Counter Rotating Vertical Axis Wind Turbine

A Final Year Project Report

Presented to

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of the Requirements for the Degree of

Bachelors of Mechanical Engineering

by

Roshaan Mahyyuddin

Azeem Mubashir

Hamza Ali Khan

Shazim Khalid

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EXAMINATION COMMITTEE

We hereby recommend that the final year project report prepared under our supervision by:

Roshaan Mahyyuddin	00000259457
Azeem Mubashir	00000241746.
Hamza Ali Khan	00000249748
Shazim Khalid.	00000250030

Titled: “Counter-rotating Vertical Axis Wind Turbine” be accepted in partial fulfillment of the requirements for the award of Mechanical Engineering degree with grade ___

Supervisor: Dr. Emad Uddin (HOD Mechanical) Dept. of Mechanical Engineering	____________________ Dated:
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ABSTRACT

The world is facing a power deficit with the supply of energy failing to meet the demand of consumers. This is largely due to the rapid depletion of non-renewable energy resources and is further compounded by the increasing reliance on electricity ranging from domestic to commercial use. This concern is valid for Pakistan as well, with our conventional reserves such as gas depleting annually resulting in power shortage which impacts households, agriculture and industries. It is an alarming situation considering the level of unemployment and the desperate need for an industrial revolution which is why the demand-supply gap needs to be addressed at the earliest.

Renewable resources such as wind have been nominated to bridge this gap for a long time however, our reliance on fossil fuels continues to rise which calls for innovation with regards to manner in which energy is extracted from these resources. This project aims to provide an effective alternative to the existing wind turbines in the form of Counter-rotating Vertical Axis Wind Turbines.

It consists of the flow and efficiency analysis with the results being used in the design phase of the turbine. The simulation results have been attached along with the parametric analysis with relevant conclusions. The design is fabricated to present a working model of the proposed wind turbine along with its performance testing results and evaluation. Finally, a comprehensive discussion on the results along with recommendations on future work is shared for reference.

ACKNOWLEDGMENTS

We would like to thank Allah Almighty for enabling us to successfully conduct this project. Secondly, we extend our heartfelt gratitude to our supervisor, Dr. Emad Uddin, whose able support and guidance helped us during the course of our project. Next, we thank all of our instructors at SMME who imparted the requisite knowledge which helped us complete our project. Finally, we would like to thank our families, especially our parents, whose unconditional support and prayers motivated us during the course of the Final Year Project.

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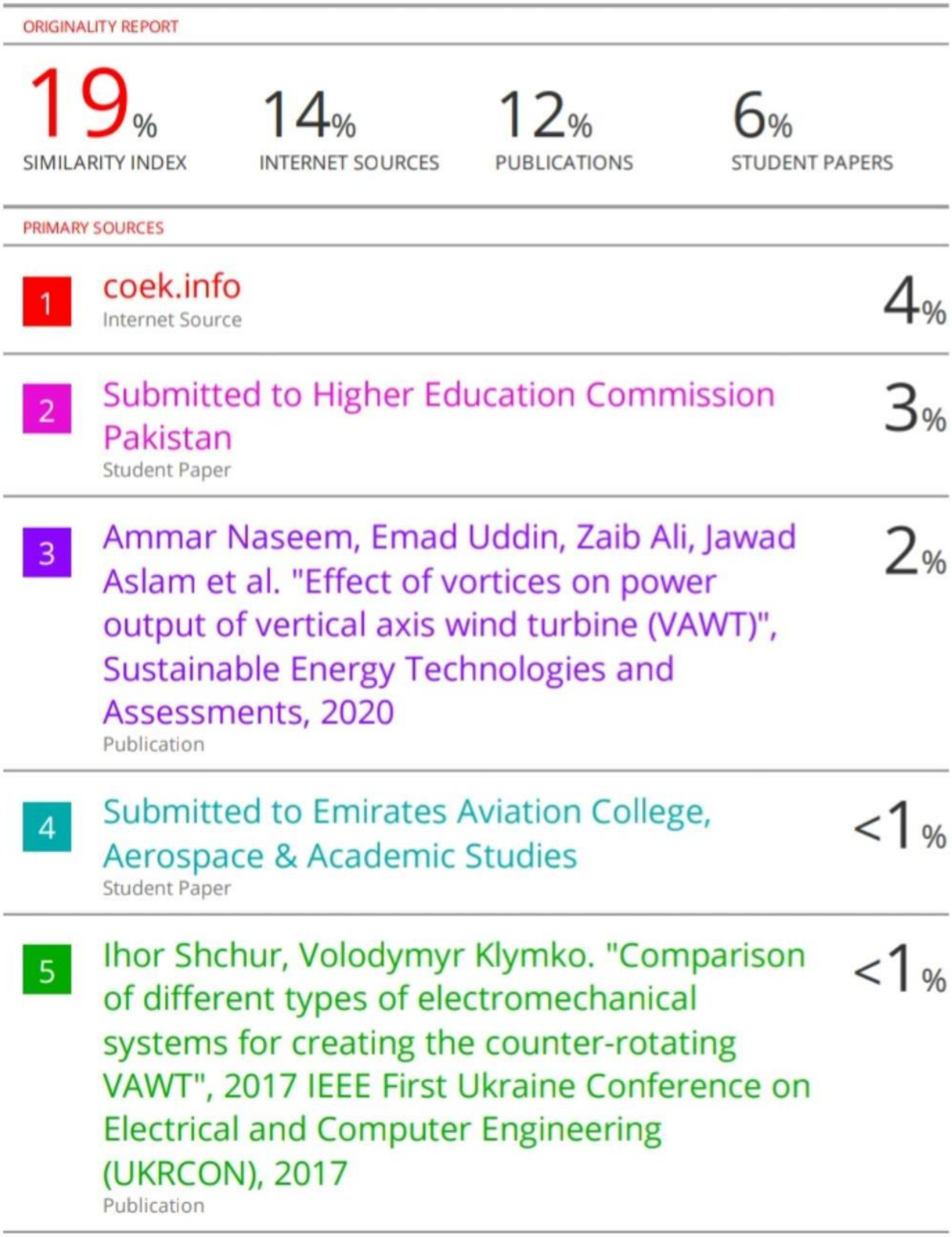

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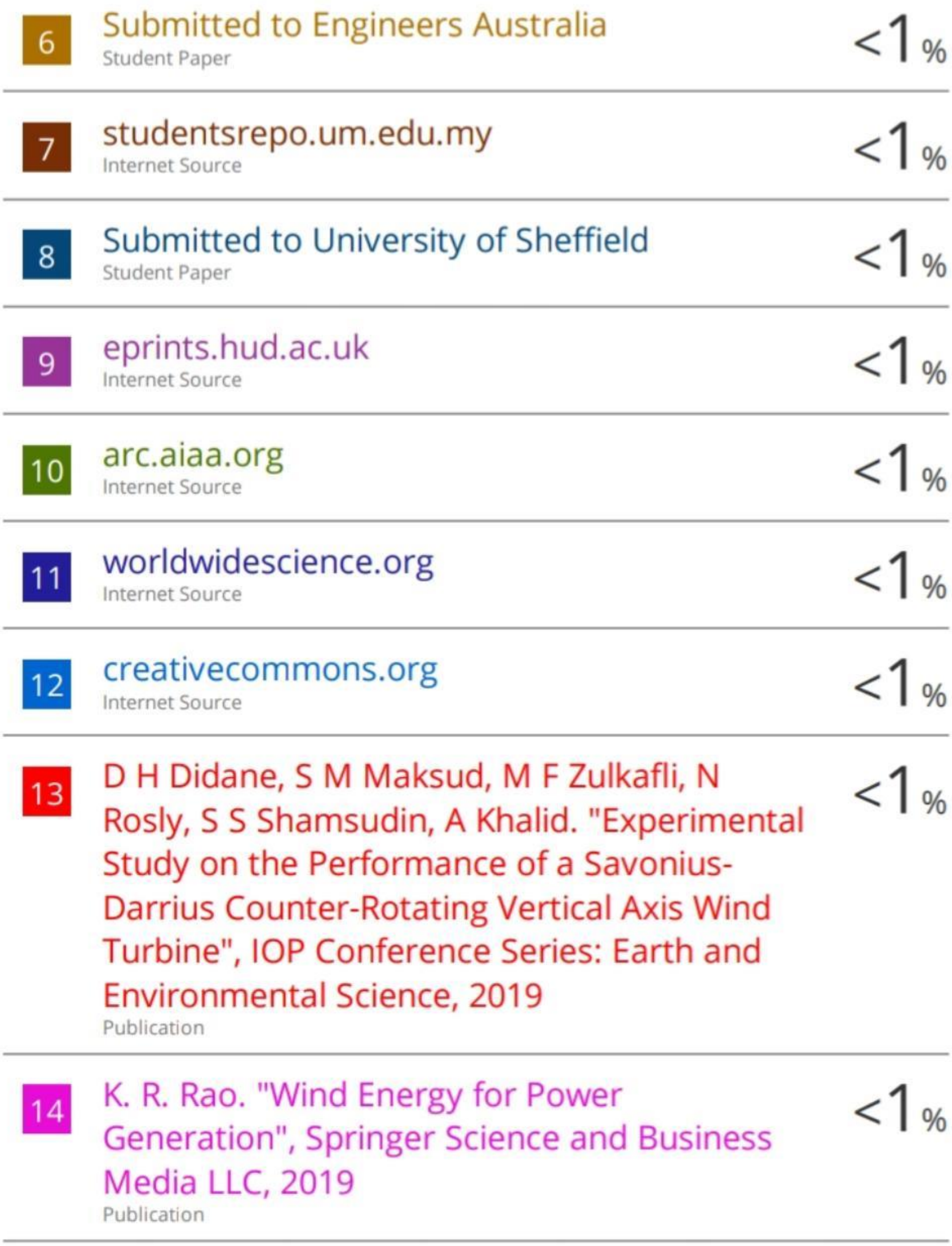

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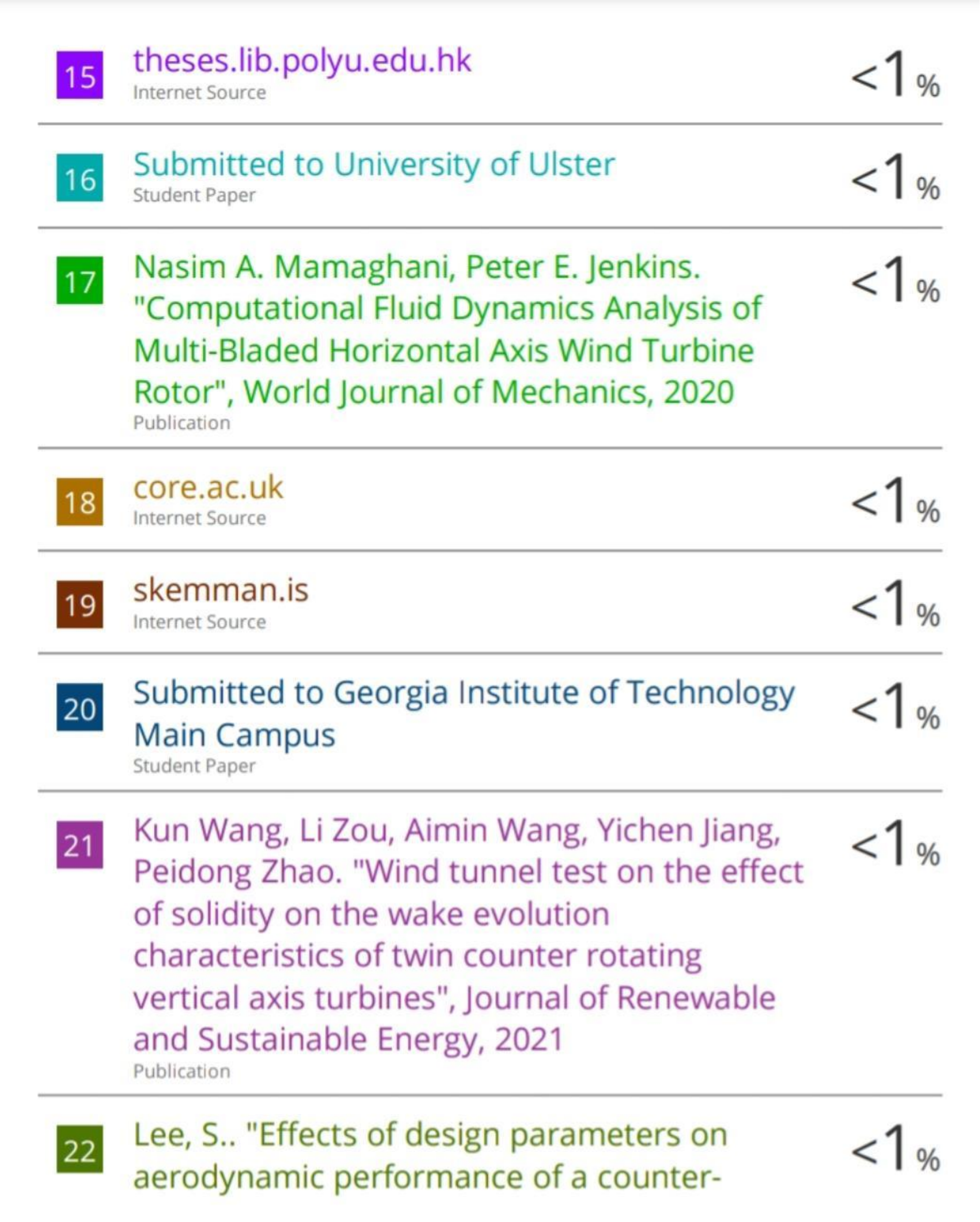

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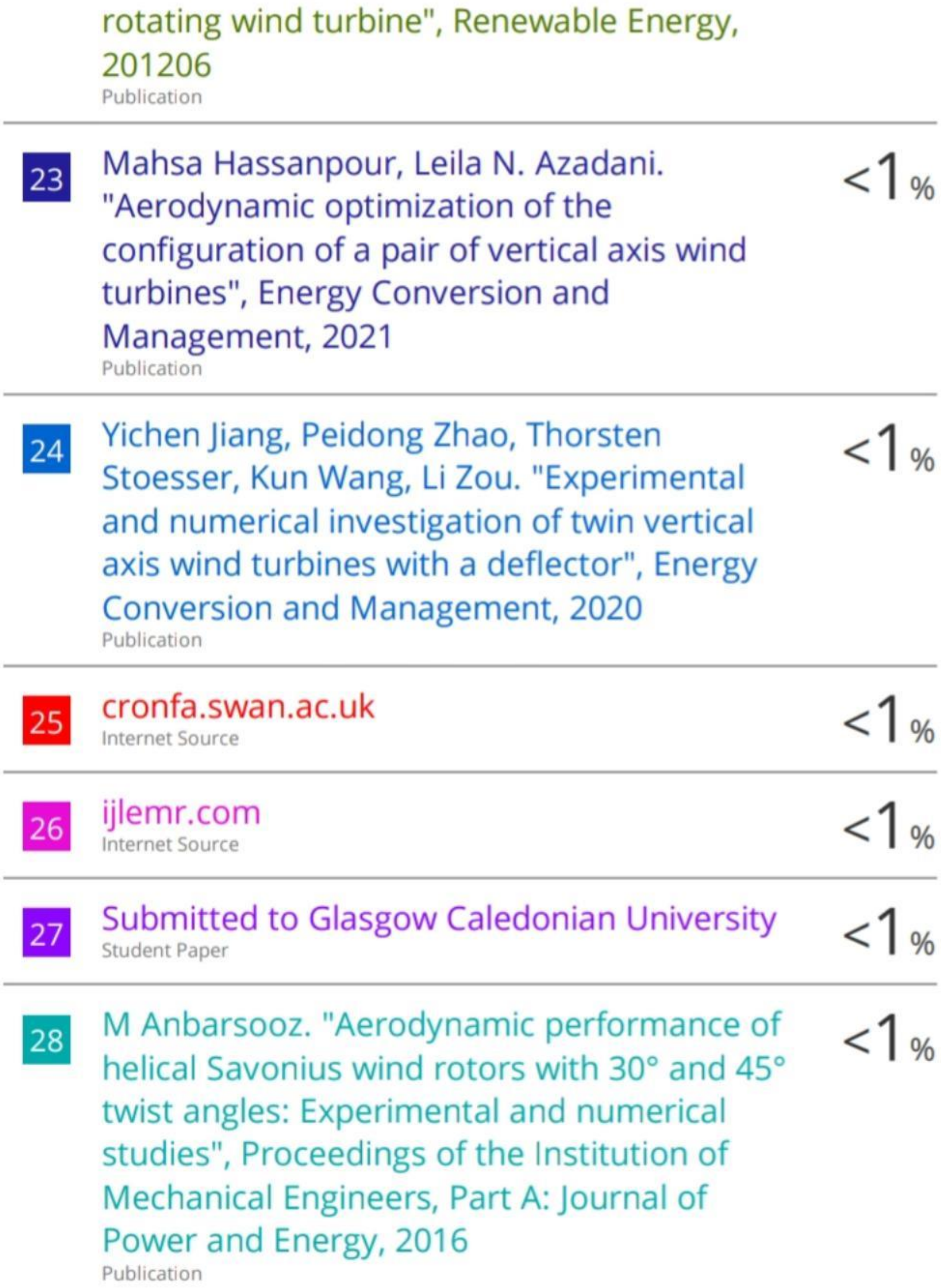

