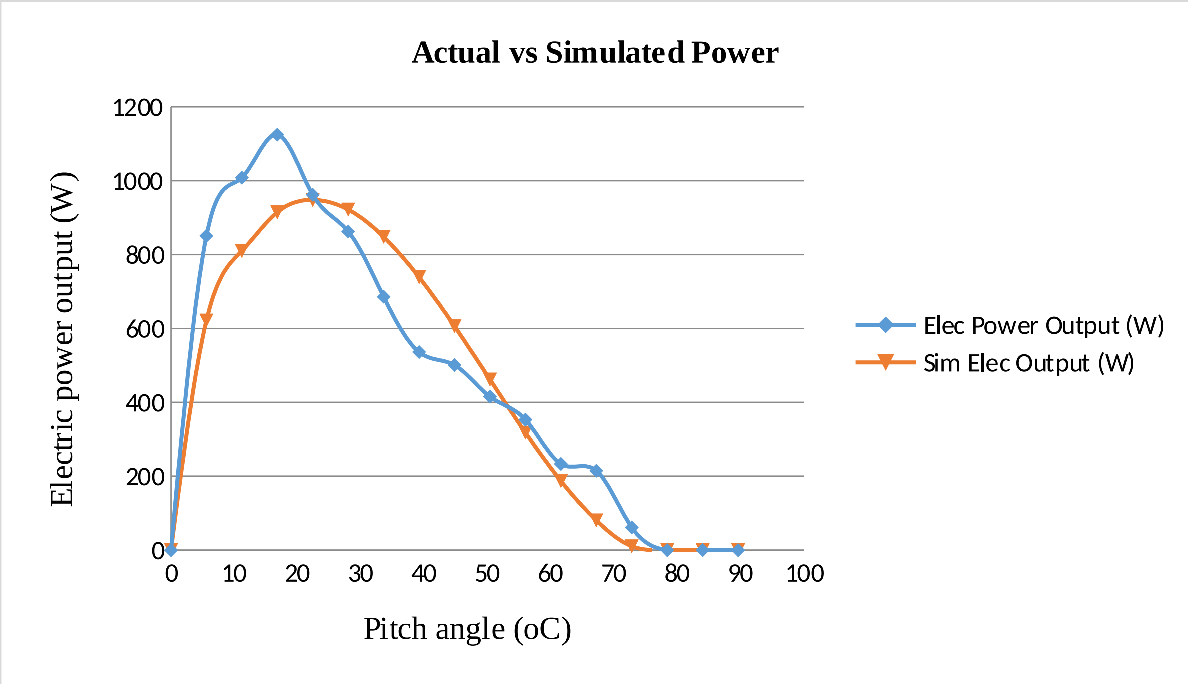

Figure 4. 4: Actual vs Simulated power output

The simulated values relate to the actual values by equation 4.2 with a coefficient of determination (R^2) of 0.9752.

where:

y = power output (W)

x = blade pitch angle (^{0}C)

The variation in the actual response values that a prediction model with specified independent parameters can explain is measured by R^2 (Eterkin and Firat, 2015; Hossain et al., 2007; Mukhopadhyay et al., 2013a). In this instance, the R^2 value was 0.9752, indicating that the model can account for 97.52 percent of the variation in the sample. According to Niladevi et al. (2009) and Sen (2008), an excellent statistical model has an R^2 between 0.75 and 1.0; the results of this investigation show that the model fits the data well. Therefore equation 4.2 may be used to predict the power output of a horizontal axis wind turbine at the various blade pitch angles with a constant wind speed of 6 m/s.

An aeroelastic simulation tool for horizontal axis wind turbines is made with Visual Basic 6. It can endure a range of aerodynamic loads that could be harmful to the wind turbine's mechanical parts, structures, and output of power (Ahlstrom, 2005). The performance of Visual Basic 6 is quite similar to the computational fluid dynamics (CFD) simulations performed by Nguyen et al. (2021) to ascertain the impact of various blade pitch angles on the forecast of power production of a horizontal axis wind turbine at diverse loadings.

When producing wind electricity, a thorough dependability and cost-evaluation method is crucial. It should be noted that the Visual Basic 6 Simulator was developed using both analytical methods (Abouzahr and Ramakumar, 1991; Giorsetto and Utsurogi, 1983; Wang et al., 1984) and Monte Carlo simulation (Billinton and Bai, 2004; R Karki and R Billinton, 2004) for evaluating the suitability of power generation systems. These simulation techniques identify the wind variation's chronology and how it affects a power system (Abouzahr and Ramakumar, 1991). Additionally, Billinton et al. (1996) provided an approach that used a time-series auto regressive and moving average (ARMA) model to mimic the hourly wind speed. Karki and Hu also provided experimental backing for this idea (2005).

