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Computational Simulation Methods for the Magnus Lift - Driven Wind Turbines

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Abstract*: Computational fluid dynamics (CFD) simulation of Magnus Lift -Driven wind turbines provide different results depending on the method of wind power capture and the nature of the turbine. The Magnus Lift -driven wind turbines, which would normally have cylindrical blades rotating either about a vertical or horizontal axis, reveals interesting CFD results. For instance, the blade aspect ratio is critical in determining the performance of the Magnus WT. The power coefficient generated by Magnus WT at low tip-speed ratio clearly justifies that the turbine would perform optimally in urban environment. This review paper focuses on these Magnus Lift -driven wind turbines, by analyzing the research results in the literature review section. The results section contains the simulation outcome based on various CFD approaches. The conclusion cites the gaps in research. More importantly, the paper reviews the factors affecting the efficiency of the Magnus wind turbine such as drag coefficient, surface roughness effect, and wind velocity.

Keywords: Computation Fluid Dynamics, Magnus-Driven Wind Turbines, Wind Tunnel, And Blade Element Momentum Theory

I. INTRODUCTION

Advancement in technology has led to the evolution of the wind power industry over the past decades. According to a survey by WWEA [1], wind power contributes to approximately 4.7% of the electricity usage across the globe [1]. In order to meet the energy needs of current and future generations, sustainable energy must be given top priority as far as research is concerned. Wind turbines are devices that have undergone several transformations working under a simple concept of tapping wind energy then converting it to kinetic energy thereafter using a generator to develop the end product as electricity [64]. Wind energy is a natural and renewable energy which can be harvested repeatedly and will never be depleted [2 - 4]. The possibility of harnessing wind energy is determined by various aspects such as area topography and the geographical location [5]. Massive wind energy harvesting is practiced through the use of horizontal axis wind turbines which use blades in the shape of an airfoil [6]. These types of turbines require at least wind speeds of 16 m/s to generate maximum power while minimum power can be harvested at a speed of 4 m/s [7]. More researchers have directed their effort in coming up with innovative WT that are sensitive to slow and gentle wind hence can still produce electricity at slower wind speeds [7]. This paper will concentrate on existing information on Magnus driven wind turbines with the blades being cylinders rotating about a vertical or horizontal axis. Notably, this work will explore factors that affect the efficiency of the Magnus wind turbine such as drag coefficient, surface roughness effect, and wind velocity and density. Before any WT is built, it is important to incorporate tools like CFD to help in getting vital information about the WT performance and construction cost. This paper will concentrate on the review of computational simulation of a Magnus driven WT. The aim of the paper is to analyze, synthesize and interpret already done scholarly CFD works and identify any gaps that can be pursued in future.

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II. LITERATURE REVIEW

A. Background information on Magnus wind turbine

In 1924, Anton Flettner applied the use of the Magnus effect in propelling his ship. Through the use of high rise cylinders that were free to rotate, he was able to generate a lift that could propel his ship [66]. This made several scientists realize that the lift force due to Magnus effect had significant magnitude, thus directing more energy towards building structures that applied this concept. This marked the discovery of the Magnus effect and continuous development of the same by various scientists [2]. From this point on, more advanced studies have been conducted to understand potential flow that develops around spinning circular blades, the combined blade element momentum theory (BEM), and the one-dimensional element theory [26]. The Flettner rotors were additionally subjected to simulation through XFlow CFD program with various heel angles of 0o, 20o, 40o and 60o being tested [65]. It was discovered that as the heel angle increased, the performance of the lift power on rotors decreased [65]. Additionally, the driving forced reduced to zero when large heel angles were applied. Also, more simulations were done to help establish the assistance a hybrid combination where the Flettner rotors were used in combination with fuel driven engines [67]. The research was to establish any possible savings that would be registered in the event that the rotors were used in combination with fuel [67]. More research around the fluid flow over Flettner rotors opined that determining the skin friction coefficient was difficult due to the instabilities in both laminar and turbulent flow [68]. According to Santoso et al. [67], applying the rotor flettner in ships helped reduce emissions.

It also helped gain power to drive the ship thus saving on fuel hence rendering the technology an environmentally friendly and futuristic innovation for the shipping industry [67, 70-73].