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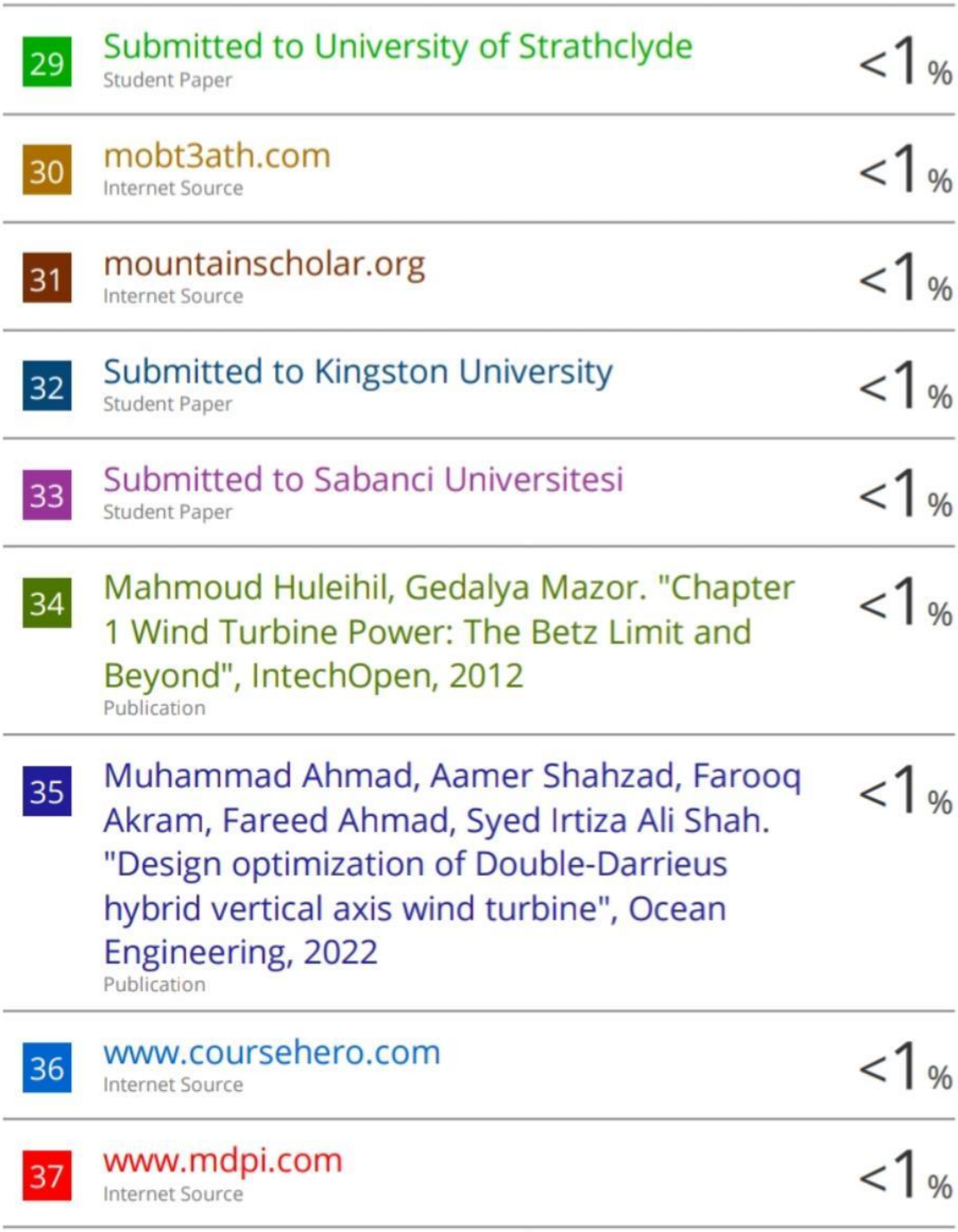

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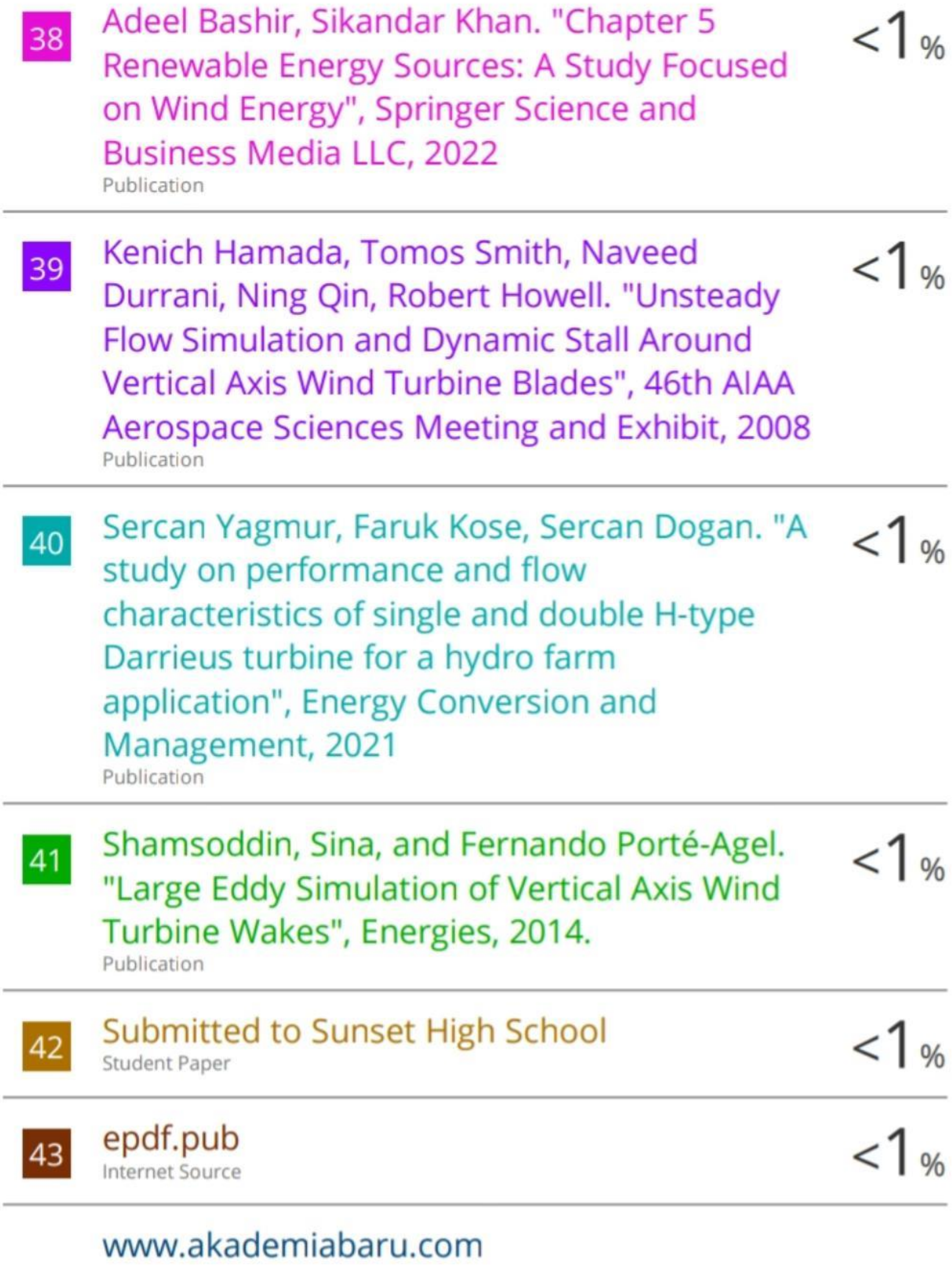

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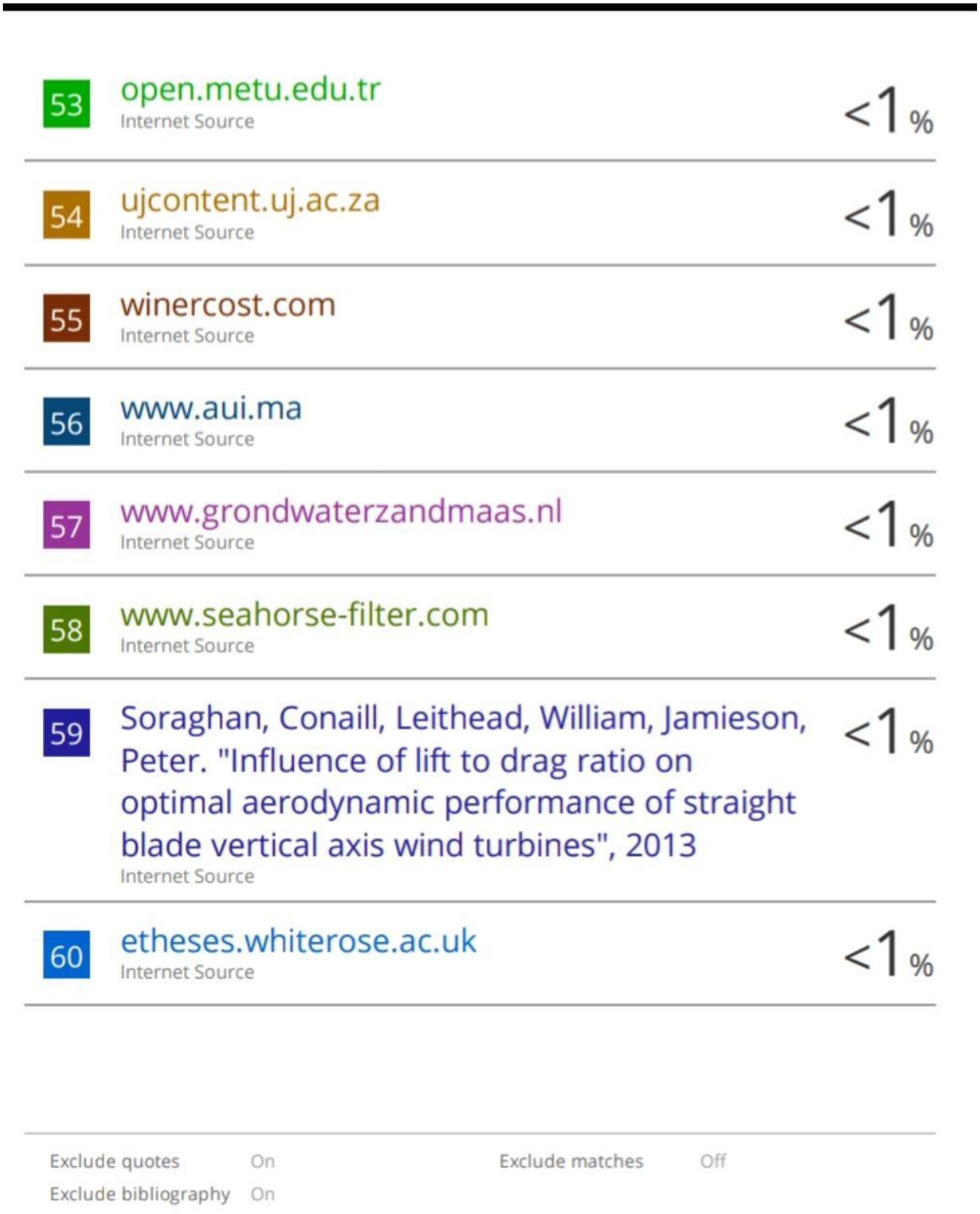

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ABBREVIATIONS

m	Metres
in	Inches
mm	Millimetres
m/s	Metres per second
RPM	Revolution per minute
Nm	Newton metre
TSR	Tip Speed Ratio
HAWT	Horizontal Axis Wind Turbine
VAWT	Vertical Axis Wind Turbine
T	Torque

Table 1 Abbreviations

C_P	Power Coefficient
C_T	Torque Coefficient
CO_2	Carbon dioxide
Λ	Tip Speed Ratio
U_∞	Wind Velocity

Table 2 Nomenclature

CHAPTER 1: INTRODUCTION

With the proliferation of population, natural resources demands have increased exponentially. And it has become very difficult to meet the demands of energy using natural resources primarily due to the depletion of non-renewable resources. Moreover, usage of fossil fuels is considered a threat to environment majorly because of the emission of carbon dioxide (CO_2) as a byproduct of the combustion process which is the main component in Green House effect. To avoid this carbon footprint issue, scientists and engineers are exploring ways to efficiently harvest energy using renewable sources of energy [1].

Pakistan has a huge potential for generating energy from renewable resources which would reduce the energy crisis that we are facing right now. This energy deficit is being faced globally which has ultimately convinced many countries to take advantage from the renewable energy sources like wind.

1.1 Wind Turbines

Wind is the best source of renewable energy. It does not produce any emission which makes it clean energy. Most of the countries are using HAWTs for electricity generation but VAWTs are also a very much viable source for electricity generation especially in areas having low wind speeds [2]. Wind turbines can be used to harvest wind energy. Wind turbines consist of blades, gearbox, rotor, gear trains, and generator. Suitable airfoils are chosen which could provide maximum energy harvesting. Wind strikes the blades and rotor resulting in deflection of air which results in generating a force on turbine. Due to this force a torque is generated and this torque is converted into electrical energy using generators.

1.2 Fundamentals of Wind Turbines

1.2.1 Swept Area

The swept area of the turbine refers to the area that the blades sweep through. Blades typically create a circle by rotation whose area is determined by the formula for the area of a circle. The swept area determines the amount of wind that the turbine will be able to tap into which makes it a key consideration in design of a wind turbine. Swept area is aa factor in the calculation of turbine power which may then be compared to the available power to determine the turbine efficiency[3].

1.2.2 Tip speed ratio

Tip speed ratio is defined as the ratio of the speed of the tip of the blade to the incoming wind speed. It is an important factor for consideration as low tip speed would result in most of the wind passing through uninterrupted resulting in loss of wind potential. On the other hand, in case of high tip speeds the blades may form a wall like structure restricting the wind flow required for power generation.

1.2.3 Power Coefficient

In wind turbines, kinetic energy from the wind is converted into mechanical energy initially. This mechanical energy is used to drive the generator which produces electrical energy. The efficiency of conversion of the kinetic energy to the mechanical energy is defined by the power coefficient. It is the ratio of the energy captured by the blades to the available energy of the wind. The maximum value for the power coefficient determined theoretically is known as the Betz Limit which cones out to be 0.593 suggesting that ot is not possible to design a turbine with an efficiency greater than 59.3%.

1.2.4 Pitch Control

Pitch control refers to altering the pitch angle of the blades relative to the wind direction in order to enhance the turbine’s performance by maintaining the optimum angle of attack at all times. It also serves as a safety mechanism to protect the blades during gusts or high wind speeds. Modern turbines operate with blades containing individual pitch control mechanisms which may be electric or hydraulic in nature.

1.3 Types of Wind Turbines

Wind turbines are mainly classified into two types: Horizontal axis wind turbines (HAWT) and Vertical axis wind turbines (VAWT). In horizontal axis wind turbines, rotational axis is parallel to the direction of wind coming while in vertical axis wind turbines it is perpendicular to the wind direction [4].