CHAPTER FIVE: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This chapter deals with the overall conclusion of the research in line with the initial objectives of the study.

5.1 Summary & Key findings

A proportional integral derivative (PID) controller was applied on a horizontal axis wind turbine (HAWT) to help in varying the blade pitch angles. A cut-in and cut-out wind speed of 3 m/s and 6 m/s were input in the software. The following blade pitch angles were established: 0.0^0, 5.6^0, 11.2^0, 16.8^0, 22.4^0, 28.0^0, 33.6^0, 39.2^0, 44.8^0, 50.4^0, 56.0^0, 61.6^0, 67.2^0, 72.8^0, 78.4^0, 84.0^0, and 89.6^0.

An optimal blade pitch angle for generating maximum electrical power was 16.8^0. A wind speed of 6 m/s yielded 1127.4W at this angle. The highest power conversion efficiency of 31% was also recorded at this blade pitch angle.

Visual Basic 6 Simulator was used to determine a relationship between blade pitch angles and the electric power production. A constant wind speed of 6 m/s was used. An equation for predicting electric power output (with an R^2 value of 0.9752) is shown below:

where:

y = electric power output (W)

x = blade pitch angle (^{0}C)

5.2 Conclusion

The study has led to three main conclusions as follows. Firstly, based on the findings of identifying various pitch angles, it islogical to conclude that a turbine can have a range of 5.60, 11.20, 16.80, 22.40, 28.00, 33.60, 39.20, 44.80, 50.40, 56.00, 61.60, 67.20, 72.80, 78.40, 84.00, and 89.60 pitch angle which will produce power. Secondly it is evidently and scientifically to conclude that at 16.80 the turbine will maximum power output of 1124.7w, rotation of the rotor will be 282rpm and power efficiency will be 31%. Thirdly is the validation of blade pitch angle and electrical power output gave a coefficient of determination R2 of 0.972.

5.3 Recommendation

Small vertical axis wind turbines can be investigated with the aim of producing electricity for domestic use. Further research should be done to enable horizontal wind turbine work where there are high wind speeds of over 6m/s or below 3m/s.

REFERENCES

Abdullah, M. A., Yatim, A., Tan, C. W. and Saidur, R. (2012). A review of maximum power point tracking algorithms for wind energy systems. *Renewable and Sustainable Energy Reviews*, *16*(5), 3220-3227.

Abouzahr, I. and Ramakumar, R. (1991). An approach to assess the performance of utility-interactive wind electric conversion systems. *IEEE Transactions of Energy Conversion*, *6*(4), 627-638.

Ahlstrom, A. (2005). *Aeroelastic Simulation of Wind Turbine Dynamics.* (PhD), Royal Institute of Technology, Stockholm, Sweden.

Baburajan, S. (2018). *Improving the efficiency of a wind turbine system using a fuzzy-pid controller.* Paper presented at the 2018 Advances in Science and Engineering Technology International Conferences (ASET).

Behera, S., Subudhi, B. and Pati, B. B. (2016). Design of PI controller in pitch control of wind turbine: A comparison of PSO and PS algorithm. *International Journal of Renewable Energy Research (IJRER)*, *6*(1), 271-281.

Bergman, T. L. (2011). *Fundamentals of heat and mass transfer*: John Wiley & Sons.

Bhutta, M. M. A., Hayat, N., Farooq, A. U., Ali, Z., Jamil, S. R. and Hussain, Z. (2012). Vertical axis wind turbine–A review of various configurations and design techniques. *Renewable and Sustainable Energy Reviews*, *16*(4), 1926-1939.

Bianchini, A., Ferrara, G. and Ferrari, L. (2015). Pitch optimization in small-size darrieus wind turbines. *Energy procedia*, *81*, 122-132.

Biegel, B., Juelsgaard, M., Kraning, M., Boyd, S. and Stoustrup, J. (2011). *Wind turbine pitch optimization.* Paper presented at the 2011 IEEE International Conference on Control Applications (CCA).

Billinton, R. and Bai, G. (2004). Generating capacity adequacy associated with wind energy. *IEEE Transactions of Energy Conversion*, *19*(3), 641-646.

Billinton, R., Chen, H. and Ghajar, R. (1996). Time-series models for reliability evaluation of power systems including wind energy. *Microelectronic Reliability, 36*(9), 1253-1261.

Burton, T., Jenkins, N., Sharpe, D. and Bossanyi, E. (2011). *Wind energy handbook*: John Wiley & Sons.