Bychkov et al. [11] did his research where he experimentally tested the operation of a Magnus wind turbine that used rotating cylinders. The intention was to establish how the model could operate optimally in comparison with its counterpart using aerofoil shaped blades. In his studies, the MWT used 6 rotating cylinders and it operated at high rotational speeds of up to 8000 rpm [11]. The aspect ratio for these rotating cylinders was set at 15. According to Bychkov et al. [11], the wind turbine that uses rotating cylinders could easily compete with the aerofoil type WT at very slow-moving winds registering speeds below 8 m/s. For sites with extremely slow wind speeds of 1-2 m/s, the MWT would still operate effectively [74-75]. This physical experiment was important as it allowed for the physical testing of Magnus driven WT in slow moving winds and possibly managed to generate more electricity compared to aerofoil lift driven WT [11]. As a result, computational simulation of the same will enable testing of Magnus driven WT in different shapes with different number of blades minimizing on the cost that would have been used in developing the physical WT. Through computation simulation, any researcher would be able to simulate both Magnus driven and aerofoil lift driven WT under same conditions among them same wind speeds, collect results, analyze and compare effectively.

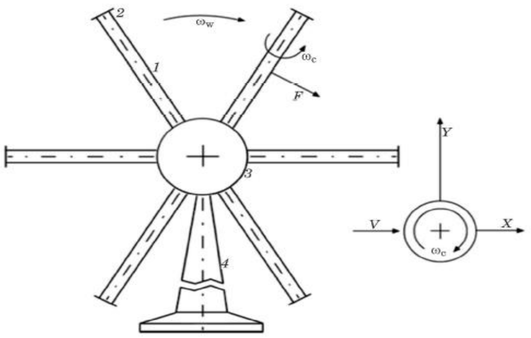

Figure 1: The Bychkov's 6 No. cylinders horizontal axis Magnus WT [11]

Figure 1 shows the Bychkov's 6 cylinders horizonal axis Magnus wind turbine. In 2007 and 2010, more patents of the Magnus Wind turbines were registered [12]. Murakami, Ito and other coworkers patented a Magnus wind turbine in 2007, which operated on 6 rotating cylinders [12]. They registered another MWT, which worked effectively on 5 rotating cylinders. These researchers were innovative in that the cylindrical blades that they used had some spiral fins introduced into them. IIDA et al. [76] conducted a numerical simulation and discovered that controlling the spanwise flow using spiral fins largely affect the performance of the MWT. Also, more research have been conducted around the unsteady flow fields around the MWT with spiral fins on the blades [77] with the attempt to improve the performance of the WT. According to KATO et al. [78], large Magnus effect is experienced on cylinders with spiral fins hence the need to apply the same effect on MWT. The performance of the MWT would greatly be improved by introduction of the spiral fins on its cylindrical blades [79].

The fig. 2 below shows advancement of the lift coefficient based on the spinning ratio derived from three models i.e., spiral fin, straight fin and one without fin [80]. From the results tabulated in the table, models with fins perform better compared to those without fins [81]. The lift coefficient CL is plotted against spinning ratio ϖ which must be less than 1 [82].

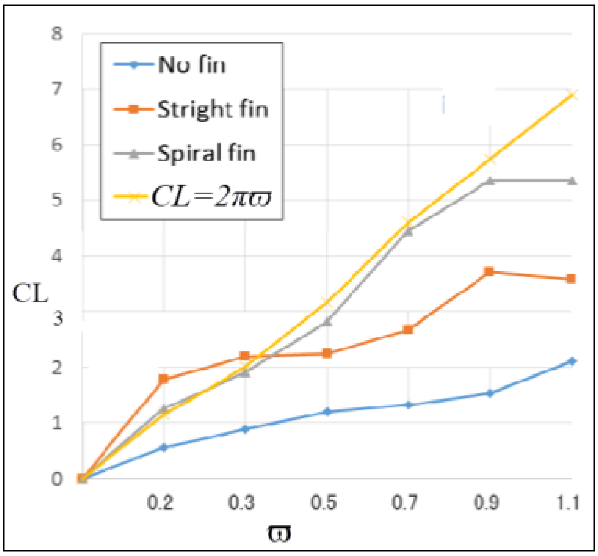

Figure 2: Lift efficient curve [79]

Sun et al. [29] presented data that showed the behavior of cylinder angular speed against its power consumption. When the cylinder of a standard MT is rotating at a constant rate, there is a tendency of the turbine to use more power than the extracted magnitude. This usually occur whenever the rotating cylinders needs more power than what the turbine is capturing [29]. To solve this issue, the inner section of the cylinders is fixed to the hub. Additionally, the angular speed of the cylinder is then selected based on the speed of wind. If the angular speed and section length of the hub-fixed cylinder are selected properly, the power output experienced is usually positive at all wind speeds as seen below in Fig. 3 [83].