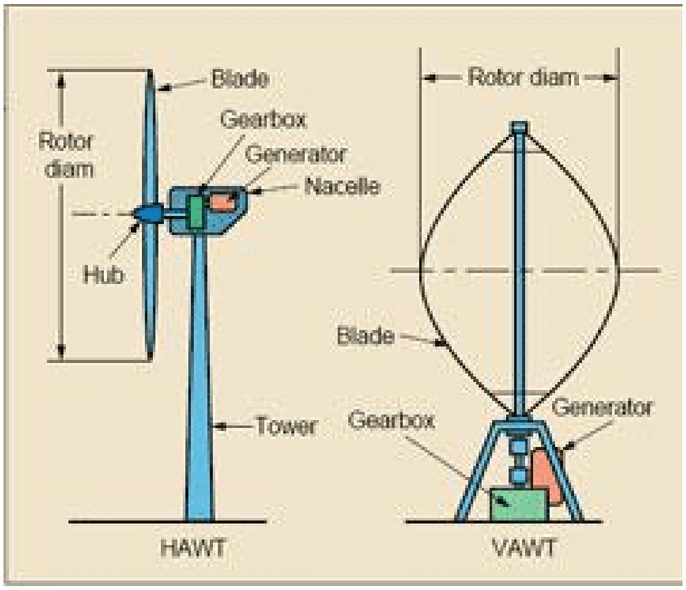


Figure 1 Difference between HAWT and VAWT

1.3.1 Vertical Axis Wind Turbines:

Vertical axis wind turbines are a good source of energy production considering, in literature, their maximum Coefficient of Power generation is greater than horizontal axis wind turbines. For the past few decades, scientists have started paying heed to the energy generation abilities of VAWTs. These are mounted at ground so they don’t require any special towers and they don’t produce any noise. A very important parameter in VAWTs is Tip-speed ratio. Very low TSR can result in very low energy production so its of utmost importance to achieve an optimal TSR in VAWTs. They have various configurations differing according to the requirements each having its own advantages and disadvantages. Due to rotational axis being perpendicular to the wind direction, VAWTs have ability to harness energy from all directions. As VAWTs are omni-directional so they do not require any yaw mechanism for rotor blades.

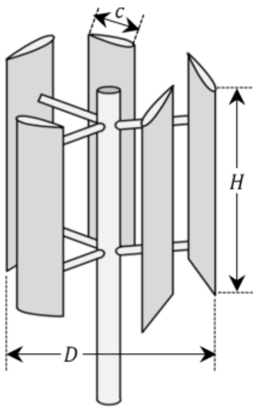


Figure 2 Vertical Axis Wind Turbine

1.3.2 Comparison of VAWTs with HAWTs

Due to gusty and turbulent wind conditions, HAWTs can face fatigue while VAWTs are designed to use gusty winds to their advantage and they generate maximum energy out of it. HAWTs are useful in areas having steady wind conditions as they generate maximum energy out of it while VAWTs are made for unsteady and turbulent conditions. HAWTs require higher wind speed to maximize energy harvesting therefore they are mounted at very high levels while VAWTs are good for low wind speeds. As in case of VAWTs, heavy components like gearbox, generator, are mounted at the ground so they don’t really require strong supporting structures which ultimately simplifies the turbine component replacement procedure and reduces the maintenance cost too. Efficiency of VAWT is low as compared to HAWT as single blade completing a whole rotation produces more energy. But if VAWTs are aligned in array form, they occupy less land area which means that energy production per unit area increases in wind farms. VAWTs can generate energy at low wind speeds and at low heights while in case of HAWTs, height is a very important factor. Considering all these factors into account, VAWTs are very useful for urban areas. A disadvantage of VAWT is the dynamic stall of blades as the angle of attack changes continuously throughout the rotational motion. It induces noise and reduces the efficiency of the turbine [4].

CHAPTER 2: LITERATURE REVIEW

The review of available literature in light of the previous work conducted on the topic is imperative in any project in order to ensure that time and resources are not wasted in the quest of information that is already available. It is a very effective way to enhance the knowledge in the field of the project and helps in evaluating the available opportunity to contribute. The project was initiated by conducting an in-depth literature review which helped us build our knowledge with regards to:

- types of wind turbines
- operation of wind turbines
- importance of wind turbines
- innovation in wind turbines
- optimization of wind turbines

2.1 Types of Vertical Axis Wind Turbines

Wind Turbines operate on two basic principles: lift and drag. Lift acts perpendicular to the direction of flow whereas drag acts in the direction of flow. Turbines that operate on the basis of drag are known as Savonius turbines whereas turbines that operate on the basis of lift are known as Darrieus turbines.

2.1.1 Savonius Turbines

Savonius turbines are drag based turbines which suggests that they generate torque using the drag force applied on them. Characteristics of these turbines include the capability to self-start which is vital in areas of installation with low and variable wind speeds. They usually consist of two half-cylindrical segments connected in a S shaped fashion. One half's convex while other half's concave segment faces the upcoming wind. As the drag coefficient of concave surfaces are more as compared to convex, differences in forces generate torque which rotates it.

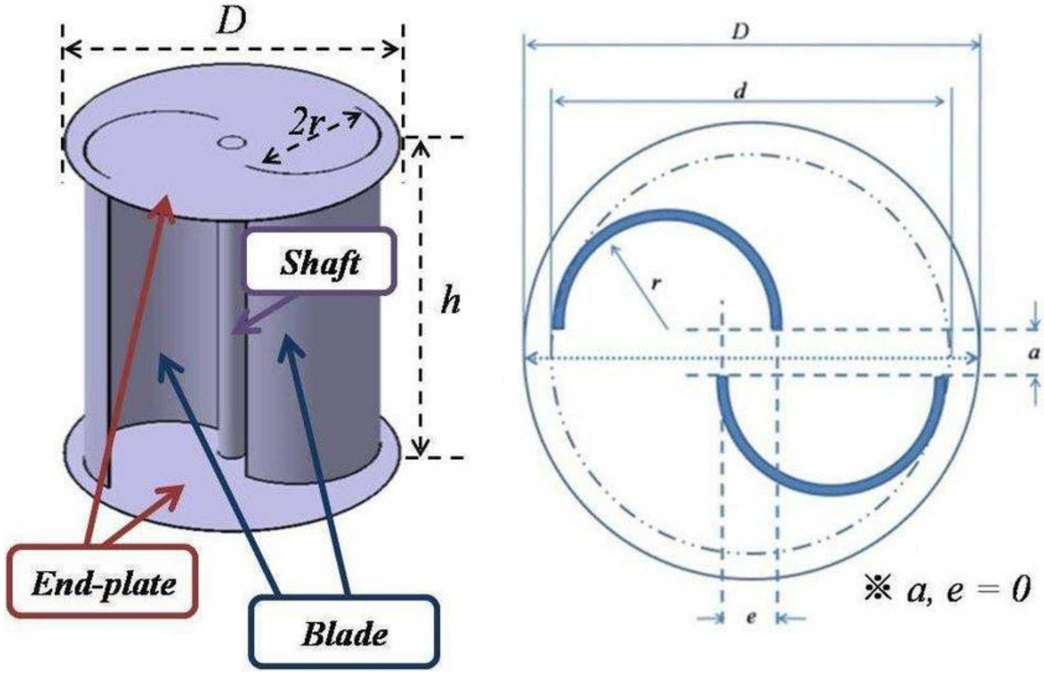


Figure 3 Savonius Wind Turbine

2.1.2 Darrieus Turbines

Darrieus turbines are lift based turbines and have shown maximum efficiency amongst Vertical Axis Wind Turbines. However, they lack the ability to self-start which makes them unreliable for low wind speed conditions. The blades may come in various shapes ranging from h-blades to helical blades. The shortcomings of each of these turbines may be compensated by combining the two types of turbines about the same axis.

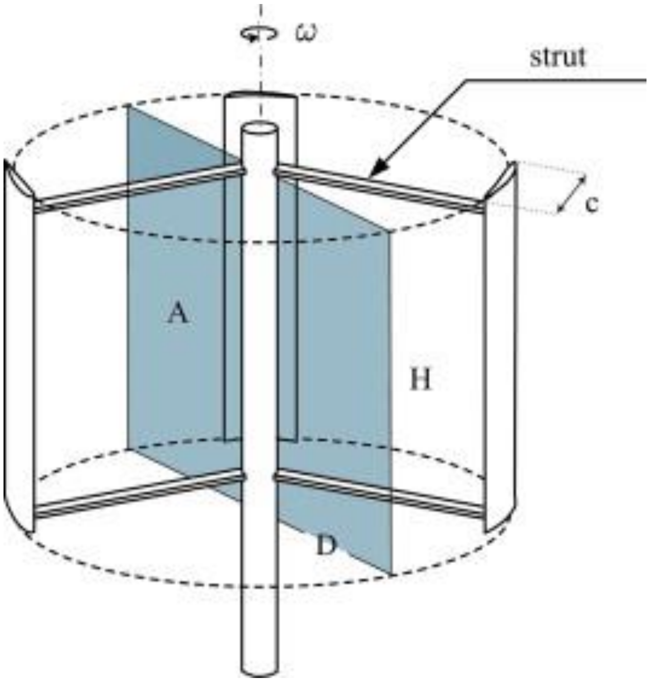


Figure 4 Darrieus Wind Turbine

2.2 Design and specifications of a simple Vertical Axis Wind Turbine

Wind turbines work on the principle of conservation of energy. The work of a turbine is to convert the kinetic energy of the wind into mechanical energy in the generator which produces electricity. The uncertainty with regards to the availability of wind energy due to the variable access of wind requires the use of devices that store energy to compensate for the duration when the wind source is lacking. Researches have shown Vertical Axis Wind Turbines to have the following advantages and disadvantages [16]:

- Advantages
    1. Adaptive to capturing wind from various directions
    2. Tower structure is not required
    3. Easier to maintain as they can be installed closer to the ground.
    4. Larger angle of airfoil allows for reduced drag at high as well as low pressures enabling better aerodynamics.
- Disadvantages
    1. Lower efficiency compared to Horizontal Axis Wind Turbines.
    2. Not suitable for high winds at larger heights.
    3. Use of cables connected to the bearing may raise downward thrust.

Research has shown that number of blades on a turbine affect the rotational speed of the turbine. With an increase in the number of blades, the ability of the turbine to capture the wind increases leading to higher efficiency. Similarly, gearbox on the turbine also influences its operation with the torque and output rising when the turbine is larger than the generator rotor part [16].

The Vertical Axis Wind Turbines may have a lower efficiency compared to a horizontal Axis Wind Turbines however, Vertical Axis Wind Turbines posses the benefit of not having to change direction with respect to change in the direction of wind. With increase in the number of blades, the rotational speed increases and with a larger gearbox on the turbine than the generator we can achieve an even greater energy generated by the generator [16] .

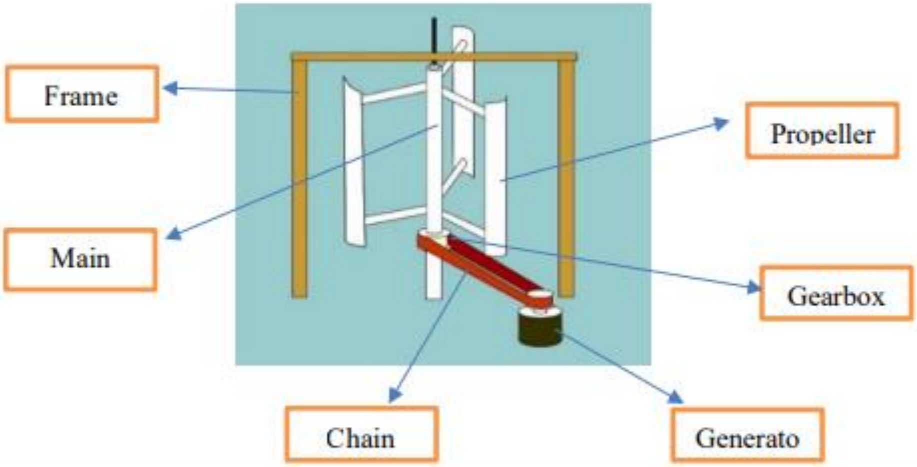


Figure 5 Components of VAWT

2.3 Configurations of Vertical Axis Wind Turbine

2.3.1 Concentric Configuration

The concentric configuration of counter rotating Vertical Axis Wind Turbines consists of multiple wind turbines mounted about the same axis. This research paper, Malael, Ion & Dragan, Valeriu. (2018), studies the performance of a Darrieus wind turbine and a savonius wind turbine mounted about the same axis with the savonius on the inside and the Darrieus on the outside. Another concentric counter-rotating configuration is the mounting of turbines vertically on top of one another however, by doing so the aerodynamics are left unaltered with no change to the power coefficient. On the other hand, the installation of a second stage turbine within the first one allows the extraction of power from the wind that would pass through unaffected otherwise [13]. The model which was studied is shown in the figure below:

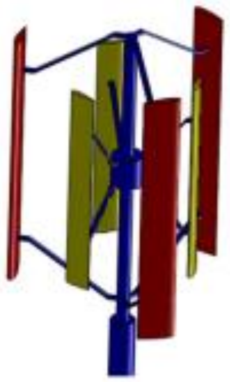


Figure 6 Concentric VAWT

The results plotted below give the torque coefficient for various wind velocities. The maximum output was achieved at velocity of 12 m/s which is where the internal turbine is at its highest efficiency.

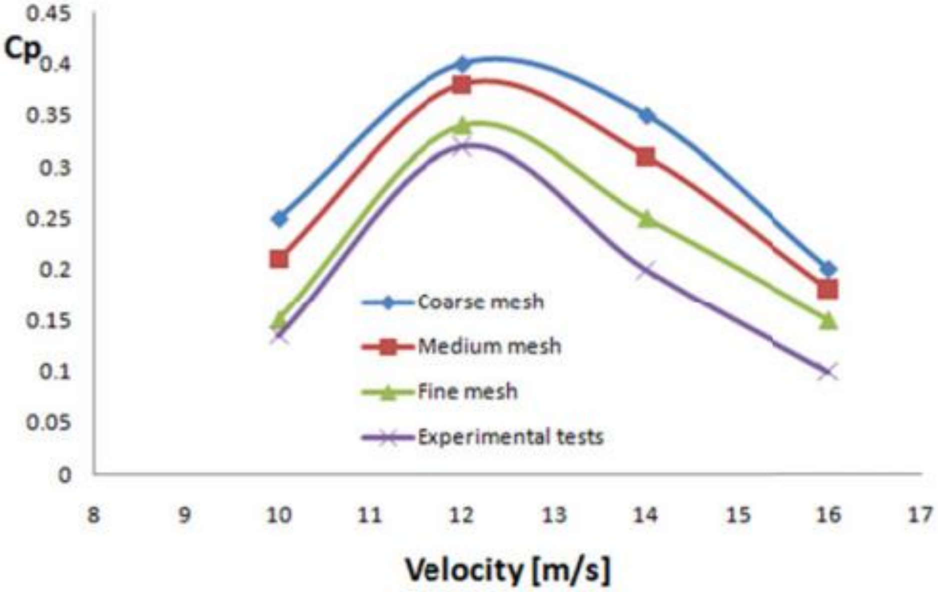


Figure 7 Output comparison for Concentric VAWT

2.3.2 Eccentric configuration

The eccentric configuration consists of turbines placed side by side in clusters. The Horizontal Axis Wind Turbines are negatively affected by nearby turbines due to distributed winds therefore, turbines have to be installed at a considerable distance to one another. Similar researches have been conducted with regards to Vertical Axis Wind

Turbines. A study by Mojtaba Ahmadi-Baloutaki [11] consists of an array of VAWTs placed next to each other with their performance evaluated and compared to isolated turbines.