Carullo, A., Ciocia, A., Malgaroli, G. and Spertiino, F. (2021). An innovative correction method of wind speed for efficiency evaluation of wind turbines.

Chavero-Navarrete, E., Trejo-Perea, M., Jáuregui-Correa, J.-C., Carrillo-Serrano, R.-V. and Rios-Moreno, J.-G. (2019). Pitch angle optimization by intelligent adjusting the gains of a PI controller for small wind turbines in areas with drastic wind speed changes. *Sustainability, 11*(23), 6670.

Chavero-Navarrete, E., Trejo-Perea, M., Jáuregui-Correa, J. C., Carrillo-Serrano, R. V., Ronquillo-Lomeli, G. and Ríos-Moreno, J. G. (2021). Pitch Angle Optimization for Small Wind Turbines Based on a Hierarchical Fuzzy-PID Controller and Anticipated Wind Speed Measurement. *Applied Sciences, 11*(1683). doi:https//doi.org/10.3390/app11041683

Chian, C.-Y., Zhao, Y.-Q., Lin, T.-Y., Nelson, B. and Huang, H.-H. (2018). Comparative study of time-domain fatigue assessments for an offshore wind turbine jacket substructure by using conventional grid-based and monte carlo sampling methods. *Energies, 11*(11), 3112.

Civelek, Z., Lüy, M., Çam, E. and Barışçı, N. (2016). Control of pitch angle of wind turbine by fuzzy PID controller. *Intelligent Automation & Soft Computing, 22*(3), 463-471.

Clarke, S. and Eng, P. (2018). Electricity generation using small wind turbines for home or farm use. *Ontario Ministry of Agriculture, Food and Rural Affairs*.

Council, G. W. E. (2017). GWEC global wind report 2019. *Global wind energy council: Bonn, Germany*.

Culotta, S., Franzitta, V., Milone, D. and Moncada Lo Giudice, G. (2015). Small wind technology diffusion in suburban areas of sicily. *Sustainability, 7*(9), 12693-12708.

Davis, N. N., Badger, J., Hahmann, A. N., Hansen, B. O., Mortensen, N. G., Kelly, M., Larsén, X. G., Olsen, B. T., Floors, R. and Lizcano, G. (2023). The Global Wind Atlas: A high-resolution dataset of climatologies and associated web-based application. *Bulletin of the American Meteorological Society, 104*(8), E1507-E1525.

Dimitrov, R. S. (2010). Inside UN climate change negotiations: The Copenhagen conference. *Review of policy research, 27*(6), 795-821.

Eastop, T. and McConkey, A. (1994). Applied Thermodynamics for Engineers and Technologists: Longman Singapore Publishers.

Ebrahim, M. A., Becherif, M. and Abdelaziz, A. Y. (2018). Dynamic performance enhancement for wind energy conversion system using Moth-Flame Optimization based blade pitch controller. *Sustainable Energy Technologies and Assessments, 27*, 206-212.

Eisa, S. A. (2019). Modeling dynamics and control of type-3 DFIG wind turbines: Stability, Q Droop function, control limits and extreme scenarios simulation. *Electrical Power System Resources*(166), 29-42.

El-Ahmar, M. H., El-Sayed, A. M. and Hemeida, A. M. (2017). *Evaluation of factors affecting wind turbine output power.* Paper presented at the Proc. of Nineteenth International Middle East Power Systems Conference (MEPCON), Cairo.

El Zein, M. (2019). Off-grid Wind Power Systems: Planning and Decision Making.

Elmahdy, E. E. (2015). A new approach for Weibull modeling for reliability life data analysis. *Applied Mathematics and computation, 250*, 708-720.

Eterkin, C. and Firat, M. (2015). A comprehensive review of thin layer drying model used in agricultural products. *Critical Reviews in Food Science and Nutrition, 57*(4), 701-717.

Ganjefar, S., Ghassemi, A. A. and Ahmadi, M. M. (2014). Improving efficiency of two-type maximum power point tracking methods of tip-speed ratio and optimum torque in wind turbine system using a quantum neural network. *Energy, 67*, 444-453.

Giordano, F., Vallan, A., Peraga, L., Leo, P. D., Carullo, A., Ciocia, A. and Spertino, F. (2020). *Comparison of correction methods of wind speed for performance evaluation of wind turbines*. Paper presented at the 24th IMEKO TC4 International Symposium, Palermo, Italy.

Giorsetto, P. and Utsurogi, K. F. (1983). Development of a new procedure for reliability modeling of wind turbine generators. *IEEE Transactions of Energy Conversion, 102*(1), 134-143.