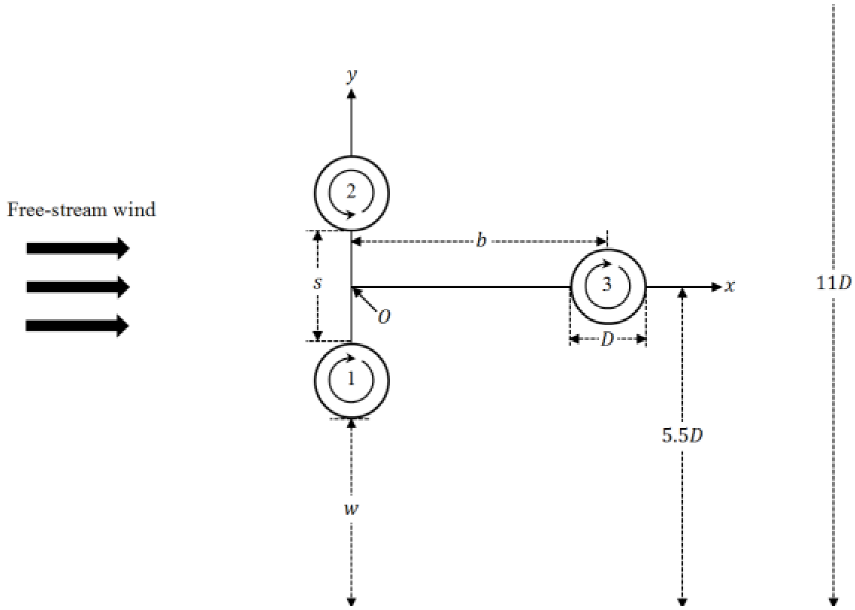


Figure 8 Eccentric VAWT

The results as shown below indicate that the results from cluster installation are not too different from isolated installations which exhibits that performance is not affected by grouped turbines [11]. Moreover, the overall turbine performance is seen to improve by the installation of turbines in a counter rotating arrangement due to the interaction of the neighboring turbines. The performance of the downstream turbine showed a considerable improvement in counter-rotating arrangement compared to co-rotating arrangement.

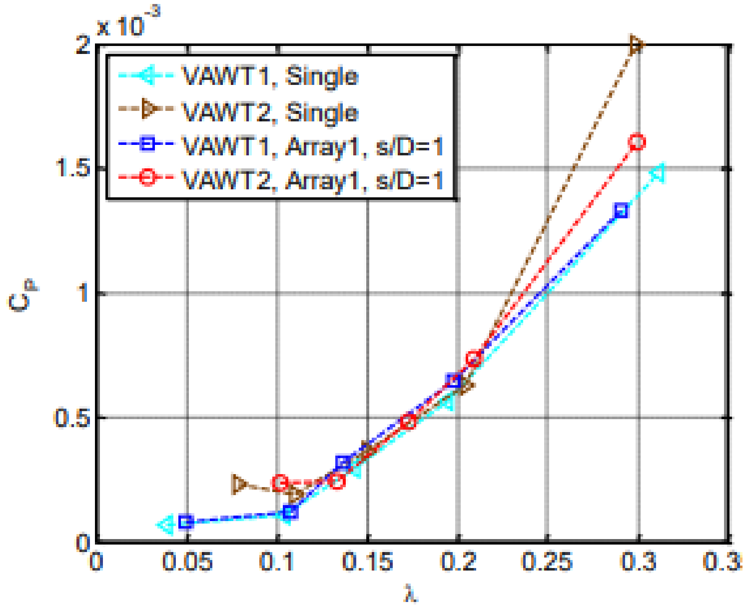


Figure 9 Coefficient of power vs Tip speed ratio

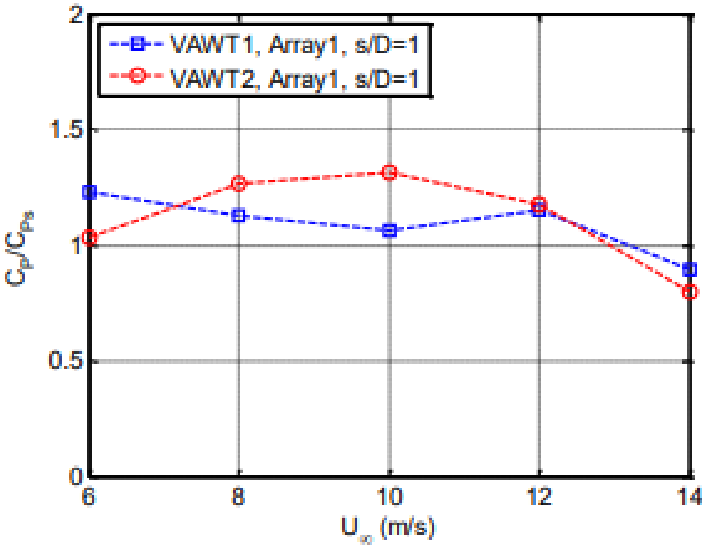


Figure 10 Coefficient ratio vs Wind Speed

2.4 Counter Rotating principle in Wind Turbines

Counter-Rotating principle takes effect by allowing two bodies to move in opposite directions relative to each other. The key advantage of the principle is the reduction in vibration by balancing the torque effects that may arise during co-rotation. Counter - Rotation is widely used phenomena with its primary application in propellers.

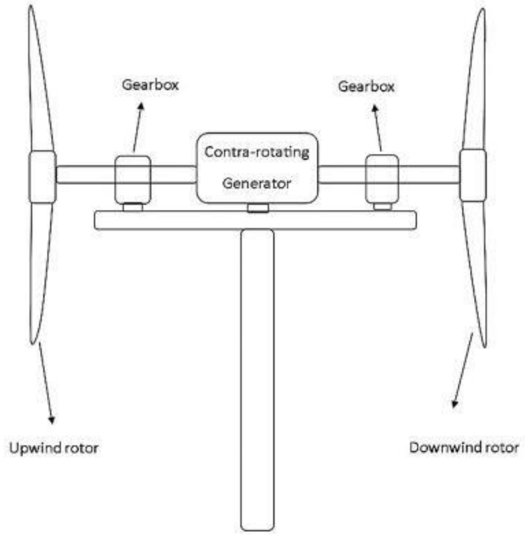


Figure 11 Principle of couner rotation

Studies have been conducted on the application of this principle towards wind turbines in order to combat a lot of the issues which prevent wind energy to truly achieve its potential. A counter rotating wind turbine consists of a front and a rear rotor which rotate in opposite directions about the same axis. Counter rotating turbines employ a more complicated mechanism when compared to single rotor owing largely to the interaction between the dual rotors. The pitch angle, rpms, radii, and blade geometry of both the rotors need to be taken into consideration when dealing with counter rotating turbines. The balance of torque resulting from the dynamic coupling related to the generator is to be taken into consideration. The transmission system of a counter rotating turbine requires a lot more attention when compared to single rotor turbines. Counter-Rotating wind turbines may be divided into several types based on the position of rotor with respect to the nacelle, the ratio of the radius of the two rotors, the type of transmission system employed, etc. The concept of counter- rotation is under application in HAWTs with a renewed focus on its effectiveness with regards to VAWTs. It may be used to create a hybrid system whereby a turbine system consisting of darrieus and savonius turbines may be created or a system consisting two identical turbines placed about the same axis.

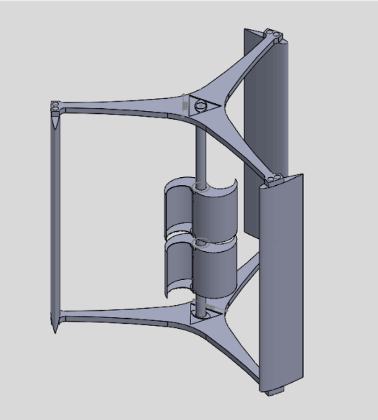


Figure 12 Counter Rotating VAWT

2.5 Types of Electromechanical Systems for a Counter-Rotating VAWT

Upon the understanding of the true potential of Vertical Axis Wind Turbines towards the clean energy, it is imperative that configurations such as counter-rotating should be explored. The initial phase in the application of the counter rotating principle in a Vertical Axis Wind Turbine is understanding its implementation in light of all tge electro-mechanical components. HAWTs have employed the use of dual rotors for a very long time so studying the rotor arrangement of HAWTs is important to verify the possibility of translating the same systems to a dual rotor VAWT. In HAWT, the most important factor towards achieving high torque is to ensure that high lift force value is obtained by ensuring high linear speed at the blade ends. This factor is taken into consideration when designing a counter rotating HAWT where the secondary turbine is mounted coaxially on the main turbine by means of a smaller diameter. This arrangement works on the principle that the main turbine is unable to extract energy from its central section of the blades which results in the wind passing through uninterrupted in that region where it is obstructed by the secondary turbine with a smaller diameter to generate power [19].

In case of VAWTs, practical knowledge is still lacking with regards to fully understanding the factors that influence its performance especially in clusters or multiple rotors. Unlike HAWTs, if VAWTs are kept along the same axis they are likely to run independently. In order to control this erratic behavior it is important that a well thought out mechanical transmission system is put in place.

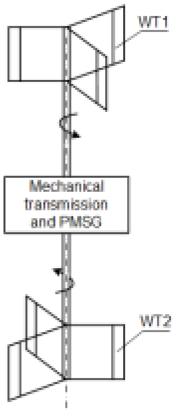


Figure 13 Design of dual rotor VAWT

Some of the options for the transmission system are discusses below:

2.5.1 Rigid Transmission with Bevel Gears

In this rigid transmission, bevel gearbox is used to transmit torque from the turbine shaft to the generators. The design that was put through the experiment is shown in the figure below. Bevel gears are mounted on shafts from the identical wind turbines and are placed inside a gearbox. The gears attached to the shafts are matched by a third bevel gear mounted on the generator shaft. A gear ratio of 0.5 to 0.2 is used in order to reach the rated rpms of the generator [19]. The system operates by allowing both the turbines to rotate under wind's influence with the resultant torque transmitted to the generator.

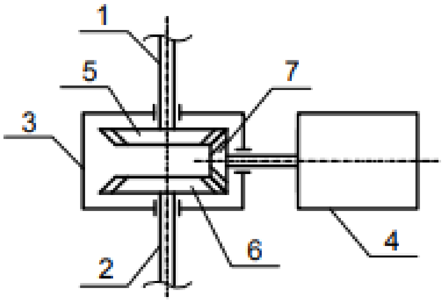


Figure 14 Rigid transmission with bevel gearbox

2.5.2 Semi-Rigid Transmission with Differential

In the semi-rigid design, bevel gears are mounted to the shafts extracted from the turbines similar to the rigid transmission case. However, two planetary gears are used to connect these gears as shown in the figure below. A carrier is attached to the arrangement whose role is to drive the generator through a bevel gear. The axles on the differential rotate in the same direction with their angular velocities influencing each other.

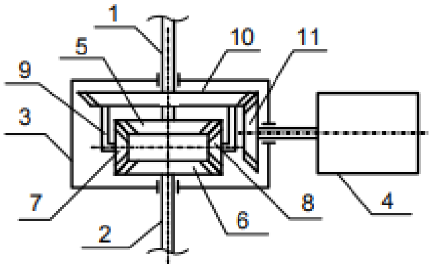


Figure 15 Semi-Rigid transmission with differential

2.5.3 Soft transmission with Double Generator

The soft transmission is the simplest form of transmission which consists of no gears and allows for the generator to be directly driven. The positive of direct drive is its reliability which is why it is also used in low power HAWT. A double rotor generator is used in this case which consists of inductor and armature rotating in opposite direction to each other [19].

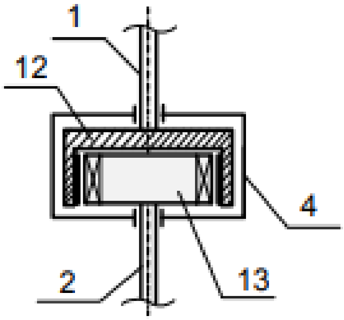


Figure 16 Soft transmission with two generators

2.5.4 Comparison of the transmission systems

The various transmission systems were discussed with a comparative study conducted on three of these systems using computer simulations. The first case consists of rigid linking through identical angular velocities. The second case allows for angular velocities to vary within the parameters of the applicable law. The third case imposes no restrictions on the angular velocities of the turbines. The results indicated that apart from the gear transmission the rest of the systems remain vulnerable at varying wind speeds. The gearless transmission exhibits excellent performance by damping the vibrations which results in it emerging as an excellent prospect for application.

2.6 Performance Evaluation of a counter-rotating VAWT

Various wind turbines are available in the industry with both commercial and experimental purposes. All of these turbines are capable to convert wind energy into electrical energy however, what differentiates them is their performance under the requisite parameters. In recent times, the concept of a counter-rotating is capturing particular attention with multiple researches being performed on the ability of the concept to enhance the energy potential from wind.

- Rotational speed

  The model is tested with wind speeds ranging from 2 m/s to 9 m/s. A direct relationship was observed between the rotational speed and the velocity of the wind with a rising trend in the rotational speed as the velocity of the wind increased as shown below [12]. A comparison of the output from a single Vertical Axis Wind Turbine with a Counter rotating wind turbine clearly showed the counter-rotating wind turbine to be at an advantage. The amalgamation of the two rotors led to better rotational speed from the counter-rotating wind turbine.

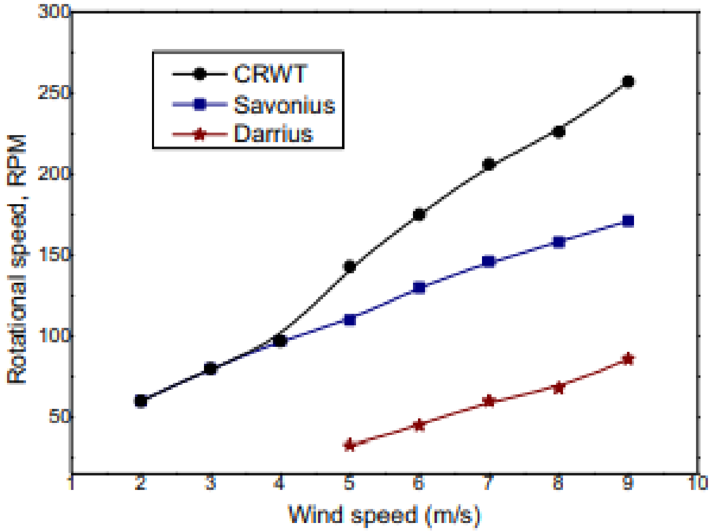


Figure 17 Rotational speed vs Wind Speed

- Mechanical torque

The figure from Didane, Djamal & Rosly, Nurhayati & Fadhli, Mohd & Shamsudin, Syariful. (2017) shows the response of the system under the range of wind speed with regards to the torque generated. The results show the torque of the Counter rotating turbine to be considerably higher although the higher output takes effect at 5m/s which is the wind speed when the Darrieus turbine starts operating at its optimum level unlike the savonius turbine which operates at low speeds such as 2 m/s [12]. This suggests that the present model is functional at low speeds such as 2 m/s however its true benefits are reaped at wind speeds higher than 5 m/s [12].

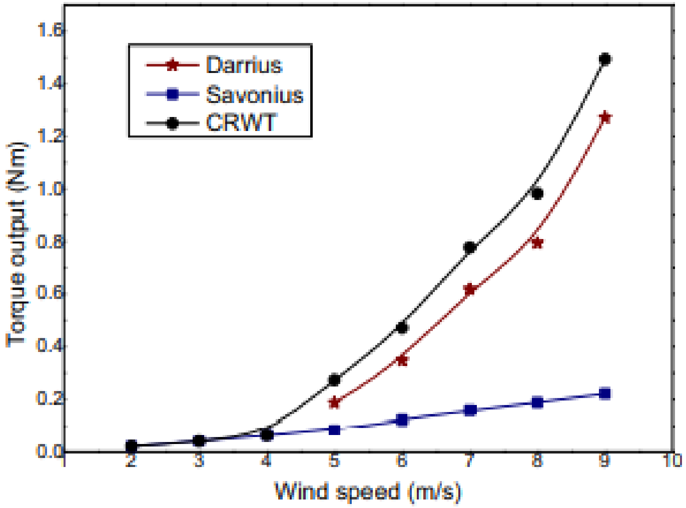


Figure 18 Torque output vs Wind Speed

- Torque coefficient

The results from the torque coefficient against the wind velocity are plotted in Figure 6 which show how efficiently the conversion of torque takes place. The Darrieus turbine performed better under higher wind conditions however its contribution to the overall efficiency was lower than the Savonius turbine. The combined efficiency continued to be higher than the single case with an average conversion of 42 percent derived from the combined rotors [12].

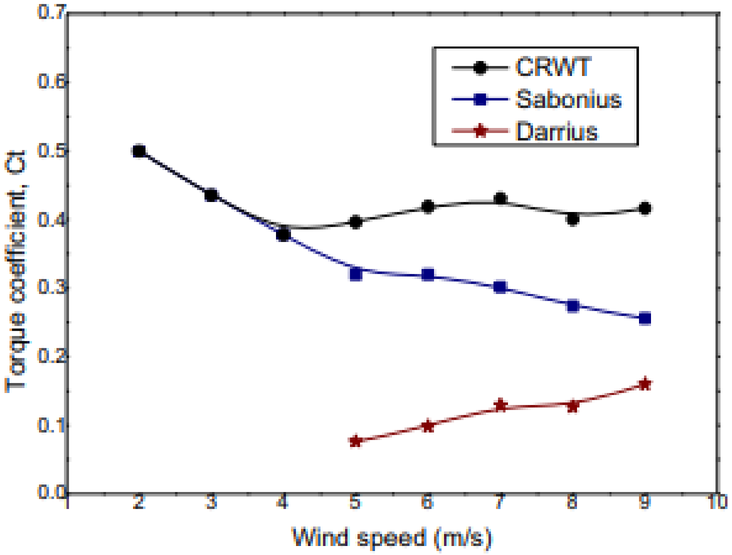


Figure 19 Torque Coefficient vs Wind Speed

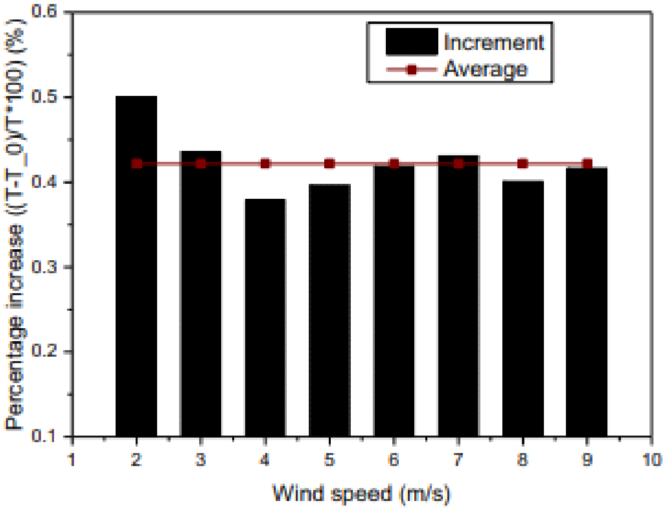


Figure 20 Percentage torque coefficient increase vs Wind Velocity

2.5 Design Problems faced in the design of a counter rotating VAWT

The design of a Vertical Axis Wind Turbine consists of challenges with the consideration of multiple parameters in the selection of each component. The first decision regarding the design phase is the selection of airfoil. It is important to take into consideration that thicker airfoils with greater camber perform better and enable the self-start mechanism. This is followed by a design decision on the material of the blade. It is imperative that the material of the blade is lightweight to ensure operation at low speeds with enough strength to sustain the operation at higher winds [17].

The transmission system needs to be designed as well with particular attention to the bearings and gear box used; These should be capable to fulfil the transmission purpose along with bearing the weight of the system that is applied on them. Design decisions on the dimensions of the shafts is another challenge. Shafts are a key member of the transmission system so they have to be carefully designed to ensure maximum transmission [37].

In order to ensure the commercial success of the turbine, it is important to ensure that turbines are designed as close to their optimum case as possible. This may be done due by increasing the swept area or by the introduction of flap and pitch systems however, this may lead to an increased cost which remains to be a very important factor in the fabrication [17]. In addition to budget constraints, designers may face weight and size requirements which further complicate the design and manufacturing phase.

2.6 Optimization of VAWT cluster

The installation of Vertical Axis Wind Turbines in clusters has shown better output than single installations. The efficiency of these clusters is influenced by a number of parameters including the turbine gap, wind angle, etc [15]. The study, Hassanpour, Mahsa & Azadani, Leila. (2021), showed that in case of the placement of turbines next to each other, the reduction in the distance between the turbines led to increase in the efficiency. The study regarding the performance of arrays showed that the power coefficient is very small at short distances with its maximum at around a distance of 1.5 turbine diameters and then a further decrease is observed [15]. A performance study on the gap in turbines, tip speed ratio and direction of wind reveals a higher power generation capability in case of side-by-side placement than a staggered installation with the observation that a staggered installation extracts higher output from the downwind turbine compared to the upwind turbine. The influence of wind direction is reduced when turbines are installed in closed vicinity with the performance of both the upwind and downwind turbine enhanced. The impact of optimum installation was studied as well with an increase of 1.8% in output recorded by merely adjusting the turbines to operate under optimum conditions [15].

A study of the effect of the rotational direction on the performance of turbines was conducted with counter rotating turbines producing greater output compared to co-rotating wind turbines. This was revealed to be due to the greater wake interaction in case of counter rotation. The addition of a deflector is a source of increasing the efficiency of turbines with results revealing an enhancement of up to 38.6% due to the addition of a deflector.

The individual effects were combined to study the overall effect of multiple parameters on the performance of turbines. The results revealed that the tip speed ratio has the largest influence on the output with the blade azimuth angle having the least impact. A overall enhancement of 9.97% was achieved by the optimization of multiple parameters compared to an isolated wind turbine [25].

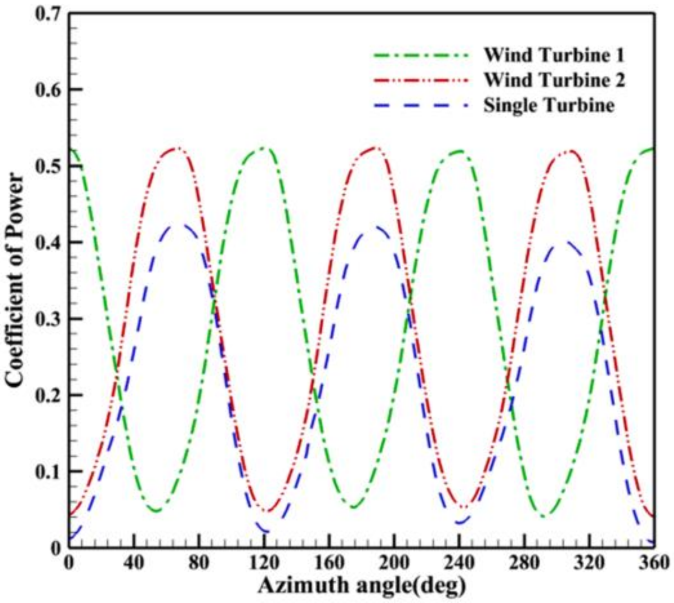


Figure 21 Power Coefficient vs Azimuth angle

Therefore, it was evaluated that the simultaneous effect of the important factors needs to considered for the maximum efficiency of the turbine. Some of the factors at optimum conditions were deemed to be:

- a horizontal distance of 1.5 turbine diameter
- vertical distance of 0
- wind angle of 90 degrees

CHAPTER 3: METHODOLOGY

The wind turbine for this study has been designed using the methodology proposed by Brusca, Lanzafame and Messina in their research. This methodology has been derived from Multiple Stream Tube Model (MSTM [46]. Figure 1 shows a flow chart of the turbine design process.

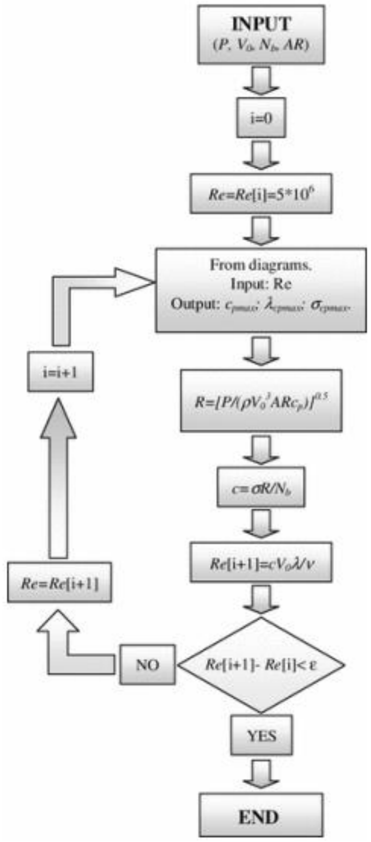


Figure 22 Design Process

The wind turbines are designed considering the wind speed and desired power output.

Power coefficient and tip speed ratio are plotted against each other as function of solidity of the rotor. Iterative method was used to calculate the turbine design parameters. The power of a Vertical axis wind turbine is given by Eq. (1).

$$P = \frac{1}{2} \rho V_{o} 32RHCp \qquad (1)$$

Power, wind speed, number of turbine blades and aspect ratio are taken as inputs. Then a plot is selected for a specific Reynolds number (Re) and maximum power coefficient, tip speed ratio and blade solidity is selected from that plot[47]. These values are then plugged in the power equation (Eq. (1)) and the wind turbine radius is found. The chord length of the airfoil is calculated using Eq. (2).

$$c = (\sigma Cpmax/Nb) * R \qquad (2)$$

Reynolds number of the wind turbine is calculated by Eq. (3).

$$Re = cVo\lambda Cpmax/v \qquad (3)$$

This Re is compared with the original Re selected at the time of selection of the wind turbine power coefficient curves. The error is reduced by repeating the same procedure. Usually after two iterations the solution is converged, and the error is reduced. VAWT rotational speed is given by Eq. (4).

$$\omega = \lambda CpmaxVo/R \qquad (4)$$

After following the design processes the design parameters of the turbine are finalized and shown in Table.

Parameter	Value
Power (W)	100Watt
Airfoil	NACA 0018
Wind speed (m/s) – 12	8m/s
Air density (Kg/m3) At 300K	1.225
Kinematic air viscosity (m2 /s)At 300K	$1.568x10^{-5}$
Rotor aspect ratio (h/R)	2(lift blade set), 5.33(drag blade set)
Number of blades (Nb)	5(lift), 2(Drag)
c_{pmax} , σ_{cpmax} , λ_{cpmax}	0.45, 0.5,[2.5(lift), 2 (drag)]
Rotor radius (m)	1
Airfoil chord length (m)	0.1
Rotational speed	20 rad/s

Table 3 Design Parameters

3.1 CFD

In this study the flow is considered incompressible. To analyze the turbulence in the flow many different models are derived from navier-stokes equations. In this study Reynolds Averaged Navier-Stokes equations (RANS) have been used to model the wakes generated in the flow by VAWT blade

The RANS equation is given as follows:

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = f_i - \frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}(2vS_{ij})$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)$$

Where fi is the external force vector, ρ is air density, p is pressure, v is kinematic viscosity, Sij is the tensor form of strain rate, u is the free stream velocity, t is time, x is the position vector, i,j are directional components.

3.1.1.VAWT Rotor Domain

Based on the geometric data retrieved from design process detailed in previous section, a CAD model of the turbine was generated. A fluid domain was created around the turbine. The domain is designed in two parts rotating fluid domain and fluid domain. This domain has been designed to validate the study. The direction of wind flow and rotation of wind turbine along with the dimensions of the validation domain is shown in Figure

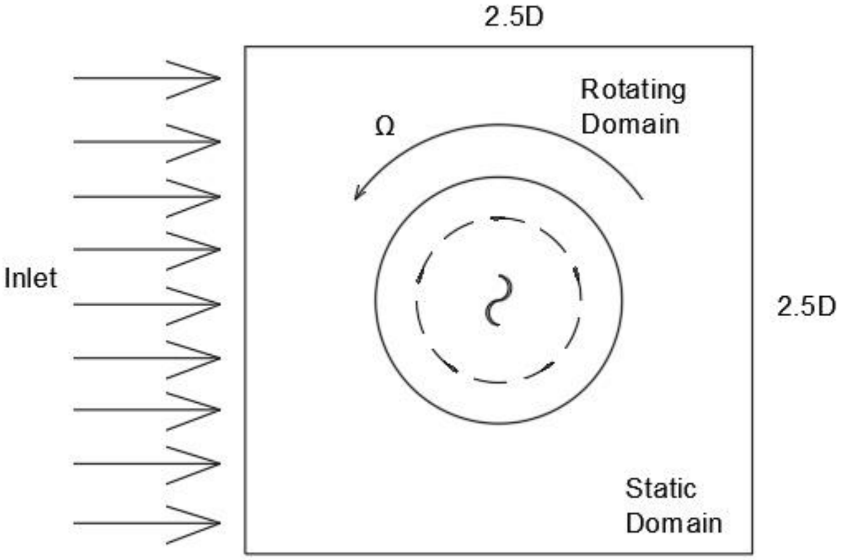


Figure 23 Rotor Domain

3.1.2 Boundary Conditions.

In this study the flow is considered incompressible. The upstream wind velocity 8 m/s for the steady flow simulation. The rotational velocity of the wind turbine has been calculated using Eq. (4). These rotational velocities have been shown in the table. A 300K ambient temperature has been considered for this study. Upstream flow is considered laminar.

3.2 Flow and efficiency analysis

The counter rotating VAWT is compared in results to the working of the simple lift and drag turbines separately. The Coefficients of performance for lift, drag, moment and power are found separately.

The flow conditions are analyzed under a steady flow condition where there is a static fluid and rotating fluid region embedded in the tests. The optimum upstream velocity is 8m/s.

The optimum TSR for the outer blades is 2.5, whereas the inner blades have a TSR for 2.

Using the data obtained from the simulations, we find that the Cp for the prototype comes out to 0.45. The power that can be harnessed from the swept area is 313.6 Watts.

Multiple that by the Cp we get a maximum extractable energy of 141.12 Watts.

The overall industrial efficiency of such project lies around 37-42%. For convenience we estimate an overall efficiency of 33%. Which gives us around 89 watts of energy that may be produced from the generator.

3.3 Design of the wind turbine

The turbine consists of 2 sets of blades aligned concentrically. The outer set of blades operates on the principle of lift generation having a diameter of 30 in and blade lengths of 31.5 in. The profile used for this set is the NACA 0018 having a chord length of 100mm. For the inner set of blades which operates on the principle of drag force due to geometry of the blades, the dimensions contain a diameter of 10 in and the blade length for these is 26 in.

The concentric mounting allows the extraction of energy with relevance to the velocity for the set of outer blades and the inner blades extract energy due to the pressure development and mass flow rate of the air through the control volume.

3.2.1 Darrieus Turbine Model

A Darrieus turbine with 6 blades was created. The model consisted of blades which were mounted on an acrylic sheet connected by bolts with a blade diameter of 31.5 in and a swept diameter of 30 in. A shaft of 25 mm was extracted from the turbine for torque transmission. The NACA 0018 airfoil was selected due to its performance and ease of manufacturing.

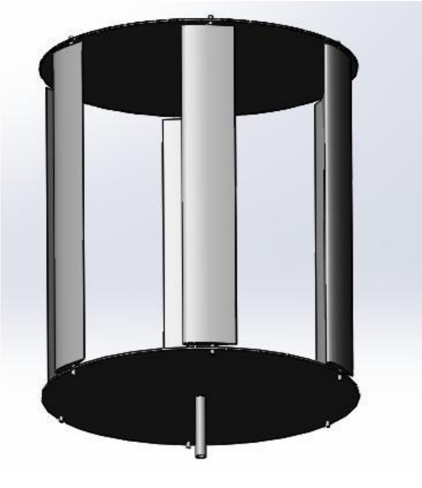


Figure 24 Darrieus turbine model

3.3.2 Savonius Turbine Model

A Savonius Turbine was designed consisting of blades formed by two semi-circles joined at the center. The blade had a convex shape on one side and concave on the other with a blade diameter of 26 in and a swept diameter of 10 in. A shaft of 8 mm was extracted from the turbine for torque transmission.