Hadiana, H., Golmohammadib, A. M., Nasabc, H. H. and Javidd, N. J. (2017). Time Parameter Estimation Using Statistical Distribution of Weibull to Improve Reliability.

Hansen, A. and Butterfield, C. (1993). Aerodynamics of horizontal-axis wind turbines. *Annual Review of Fluid Mechanics, 25*(1), 115-149.

Hodzic, M. and Tai, L.-C. (2016). Grey predictor reference model for assisting particle swarm optimization for wind turbine control. *Renewable energy, 86*, 251-256.

Hossain, M., Woods, J. and Bala, B. (2007). Single layer drying characteristics and colour kinetics of red Chilli. *International Journal of Food Science and Technology*, *42*(11), 1367-1375.

Howell, R., Qin, N., Edwards, J. and Durrani, N. (2010). Wind tunnel and numerical study of a small vertical axis wind turbine. *Renewable energy, 35*(2), 412-422.

Jacobson, M. Z., Delucchi, M. A., Bauer, Z. A., Goodman, S. C., Chapman, W. E., Cameron, M. A., Bozonnat, C., Chobadi, L., Clonts, H. A. and Enevoldsen, P. (2017). 100% clean and renewable wind, water, and sunlight all-sector energy roadmaps for 139 countries of the world. *Joule, 1*(1), 108-121.

Johari, M. K., Jalil, M. and Shariff, M. F. M. (2018). Comparison of horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). *International Journal of Engineering and Technology, 7*(4.13), 74-80.

Kalyani, V. L., Dudy, M. K. and Pareek, S. (2015). Green energy: The need of the world. *Journal of Management Engineering and Information Technology, 2*(5), 18-26.

Kang, J., Meng, W., Abraham, A. and Liu, H. (2014). An adaptive PID neural network for complex nonlinear system control. *Neurocomputing, 135,* 79-85.

Kanyako, F. and Baker, E. (2021). Uncertainty analysis of the future cost of wind energy on climate change mitigation. *Climatic Change, 166*(1-2), 10.

Karki, R. and Billinton, R. (2004). Cost-effective wind energy utilization for reliable power supply. *IEEE transactions on energy conversion, 19*(2), 435-440.

Karki, R. and Billinton, R. (2004). Cost-effective wind energy utilization for reliable power supply. *IEEE Transactions of Energy Conversion, 19*(2), 435-440.

Karki, R. and Hu, P. (2005, 1-4 May). *Wind power simulation model for reliability evaluation.* Paper presented at the Proc. IEEE Can. Conf. Electr. Comput. Eng., Saskatoon, Saskatoon, Canada.

Karthikeyan, N., Murugavel, K. K., Kumar, S. A. and Rajakumar, S. (2015). Review of aerodynamic developments on small horizontal axis wind turbine blade. *Renewable and Sustainable Energy Reviews, 42,* 801-822.

Kazimierczuk, A. H. (2019). Wind energy in Kenya: A status and policy framework review. *Renewable and Sustainable Energy Reviews, 107*, 434-445.

Kinzel, M., Mulligan, Q. and Dabiri, J. O. (2012). Energy exchange in an array of vertical-axis wind turbines. *Journal of Turbulence, 13*(1), N38.

Kohout, J. (2022). Three-parameter Weibull distribution with upper limit applicable in reliability studies and materials testing. *Microelectronics Reliability, 137*, 114769.

Kumar, D. and Chatterjee, K. (2016). A review of conventional and advanced MPPT algorithms for wind energy systems. *Renewable and Sustainable Energy Reviews, 55*, 957-970.

Kumar, R., Raahemifar, K. and Fung, A. S. (2018). A critical review of vertical axis wind turbines for urban applications. *Renewable and Sustainable Energy Reviews, 89*, 281-291.

Lignarolo, L., Ragni, D., Krishnaswami, C., Chen, Q., Ferreira, C. S. and Van Bussel, G. (2014). Experimental analysis of the wake of a horizontal-axis wind-turbine model. *Renewable energy, 70*, 31-46.

Liu, J., Lin, H. and Zhang, J. (2019). Review on the technical perspectives and commercial viability of vertical axis wind turbines. *Ocean Engineering, 182*, 608-626.

Long, Y., Chen, Y., Xu, C., Li, Z., Liu, Y. and Wang, H. (2023). The role of global installed wind energy in mitigating CO2 emission and temperature rising. *Journal of cleaner production, 423*, 138778.

Martón, I., Villanueva, J. F., Carlos Alberola, S., Gallardo, S. and Sánchez, A. (2021). *Aprendizaje basado en proyectos en la asignatura Energía y Desarrollo Sostenible.* Paper presented at the IN-RED 2020: VI Congreso de Innovación Educativa y Docencia en Red.

Martón Lluch, I., Gallardo Bermell, S., Villanueva López, J. F., Carlos Alberola, S. and Sánchez Galdón, A. I. (2019). *Aprendizaje basado en proyectos en el Grado en ingeniería de la energía.* Paper presented at the IN-RED 2019. V Congreso de Innovación Educativa y Docencia en Red.

Mathew, M. (2022). Nuclear energy: A pathway towards mitigation of global warming. *Progress in Nuclear Energy, 143*, 104080.

Menezes, E. J. N., Araújo, A. M. and Da Silva, N. S. B. (2018). A review on wind turbine control and its associated methods. *Journal of cleaner production, 174*, 945-953.

Merabet, A., Thongam, J. and Gu, J. (2011). *Torque and pitch angle control for variable speed wind turbines in all operating regimes.* Paper presented at the 2011 10th International Conference on Environment and Electrical Engineering.

Ming, T., Caillof, S. and Liu, W. (2016). Fighting Global Warming by GHG removal: Destroying CFCs and HCFCs in Solar-Wind power plant hybrids producing renewable energy with no intermittency. *International Journal of Greenhouse Gas Control*.

Ming, T., Caillol, S. and Liu, W. (2016). Fighting global warming by GHG removal: Destroying CFCs and HCFCs in solar-wind power plant hybrids producing renewable energy with no-intermittency. *International Journal of Greenhouse Gas Control, 49*, 449-472.

Molina, M. G. and Mercado, P. E. (2011). Modelling and control design of pitch-controlled variable speed wind turbines *Wind turbines* (pp. 374-402): IntechOpen.

Möllerström, E., Gipe, P., Beurskens, J. and Ottermo, F. (2019). A historical review of vertical axis wind turbines rated 100 kW and above. *Renewable and Sustainable Energy Reviews, 105*, 1-13.

Mukhopadhyay, D., Sarkar, J. P. and Dutta, S. (2013a). Optimization of process factors for the efficient generation of biogas from raw vegetable wastes under the direct influence of plastic materials using Taguchi methodology. *Desalination and Water Treatment, 15*(13), 2781-2790.

Mukulo, B., Ngaruiya, J. and Kamau, J. (2014). Determination of wind energy potential in the Mwingi-Kitui plateau of Kenya. *Renewable energy, 63*, 18-22.

Muljadi, E. and Butterfield, C. P. (2001). Pitch-controlled variable-speed wind turbine generation. *IEEE transactions on Industry Applications, 37*(1), 240-246.

Nasiri, M., Milimonfared, J. and Fathi, S. (2014). Modeling, analysis and comparison of TSR and OTC methods for MPPT and power smoothing in permanent magnet synchronous generator-based wind turbines. *Energy Conversion and Management*, *86*, 892-900.

Neammanee, B., Sirisumrannukul, S., Chatratana, S. and Muyeen, S. (2010). *Control strategies for variable-speed fixed-pitch wind turbines.* Paper presented at the Wind power.

Nguyen, M. T., Balduzzi, F. and Goude, A. (2021). Effect of pitch angle on power and hydrodynamics of a vertical axis turbine *Ocean Engineering, 238*(1), 321-336.

Niladevi, K., Sukumaran, R. K., Jacob, N., Anisha, G. and Prema, P. (2009). Optimization of laccase production from a novel strain—Streptomyces psammoticus using response surface methodology. *Microbiological Research, 164*(1), 105-113.

Noton, M. (2014). *Modern Control Engineering: Pergamon Unified Engineering Series*: Elsevier.

Ouyang, T., Kusiak, A. and He, Y. (2017). Modeling wind-turbine power curve: A data partitioning and mining approach. *Renewable energy, 102*, 1-8.

Pedrosa, B., Correia, J. A., Rebelo, C. A. and Veljkovic, M. (2020). Reliability of fatigue strength curves for riveted connections using normal and weibull distribution functions. *ASCE-ASME Journal of Risk and Uncertainty in Engineering Systems, Part A: Civil Engineering, 6*(3), 04020034.

Petrusevska, I. (2022). *The Energy Crisis and the Use of Renewable Energy Sources.* Paper presented at the Proceedings of the International Scientific Conference" Social Changes in the Global World".

Pope, K., Dincer, I. and Naterer, G. (2010). Energy and exergy efficiency comparison of horizontal and vertical axis wind turbines. *Renewable energy, 35*(9), 2102-2113.

Porté-Agel, F., Wu, Y.-T., Lu, H. and Conzemius, R. J. (2011). Large-eddy simulation of atmospheric boundary layer flow through wind turbines and wind farms. *Journal of Wind Engineering and Industrial Aerodynamics, 99*(4), 154-168.