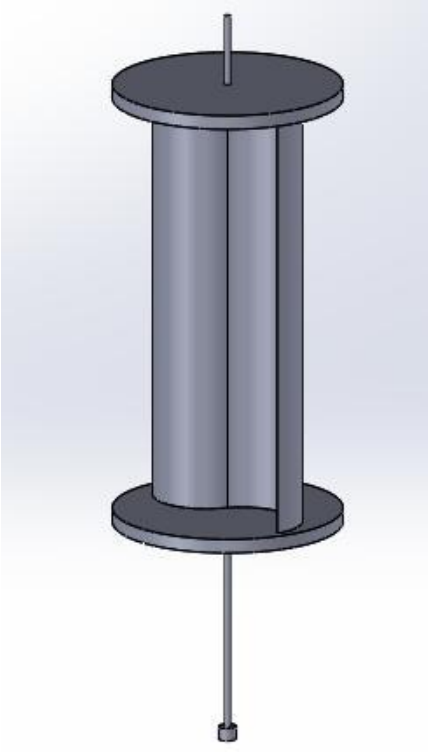


Figure 25 Savonius Turbine model

3.2.3 Support Frame

A support frame, made of wood was used as support structure to enhance the structural integrity of the project. Studs were mounted on the lower level of the support to allow the turbine to rest when not under operation.

Figure 26 Support frame

3.2.4 Generator assembly

Two shafts were extracted from both the turbines respectively with a generator and pulley assembly mounted on each. The 9 inch pulley was driven by a belt in order to transmit the torque generated by the turbines to the generators.

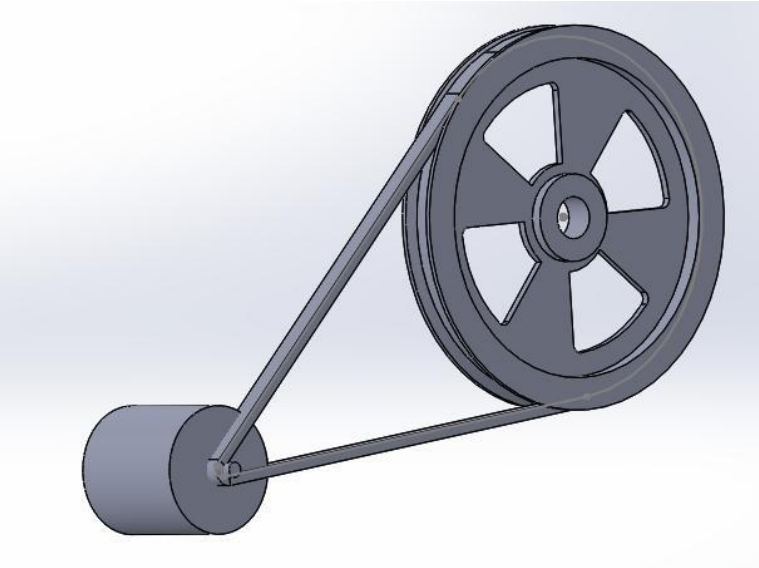


Figure 27 Generator and pulley assembly

3.2.5 Bearing

Deep groove ball bearings were used at each end of the turbines to allow relative motion. Two sets of bearings were used for each turbine. Main bearings were mounted on the shaft from the Darrieus Turbine with smaller bearings mounted on the Savonius Turbine. The sets of bearings were fitted in a bearing fitting. The bearing specifications for each of the turbine is given below:

Darrieus Turbine

- Outer Diameter: 63 mm
- Inner Diameter: 25 mm

Savonius Turbine

- Outer Diameter: 25 mm
- Inner Diameter: 8 mm

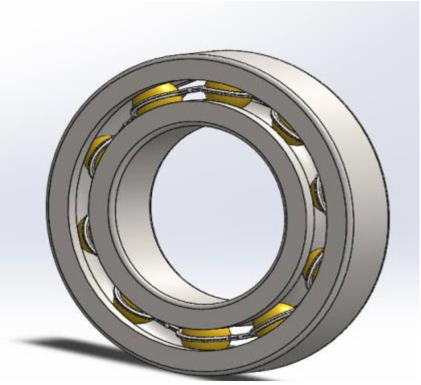


Figure 28 Bearing

3.2.6 Assembly model

The assembly of the counter rotating Vertical Axis Wind Turbine with and without the support structure is shown below. The shaft connected to the Darrieus turbine is connected to the upper pulley with the shaft from the Savonius turbine passing through and connected to the lower pulley with belts driving both the generators.

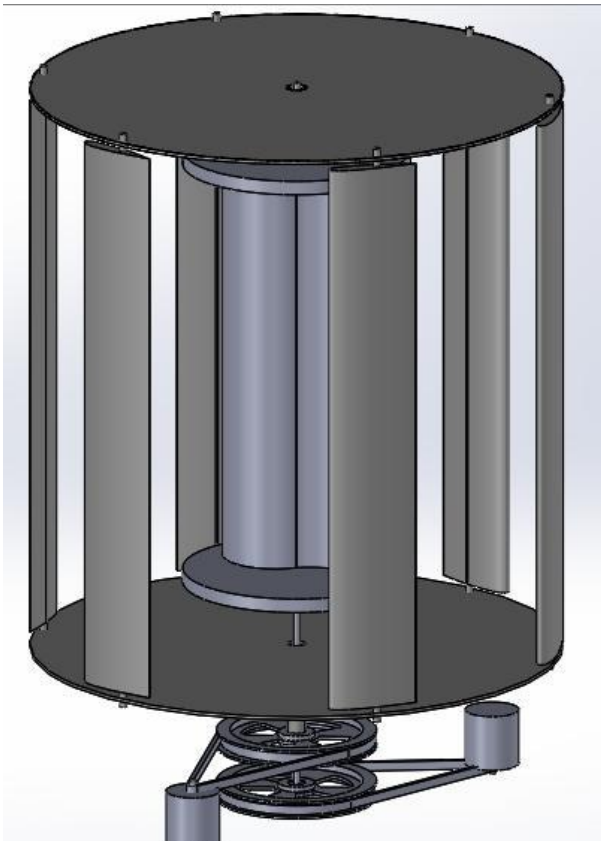


Figure 29 Assembly without support structure

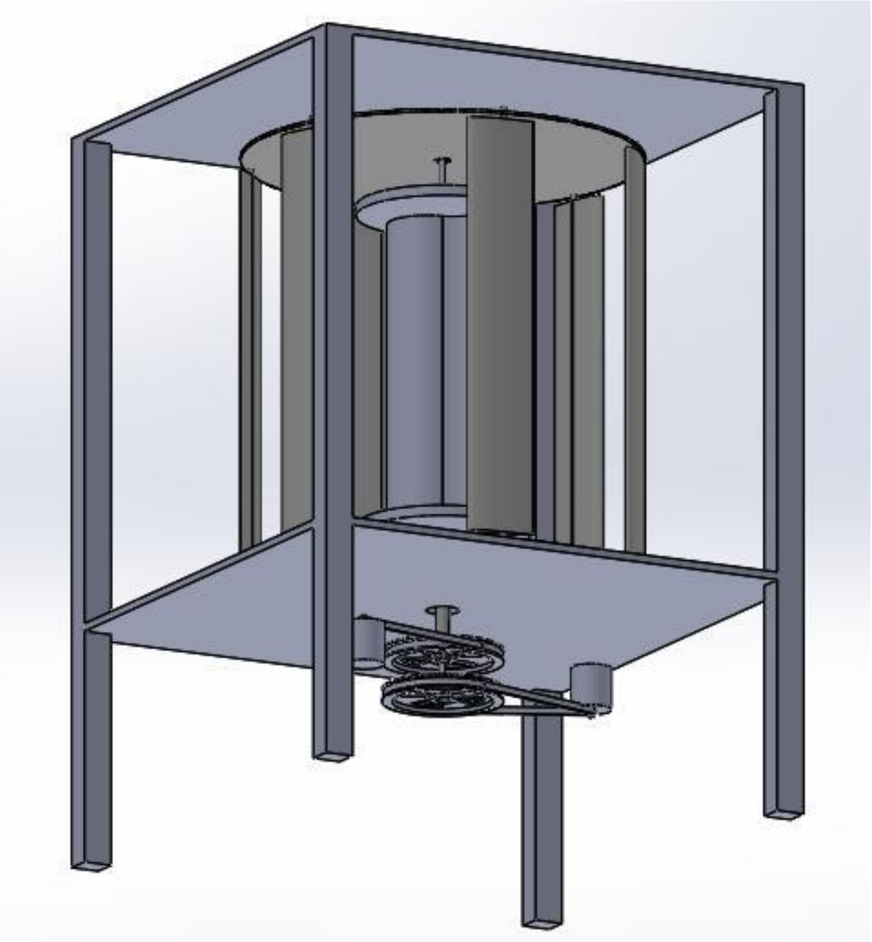


Figure 30 Model Assembly with support structure

3.4 Fabrication

The fabrication process was conducted by manufacturing the individual parts before assembling them to reveal the final prototype. The blades were manufactured of PVC material according to the specifications in the model after validation through the results from flow simulation. The blades were mounted using bolts on acrylic sheets which were cut to size and used for their durability. A shaft was extracted from each shaft with the torque acquired through the rotation of turbine being passed to the generator through a transmission system. The transmission system consisted of deep groove ball bearings to allow relative motion along with a pulley and belt system used for efficient transmission. A wooden structure was manufactured for the Vertical Axis Wind Turbine to support the project by enhancing its structural integrity and eliminating any undue vibration.

Studs were mounted on the support base to allow the turbine to rest when not under operation. A neck was created at the top surface of the support to lift the turbine off the studs during operation. This was done to suspend the turbine to reduce friction while maintaining the structural integrity and low vibration levels. These individual parts were then assembled and the project was put through the testing phase.

Figure 31 Fabricated Counter-Rotating VAWT

3.4.1 Cost Breakdown

Lamination sheets	3000
Thread rod	2200
Acrylic Sheets 2500	7500
Silicon Bonding Agent	220
PVC Pipes	1800
Iron Pipe	800
Main Bearing	2500
Small bearing	640
Stud Bearing	1200
Nuts and Bolts	700
Wooden Support	2000
Pulleys and Generators	8000
Miscellaneous	9000
Total	48120

Table 4 Cost Breakdown

3.5 Performance testing

The performance testing was carried out upon the completion and fabrication of prototype. The performance testing consists of two sections. Firstly, the turbine’s performance will be quantified in terms of power by calculating the break power of the turbine by applying a counter load to the turbine rotation. The load at which the turbine breaks to a halt shall give us the torque generated by the turbine which may be used to formulate the power generation capability of the turbine. Secondly, the actual power output shall be quantified through a multimeter to achieve the power being generated by the generators.

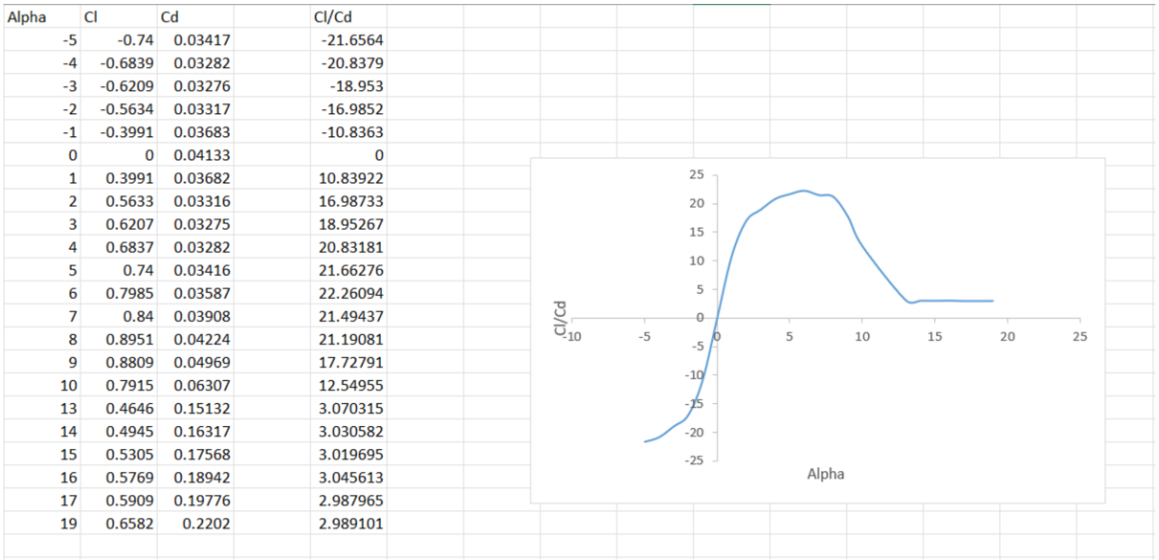
3.6 Performance analysis

The performance of the prototype will be evaluated in terms of the power delivered through electricity and the rpm at which the output of the system stabilizes and reaches optimum power generation levels.

CHAPTER 4: RESULTS AND DISCUSSIONS

4.1 NACA 0018 Airfoil

The primary blade set consists of five NACA 0018 airfoil blades. The lift force generated due to the pressure differential across its cross-section is the force that drives this airfoil shaped blade. The efficiency of these lift type blades is largely dependent on the lift-to-drag ratio which is in turn dependent on the angle of attack (α). A plot between the lift-to-drag ratio and angle of attack (α) for the 0018 airfoil is as follows:



Alpha	Cl	Cd	Cl/Cd
-5	-0.74	0.03417	-21.6564
-4	-0.6839	0.03282	-20.8379
-3	-0.6209	0.03276	-18.953
-2	-0.5634	0.03317	-16.9852
-1	-0.3991	0.03683	-10.8363
0	0	0.04133	0
1	0.3991	0.03682	10.83922
2	0.5633	0.03316	16.98733
3	0.6207	0.03275	18.95267
4	0.6837	0.03282	20.83181
5	0.74	0.03416	21.66276
6	0.7985	0.03587	22.26094
7	0.84	0.03908	21.49437
8	0.8951	0.04224	21.19081
9	0.8809	0.04969	17.72791
10	0.7915	0.06307	12.54955
13	0.4646	0.15132	3.070315
14	0.4945	0.16317	3.030582
15	0.5305	0.17568	3.019695
16	0.5769	0.18942	3.045613
17	0.5909	0.19776	2.987965
19	0.6582	0.2202	2.989101

Figure 32 Airfoil data

The plot shows an optimal angle of attack (α) of around 5-6 degrees. Other airfoil shapes can provide a better lift-to-drag ratio but the ease of manufacturing due to the symmetrical cross-section makes 0018 an overall better choice.

4.2 S-Type Drag Blade

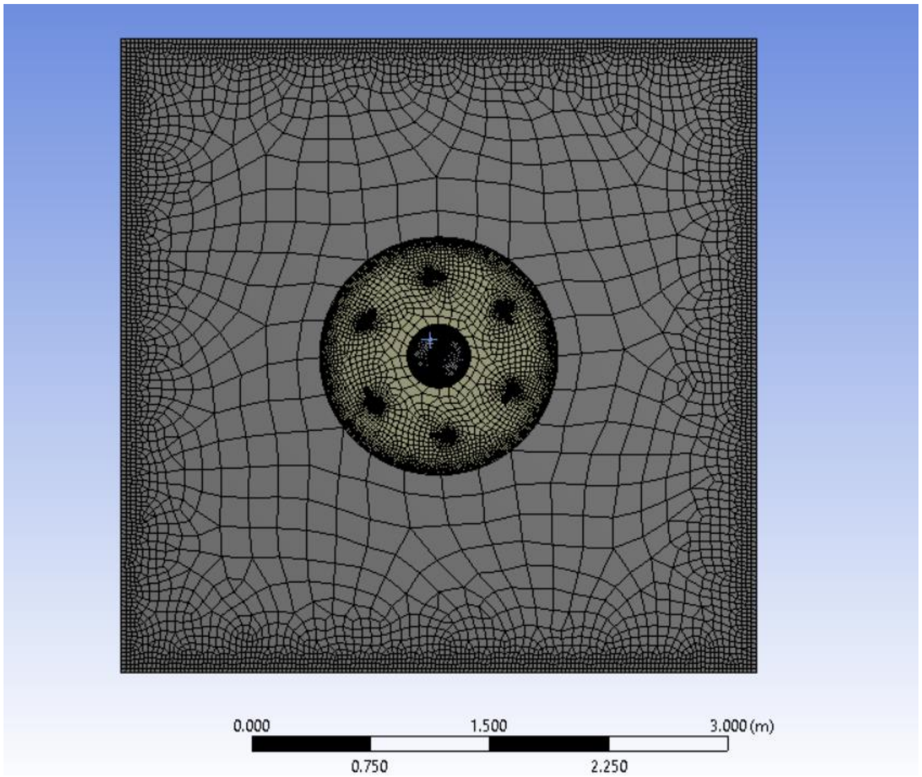
The inner configuration is two bucket shaped blades that rotate under the influence of drag force experienced because of their orientation with respect to the pre-dominant flow direction. These blades require a large amount of torque to rotate and are generally less efficient than their lift type counterparts. The reason for that being the absence of high-pressure stagnant wind that could generate the large drag forces required to rotate these blades. However, in this scenario, high pressure stagnant wind is being generated in the wake of the lift type blades making the drag force larger for the inner blade set.