Ragheb, M. (2011). Vertical axis wind turbines. *University of Illinois at Urbana-Champaign, 1*(40).

Rehman, S., Alam, M. M., Alhems, L. M. and Rafique, M. M. (2018). Horizontal axis wind turbine blade design methodologies for efficiency enhancement—A review. *Energies, 11*(3), 506.

Riziotis, V., Voutsinas, S., Politis, E. and Chaviaropoulos, P. (2004). Aeroelastic stability of wind turbines: the problem, the methods and the issues. *Wind Energy: An International Journal for Progress and Applications in Wind Power Conversion Technology, 7*(4), 373-392.

Saidur, R., Islam, M., Rahim, N. and Solangi, K. (2010). A review on global wind energy policy. *Renewable and Sustainable Energy Reviews, 14*(7), 1744-1762.

Savino, M. M., Manzini, R., Della Selva, V. and Accorsi, R. (2017). A new model for environmental and economic evaluation of renewable energy systems: The case of wind turbines. *Applied energy, 189*, 739-752.

Schinas, N., Vovos, N. and Giannakopoulos, G. (2007). An autonomous system supplied only by a pitch-controlled variable-speed wind turbine. *IEEE transactions on energy conversion, 22*(2), 325-331.

Schöbel-Rutschmann, S. (2008). *Wind Turbines as Cultural Landscape Elements. A Qualitative Analysis of Structure.* Paper presented at the EURAU´ 08.

Sen, Z. (2008). Solar Energy Fundamentals and Modeling Techniques: Atmosphere, Environment, Climate Change and Renewable Energy.

Senjyu, T., Kaneko, T., Yona, A., Urasaki, N., Funabashi, T., Yamada, F. and Sugimoto, S. (2007). *Output power control for large wind power penetration in small power system.* Paper presented at the 2007 IEEE Power Engineering Society General Meeting.

Sethi, A. K. and Ravichandran, V. (2011). *Pitch Control of Horizontal Axis Wind Turbine.*

Sherman, J. (2007). *Wind power*: Capstone.

Sijmons, D. and Van Dorst, M. (2012). Strong feelings: Emotional landscape of wind turbines. *Sustainable energy landscapes: Designing, planning, and development, 7*, 45.

Sørensen, J. N. (2016). *General momentum theory for horizontal axis wind turbines* (Vol. 4): Springer.

Spertino, F., Ciocia, A., Leo, P. D., Iuso, G., Malgaroli, G. and Roberto, L. (2017, September 2017). *Experimental testing of a horizontalaxis wind turbine to assess its performance.* Paper presented at the 22nd IMEKO-TC4 International Symposium, Palermo, Italy.

Sruthi, M. A., Sai, C. P. and Kumar, M. V. (2017). Controlling flicker caused due to power fluctuations by using individual pitch control for a variable speed DFIG based wind turbine. *Int. Res. J. Eng. Technol, 4*(3), 286-293.

Sudhamshu, A., Pandey, M. C., Sunil, N., Satish, N., Mugundhan, V. and Velamati, R. K. (2016). Numerical study of effect of pitch angle on performance characteristics of a HAWT. *Engineering Science and Technology, an International Journal, 19*(1), 632-641.

Taher, S. A., Farshadnia, M. and Mozdianfard, M. R. (2013). Optimal gain scheduling controller design of a pitch-controlled VS-WECS using DE optimization algorithm. *Applied soft computing, 13*(5), 2215-2223.

Takase, M., Kipkoech, R. and Essandoh, P. K. (2021). A comprehensive review of energy scenario and sustainable energy in Kenya. *Fuel Communications, 7*, 100015.

Tjiu, W., Marnoto, T., Mat, S., Ruslan, M. H. and Sopian, K. (2015). Darrieus vertical axis wind turbine for power generation I: Assessment of Darrieus VAWT configurations. *Renewable energy, 75*, 50-67.

Todorov, M. and Vukov, G. (2010). *Parametric torsional vibrations of a drive train in horizontal axis wind turbine.* Paper presented at the Proc. 1ère Conférence Franco-Syrienne sur les Energies Renouvelables.

Tremblay, A.-M. (1975). Comment on: Negative Kelvin temperatures: Some anomalies and a speculation. *Am. J. Phys*, *44*(10), 994-995.

Wang, X., Dai, H. and Thomas, R. J. (1984). Reliability modeling of large wind farms and electric utility interface systems. *IEEE Transactions of Energy Conversion, 103*(3), 569-575.

Xiao, Y., Huo, W. and Nan, G. (2015). Study of variable pitch control for direct-drive permanent magnet wind Turbines based on fuzzy logic algorithm. *JOURNAL OF INFORMATION &COMPUTATIONAL SCIENCE, 12*(7), 2849-2856.

Xu, G. and Sankar, L. N. (2000). Computational study of horizontal axis wind turbines. *Sol. Energy Eng., 122*(1), 35-39.

Zhang, J., Cheng, M., Chen, Z. and Fu, X. (2008). *Pitch angle control for variable speed wind turbines.* Paper presented at the 2008 Third international conference on electric utility deregulation and restructuring and power technologies.

Zhang, X., Pei, W., Deng, W., Du, Y. and Qi, Z. (2015). Emerging smart grid technology for mitigating global warming. *Journal of Energy*.

Zou, M., Fang, D., Djokic, S. and Giorgio, V. D. (2020). Evaluation of wind turbine power outputs with and without uncertainties in input wind speed and wind direction data. *IET Renewable*.

APPENDICES

APPENDIX ONE: KINANGOP WEATHER

Table A1.1: Real-time Wind & Weather Report for Kinangop area

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Ave/year
Wind probability	54	31	41	42	17	8	12	18	22	31	39	49	30
Average wind speed (m/s)	6.2	5.5	5.6	6.3	6.3	6.5	7.6	6.1	6.2	5.4	6.1	6.6	6.2
Average temp (°C)	24	23	23	23	22	20	21	21	22	22	23	22	22

Source: (**https://www.timeanddate.com/weather/@183225/historic?month=8&year=2017**)

Table A1.1 shows real-time observations from the weather station located in Kinangop station. This area was chosen because the average wind temperate was 6 m/s. the average temperature of the area was around 22^{0}C which was conducive for the wind turbine. High temperature above 25^{0}C or temperature below 20^{0}C generates a lot of friction, which is not good for the motor.

Table A1.2 shows the *k* value of the different terrains. The higher the *k* values the better for the wind turbine. Kinangop area has a *k* value of 3.5

Table A1.2: Value of k for different terrains

Terrain	Value of *k*
Mountains	2.0
Hills	2.5
Coast	3.0
Plain	3.5
Islands, Open sea	4.0

Source: Biegel *et al.* (2011)

From the tables, Kinangop area wind distribution has an average wind speed of 6 m/s and *k* of 3.5. Wind shear was not considered because the wind turbine was only 5 metres high. Direction of the wind was not a consideration because the area was plain; thus wind from any direction was able to rotate the blade. There were no high buildings or high mountains in the area. high buildings or mountains affect the wind direction and speed of the wind (Porté-Agel *et al.*, 2011).

APPENDIX TWO: THEORY OF A BLADE PITCH ANGLE

The wind turbine functions by transforming the kinetic energy produced by the wind into mechanical energy. Figure A2.1 depicts a wind turbine blade's cross section and the forces operating on it.

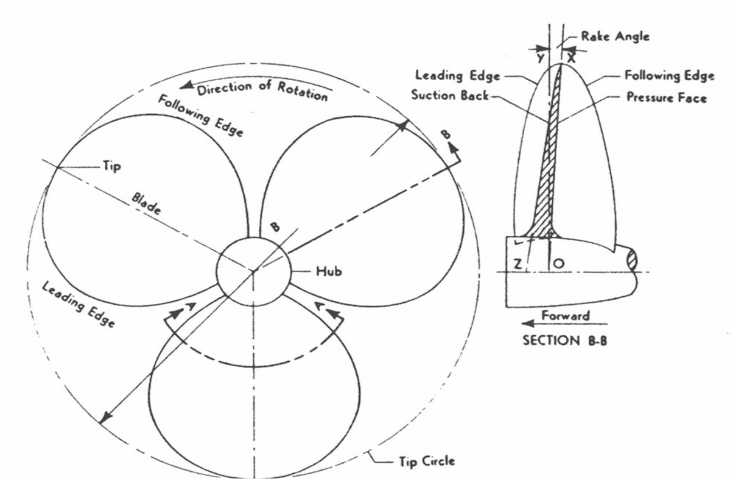

Figure A2.1: Cross section of the wind turbine blade

Adopted from Sethi and Ravichandran (2011).

The turbines are three-bladed, rotating on a horizontal axis, and pitch controlled, as illustrated in Figure 8. While the wind speed fluctuates over the region the blades sweep, it remains constant over time. The rotor's numbering system consisted of 1, 2, and 3 blades, and its position was determined by the angle θ = [θ*2π/3].