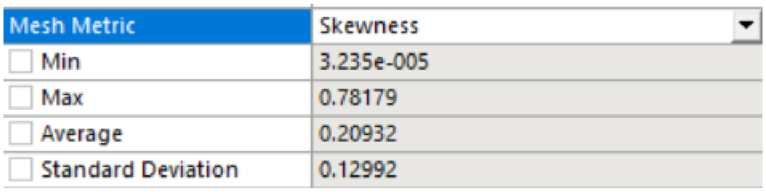
4.3 Numerical Analysis

In order to calculate the constantly varying lift and drag forces, numerical analysis is performed. Furthermore, the plot between tip speed ratio and coefficient of performance is also required which will be obtained using the moment acting on each blade set.

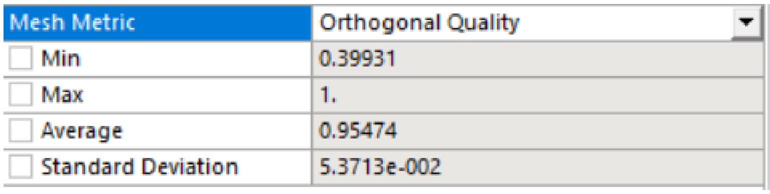
4.4 Pre-analysis setup

In order to conduct the numerical analysis, a two-dimensional model of the entire system is made with separate domains for each blade set so that they can rotate independently. Each lift type blade is fixed with a set angle of attack of around six degrees with respect to the incoming wind. A refined mesh is generated with an average skewness of approximately 0.2 and a total of around 65,000 elements.

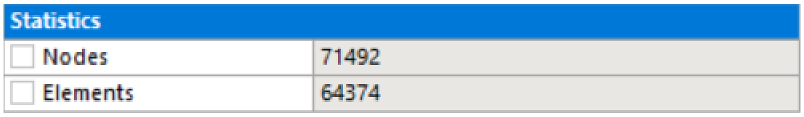




Mesh Metric	Skewness
☐ Min	3.235e-005
☐ Max	0.78179
☐ Average	0.20932
☐ Standard Deviation	0.12992



Mesh Metric	Orthogonal Quality
☐ Min	0.39931
☐ Max	1.
☐ Average	0.95474
☐ Standard Deviation	5.3713e-002



Statistics	
☐ Nodes	71492
☐ Elements	64374

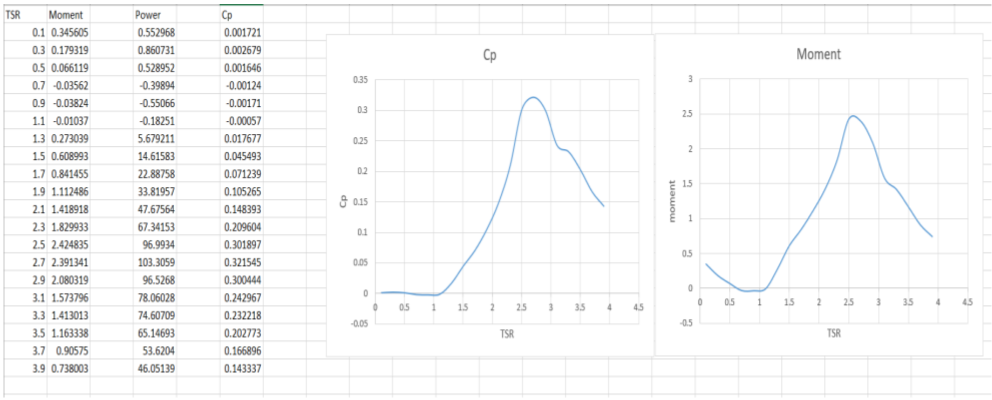
Figure 33 Mesh

4.5 Analysis parameters

A transient pressure-based study is conducted with a viscous k-omega model which is often used to simulate the turbulent flow generated in case of turbines. Furthermore, shear stress transport equations are also implemented which are known to give better results closer to the walls which in this case are the turbine blades. Respective mesh interfaces are assigned to each domain. Air properties are input in accordance with the turbulent flow which is marked by a Reynolds number of around 50000 for the given wind speed and blade specifications. For the transient study, the number of timesteps for each tip-speed-ratio is kept 200 while the size of timestep is varied to simulate a total of 10 turbine revolutions at each TSR. A convergence of exponent negative four is targeted for each timestep with the number of iterations being 50 per timestep.

4.6 Interpretation of numerical data

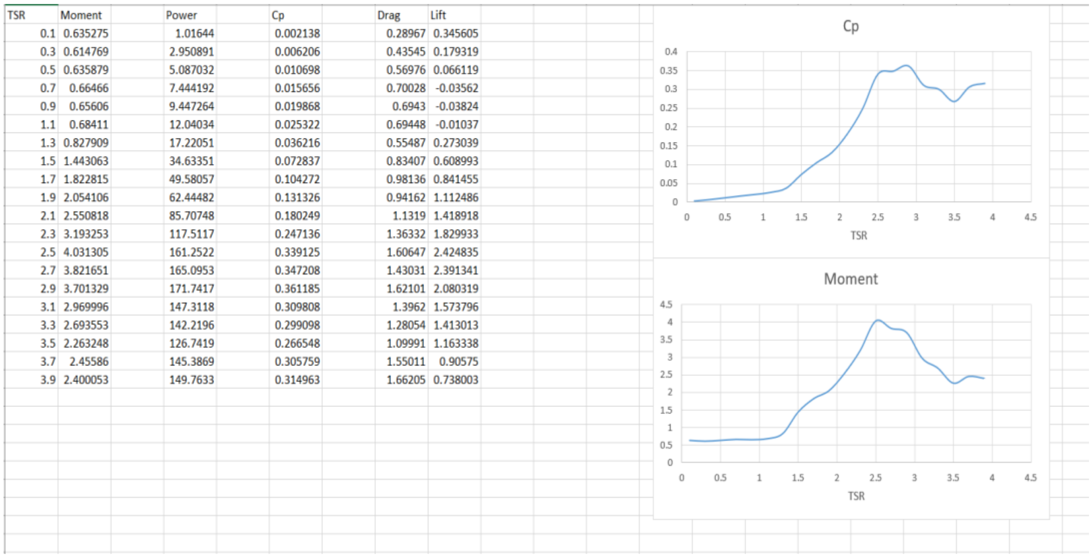
Data obtained from the numerical analysis shows significant variation in the lift and drag forces acting on the blades. This cyclic loading can be cause of fatigue in the turbine blades making it necessary to use a use a material that is capable of resisting fatigue inducing loads. In general, the relation between the tip-speed-ratio and coefficient of performance is a bell-shaped curved with optimum TSR being the one with the highest value of COP. The Cp and moment behavior with respect to varying TSR obtained from the numerical analysis is as follows:



TSR	Moment	Power	Cp
0.1	0.345605	0.552968	0.001721
0.3	0.179319	0.860731	0.002679
0.5	0.066119	0.528952	0.001646
0.7	-0.03562	-0.39894	-0.00124
0.9	-0.03824	-0.55066	-0.00171
1.1	-0.01037	-0.18251	-0.00057
1.3	0.273039	5.679211	0.017677
1.5	0.608993	14.61583	0.045493
1.7	0.841455	22.88758	0.071239
1.9	1.112486	33.81957	0.105265
2.1	1.418918	47.67564	0.148393
2.3	1.829933	67.34153	0.209604
2.5	2.424835	96.9934	0.301897
2.7	2.391341	103.3059	0.321545
2.9	2.080319	96.5268	0.300444
3.1	1.573796	78.06028	0.242967
3.3	1.413013	74.60709	0.232218
3.5	1.163338	65.14693	0.202773
3.7	0.90575	53.6204	0.166896
3.9	0.738003	46.05139	0.143337

Figure 34 CFD Results for lift type VAWT

The optimum TSR comes out to be 2.7 at which maximum Cp is observed. The max Cp value is 0.321545 which makes the actual power (before machine and generator losses) around 110W.



TSR	Moment	Power	Cp	Drag	Lift
0.1	0.635275	1.01644	0.002138	0.28967	0.345605
0.3	0.614769	2.950891	0.006206	0.43545	0.179319
0.5	0.635879	5.087032	0.010698	0.56976	0.066119
0.7	0.66466	7.444192	0.015656	0.70028	-0.03562
0.9	0.65606	9.447264	0.019868	0.6943	-0.03824
1.1	0.68411	12.04034	0.025322	0.69448	-0.01037
1.3	0.827909	17.22051	0.036216	0.55487	0.273039
1.5	1.443063	34.63351	0.072837	0.83407	0.608993
1.7	1.822815	49.58057	0.104272	0.98136	0.841455
1.9	2.054106	62.44482	0.131326	0.94162	1.112486
2.1	2.550818	85.70748	0.180249	1.1319	1.418918
2.3	3.193253	117.5117	0.247136	1.36332	1.829933
2.5	4.031305	161.2522	0.339125	1.60647	2.424835
2.7	3.821651	165.0953	0.347208	1.43031	2.391341
2.9	3.701329	171.7417	0.361185	1.62101	2.080319
3.1	2.969996	147.3118	0.309808	1.3962	1.573796
3.3	2.693553	142.2196	0.299098	1.28054	1.413013
3.5	2.263248	126.7419	0.266548	1.09991	1.163338
3.7	2.45586	145.3869	0.305759	1.55011	0.90575
3.9	2.400053	149.7633	0.314963	1.66205	0.738003

Figure 35 CFD Results for combined VAWT

The optimum TSR comes out to be 2.9 at which maximum Cp is observed. The max Cp value is 0.361185 which makes the actual power (before machine and generator losses) around 170W. The improvement in Cp validates the combined design and shows that the stagnant flow generated by the lift type blades is being utilized by the drag type blades.

4.7 Plots

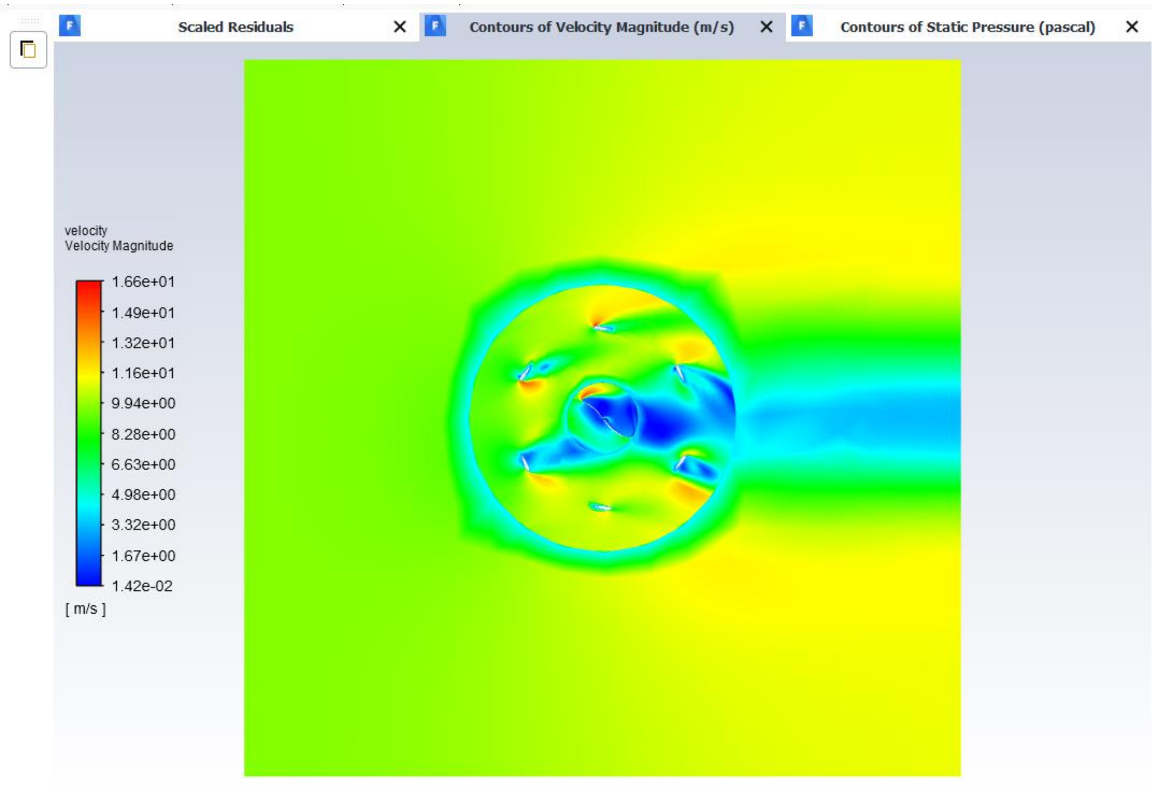


Figure 36 Contour of Velocity Magnitude

Higher velocity on the upper side of the front facing airfoil with the most optimum angle of attack indicates the necessary pressure differential that causes the lift force (driving force) to act on the blade. With blades having high angular velocity and consequent inertia, one of the blades will always be in this position resulting in continuous torque acting on the blade set. As far as the inner blades are concerned, the stagnant wind can be observed which results in high drag forces acting on the inner blade set turning it with relatively high angular velocity.

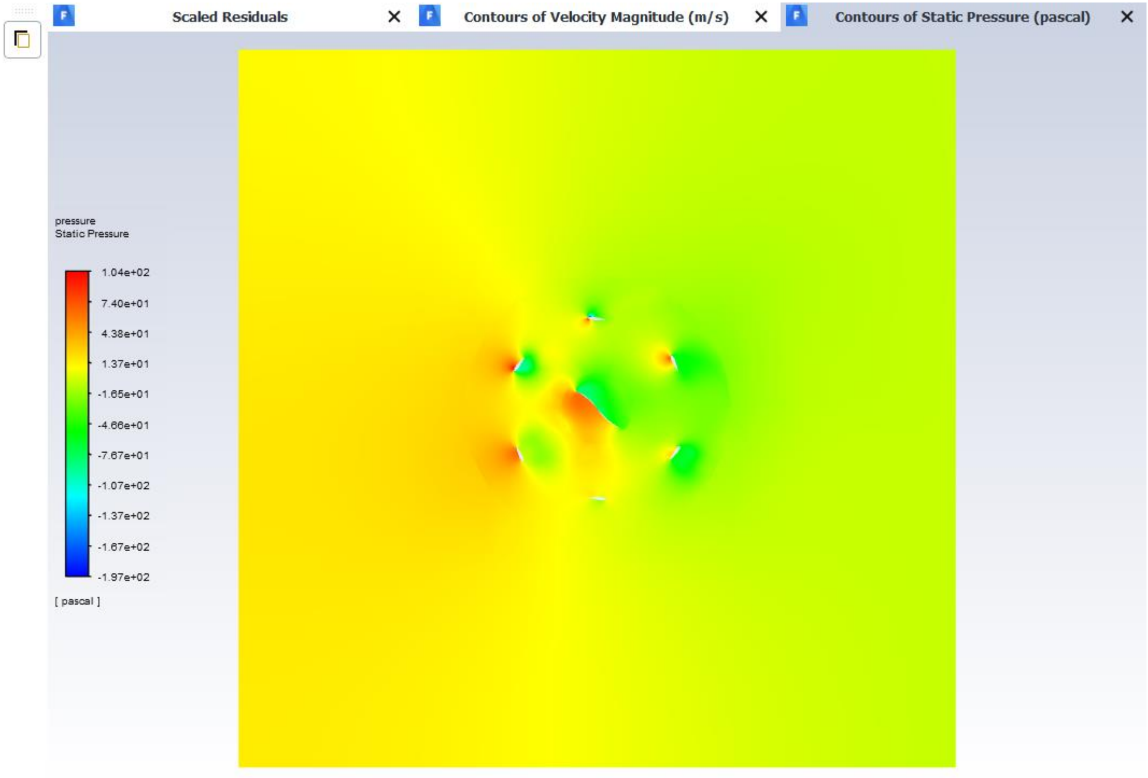


Figure 37 Contour of static pressure

Much like the velocity contour, the static pressure contour further elaborates the situation by displaying pressure at various points of interests. The aforementioned pressure gradient due to velocity difference can be seen here.

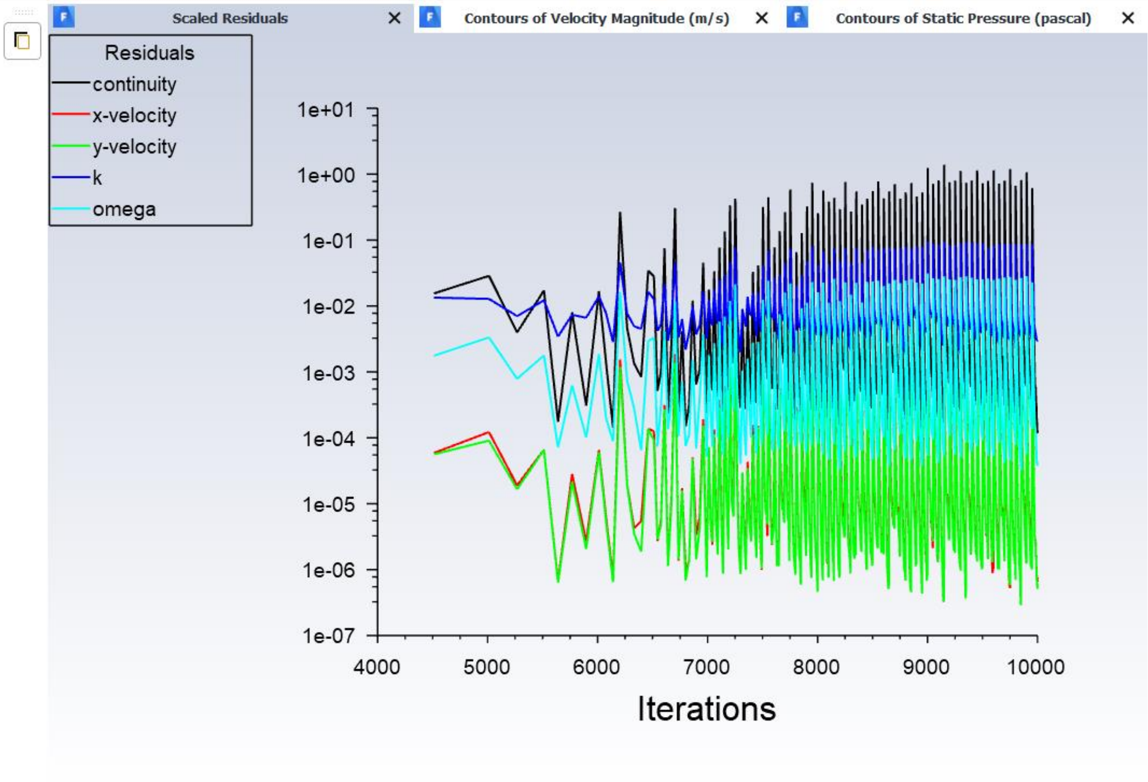


Figure 38 Convergance

The convergence plot for various parameters can be seen in the figure above. Target convergence as mentioned before is set to be 10e-4. We can see almost all parameters achieve this convergence for each timestep in 50 iterations.

4.8 Torque optimization

For the given wind speed of 8m/s, the optimum TSR obtained from the numerical analysis is coming out to be very high. To achieve the maximum possible COP, the turbine must sustain an angular speed of around 450 rpm which is very high. The design needs to be optimized to reduce the optimum TSR and this can be achieved by improving the forces acting on the lift type blades. Improvement can be made in a number of different ways but ultimately, the design becomes very complex. One way to improve torque is to employ active pitch control using servomotors. Another way is to make the blades helical instead of straight to improve torque. However, both these methods bring manufacturing complexities making them less favorable for a design of this stage.

4.9 Design changes

In order to reduce optimum TSR and improve system stability/manufacturing ease, the number of blades for the lift type set is increased from 5 to 6. The new optimum TSR comes out to be around 2.00.

4.10 Performance Testing Results

In order to validate the computational results, experimental results are obtained using a braking mechanism to measure braking torque. For this purpose, a separate flow analysis is conducted on the same TSR as obtained experimentally to calculate torque as well.

Lift blades: 60 rpm

Drag blades: 200 rpm

TSR: 0.31415

Using the maximum torque with standard deviation applied for accurate results, torque on each blade set comes out to be:

Lift: 0.9434 N-m

Drag: 0.41058 N-m

Experimental torques and their comparison with the above mentioned computational torques is as follows:

We have seen that in case of simple drag type, a weight of 1443 grams can be lifted for 14 cm and then it is held there solely by the turbine.

We have also recorded that for simple lift type case, the weight of 2153 grams can be lifted for 27 cm and then it is held there solely by the turbine.

In case of concurrent working in counter-rotating arrangement, results at 1075 g for savonius and around 3900 g for darrieus were recorded.

Upon saturation, the savonius can uplift 1500 g at a height of 11.5 cm and the darrieus type can lift 3500 g at a height of 22.5 cm.

From these readings, calculations for brake power were done and are attached.

Given the force value and the radius that works for the weight system:

We see that torque can be found as

$$T = F * r$$

And that the power can be calculated as follows for given rpm:

$$P = 2 * pi * n * T/60$$

The aforementioned relations are used to calculate brake powers for each case.

For given data we see that r_{Darrius} = 2.51 cm and r_{savonius} = 2.07 cm.

- Savonius in case of solo rotation

$F_{\text{savonius SOLO}} = 14.16$ N   n = 180 rpm

The torque and power come out to be

Ţ = 0.293 N-m   P= 5.523 W

- Savonius in case of combined rotation

$F_{\text{savonius COMB}} = 10.54$ N   n = 140 rpm

The torque and power come out to be

Ţ = 0.218 N-m   P= 3.11 W

- Darrieus in case of solo rotation

$F_{\text{Darrius SOLO}} = 34.34$ N   n = 77 rpm

The torque and power come out to be

Ţ = 0.862 N-m   P= 6.95 W

- Darrieus in case of combined rotation

$F_{\text{Darrius COMB}} = 38.26$ N   n = 90 rpm

The torque and power come out to be

Ţ = 0.96 N-m   P= 9.05 W

4.11 Performance Analysis

Using the parameters achieved during the experimental analysis and simulating them using ANSYS software, we see that the values obtained during the experiment are very close to the standard deviation results obtained and thus show the validity of the result. The cause for such low torque values is the rpm for the turbines, if operated at higher speeds, the turbines are able to harvest greater wind energy and provide a better result.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

This project aimed at providing a sustainable renewable energy system which could help maximize the wind potential of Pakistan. A detailed literature review regarding the present technologies and the research work performed on similar projects was studied. The design challenges and the optimization techniques were analyzed with the final proposal consisting of a counter-rotating Vertical Axis Wind Turbine due to the maximum output as discussed in the project above.

The entire methodology followed for the successful completion of the project is provided. A detailed flow analysis was conducted and the results were attached. Results from the parametric analysis were then used in the design phase of the project with attempt made to mimic as close to optimum conditions as possible. A design was proposed according to the analysis conducted and attached in the report. All the design decisions taken were discussed in addition to the alternatives available and the reasoning behind the specific choices.

A comprehensive account of the fabrication phase including the procurement of materials and the cost breakdown of the project is provided. Any deviation from the proposed design for the sake of fabrication was listed.

The turbine was passed through a thorough performance testing plan with its results attached for reference. A performance evaluation with respect to the available literature and the project objectives was conducted to give an account of the success of the project.

This project was an endeavor to play a part in the transition towards cleaner energy sources. The project achieved its purpose of proof of concept regarding the effectiveness of Counter-Rotating Vertical Axis Wind Turbines. There remains an extensive potential and scope for application of engineering knowledge to eradicate the problems facing these turbines.

An area of further studies is the transmission system between the rotors and the generators along with the selection of the airfoil in light of both performance and ease of manufacturing. Wind Turbines are an extremely useful resource to counter the energy shortfall in the urban environment. Further studies and research needs to be conducted to ensure that the most optimum form of Vertical Axis Wind Turbines are made available to aid the quest of renewable energy resources.

The project was an excellent opportunity to study the need for renewable energy and avenues that could lead towards bridging the demand and supply in the field. The project demonstrated the limitations currently available with regards to wind turbines with an attempt made to understand and address these problems. A concept proof with regards to Counter Rotating Vertical Axis Wind Turbine was presented along with a detailed design and simulation results. The successful completion of the project included a fabricated model with the results achieving the stated objective.

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APPENDIX

Engineering Drawing

Engineering drawings of the counter rotating Vertical Axis Wind Turbine can be found below.

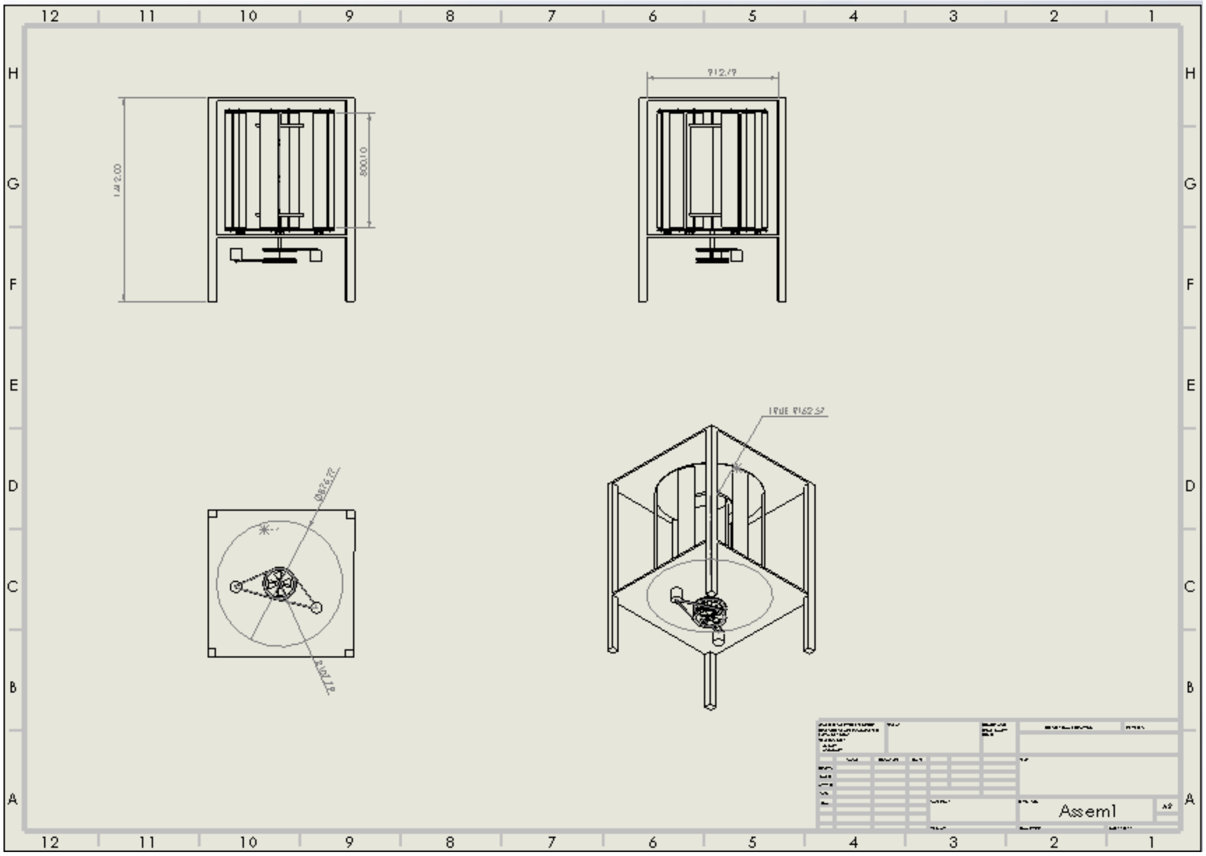

Figure 39 Engineering Drawing

Renderings:

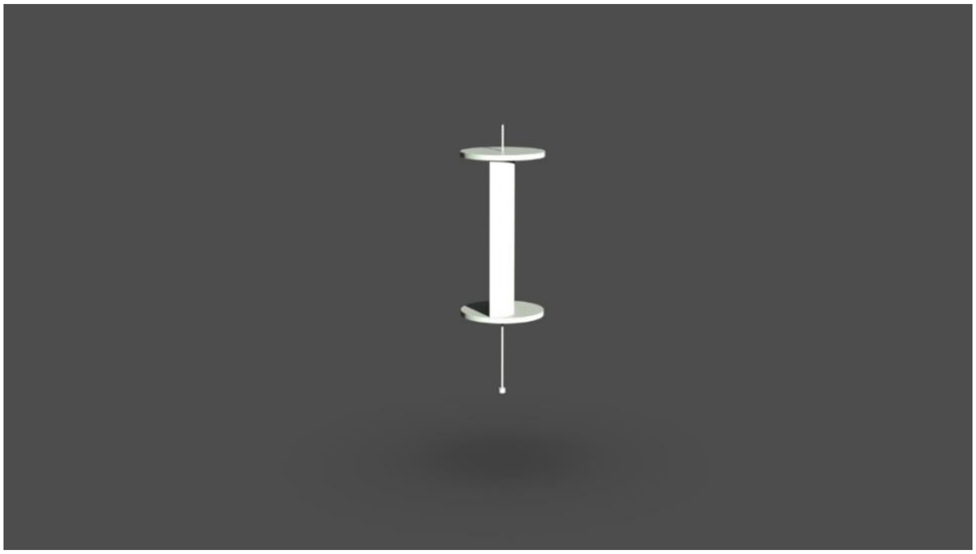

Figure 40 Savonius Turbine

Figure 41 Combined Turbine Assembly.

Figure 42 Pulley arrangement.

Figure 43 External Structure.

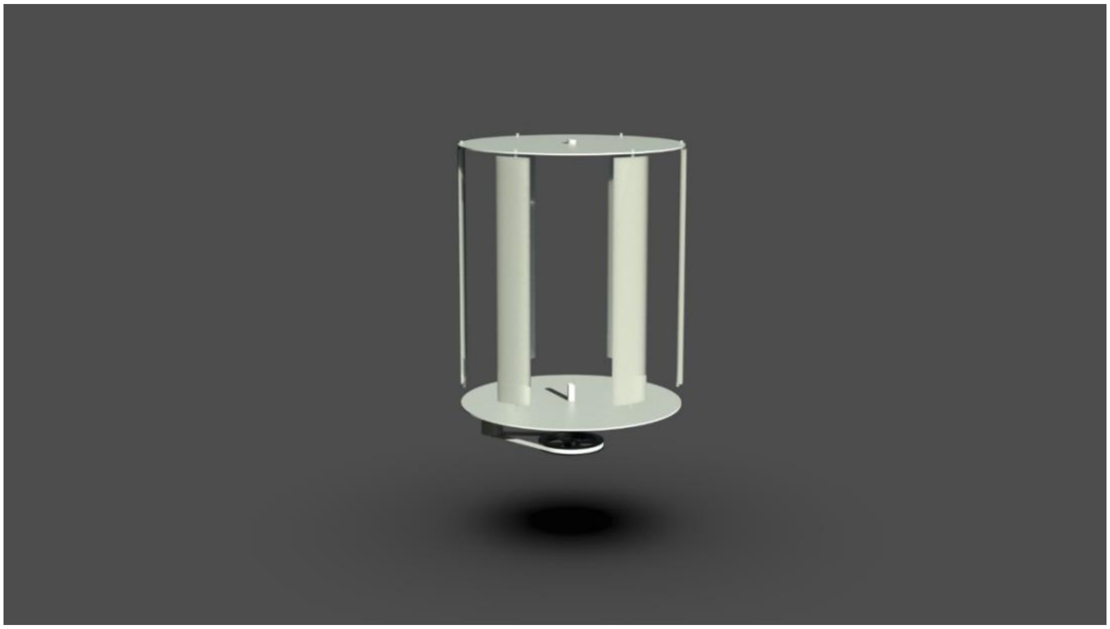

Figure 44 Darrius Turbine

Figure 45 Complete Concentric Counter-Rotating VAWT Assembly.