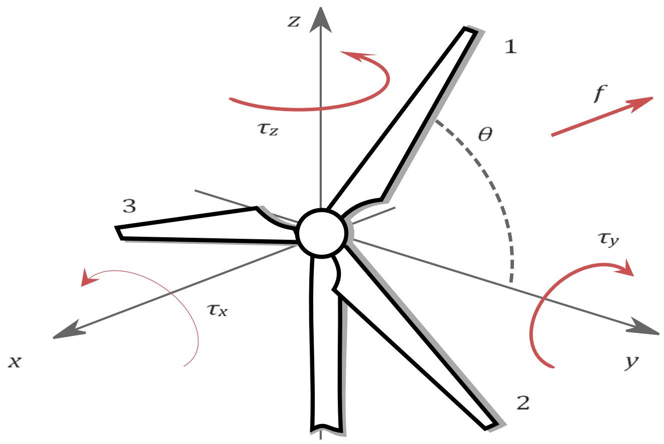

Figure A2.2: Three bladed HAWT

These pitch angles have an impact on the net force, f ∈ r, acting on the entire structure as well as the torque, τ = (τx, τy, τz) ∈ r3, generated around the three primary axes.

The pitch and pitch angle have the following relationship:

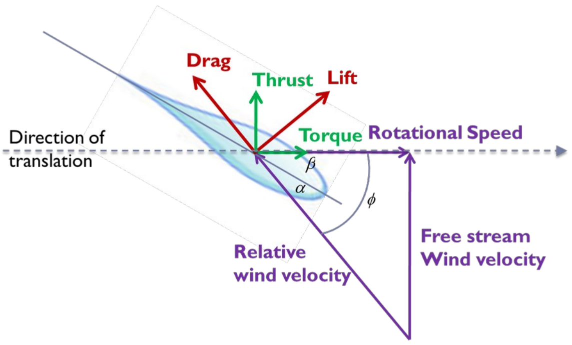

Figure A2.3: Blade pitch angle and related forces

Adopted from Sethi and Ravichandran (2011).

Drag and lift force

Lift refers to the force exerted on an object in a direction perpendicular to the flow direction. Lift can only occur when there is a circulating flow of fluid around an object, such as the flow around a revolving cylinder. Both the static pressure and the velocity above the object are reduced. Due to the decrease in velocity, the static pressure increases. The lift force, also known as the upward force, is the force that acts in an upward direction. The force exerted on an object in the same direction as the incoming flow is referred to as drag. In order to operate effectively, a wind turbine requires a significant amount of lift force and minimal drag force. At tiny angles of attack, the lift force exceeds the drag force. As the angles of attack (α) increase beyond a certain threshold, the lift force decreases and the drag force increases. The event demonstrates the crucial role that the blade pitch angle plays (Grant, 2011). Any change in the velocity of the wind or the rotational speed of the rotor leads to a corresponding adjustment in the ratio of the speed at the tip of the rotor to the wind speed, which subsequently impacts the efficiency of power conversion and the average power generated. The blade rotates due to the aerodynamic forces generated by the resulting relative velocity, resulting in the release of mechanical energy. Isaac Newton The third law of motion states that the forces exerted by two objects on one other, known as the action and response forces, are equal in magnitude and opposing in direction. This suggests that the lift force and the draft force are antithetical and equivalent.

APPENDIX THREE: CALCULATIONS

A3.1 Calculations of Input Power

To calculate input power,

Power = **(A3.1)**

This means that,

(A3.2)

Therefore,

Power =

Thus,

Power = **(A3.3)**

where:

Source: Sethi and Ravichandran (2011)

If,

r = is the radius from centre of the shaft

Then,

tan **(A3.4)**

and,

2

Therefore,

Pitch =

Thus

(A3.5)

Power $_{max}$ = **(A3.6)**

A3.2 Tip speed ratio.

Tip speed of the blade enables to find tip speed ratio (

Therefore, calculating available power in the wind turbine;

t_s = **(A3.7)**

where:

t_s = speed of the blade

Knowing the tip speed of the blade allows us to find the tip speed ratio, that is;

ƛ = **(A3.8)**

where:

T_s is the tip speed

v is speed of the wind

ƛ is the tip speed ratio

Source: Eisa (2019).

Optimal ƛ (tip speed ratio) can also be found by,

ƛ $_{opt}$ = **(A3.9)**

where:

n is the number of blades

A3.3 Power coefficient of a wind turbine

Power coefficient of wind energy, c_p

c_p =

Pmax = **(A3.10)**

Source: Riziotis *et al.* (2004)

where:

c_{p} = power coefficient

ƛ = tip speed ratio

Θ = pitch angle

Power coefficient is a function of the pitch angle and the tip speed.