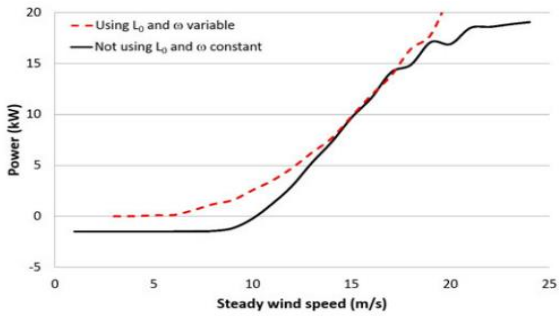

Figure 3: Power output for hub-fixed and standard wind turbines with ω as cylinder angular speed and length as L_0.

According to Sun et al., the figure above compared WT with the same geometry i.e. B=3, D=1m, L=5m with the angular speed at 30rpm. The hub-fixed cylinder WT showed net power output for all the spinning rates while the standard MT experienced net power consumption under low wind speeds.

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More innovative concepts of wind turbines are generated through the help of simulation. In 2017, a midsized WT was invented through simplified power model which was based on symbolic regression and BEM (Blade Element Momentum) Theory [49]. From the simulation, the efficiency of the WT was experienced upon optimization of the rate of wind, number of cylinders among others. Notably, such WTs are feasible for use in urban environment due to its power coefficient under low wind speeds. Other advance innovations about the WTs were developed. In 2016, [50] developed a conceptual design where the MWT had its cylinders covered with solar panels. The results were interesting as covering the blades with solar panels increased the turbine's power coefficient. For this particular research, the researchers develop a WT that uses spinning cylinders that rotate due to Magnus effect instead of the aero foil blades [47] [51]. This is because the MWT yields a higher C_l values that are much higher compared to aero foil wing profile [52] hence the possibility of improved turbine efficiencies is achievable [53 - 57]. In the event that the cylindrical blades are covered with solar panels, then the efficiency of the panels is accounted to around 0.3 thus increasing the performance of the WT [58]. This is an interesting approach; however, the paper will focus on studying the surface profile of the spinning cylinders and the lift and drag force experienced on them. Notably, research was done around turbines with cylindrical balloons left free to rotate in air and generate traction force [59]. This type of system was determined to be suitable in areas which experience crosswinds hence the turbine location did not depend on direction of wind. Omnidea [61] utilizes the cylindrical balloons to simulate a wind turbine in a space with high altitude winds thus being able to generate sufficient power from the turbine [63]. The cylindrical balloons employ both aerodynamic and aerostatic lift mechanisms thus getting a traction force that makes the blades to rotate [60].

B. Factors affecting the efficiency of MWT

a. Surface Profile and roughness Effect on Wind Turbine Blades

Murakami et al. [12], through demonstrations proved that in the event that the spiral fins were added to the cylindrical blades as in Figure 2, then high torque and almost double the lift coefficient would be experienced as compared to the rotating cylinders with smooth surfaces. Despite most of these discoveries being done physically, simulation would have been cost effective methods of comparing the results from these turbines. However, there can be a gap to be filled by comparing the impact of having a Magnus WT with cylindrical blades with rough surfaces to one with spirals as in the case of Murakami et al [12].

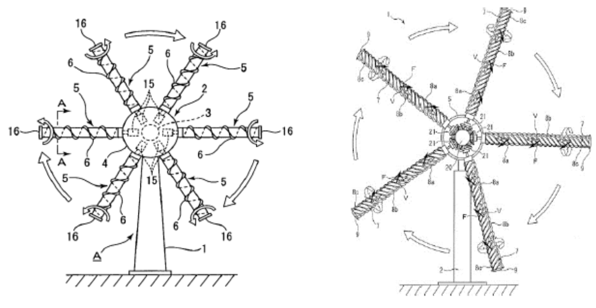

Figure 4: Magnus WT with spiral fins on blades with rotating cylinders upgraded from 6 to 5 [12]

More advancement was realized on the works of Murakami and coworkers. Kato et al. [13] and Murakami et al. [14] investigated the perceived effectiveness of the spiral MWT to the non-spiral one. The two researchers compared the effectiveness of the MWT with rotating cylinders embedded with spiral fins by conducting the PIV (Particle Image Velocimetry) and thereafter documented their results. Mecaro Co [15] in Japan later manufactured the turbine designed and simulated by Murakami. According to Murakami et al. [14], the MWT that was patented in 2010 that utilized five No. blades was capable of producing 3kW of electrical power.

The main difference between the Magnus driven WT and the WT with airfoil shaped blades is the mechanism employed while harvesting wind energy [27]. Magnus driven WT has the capability of harvesting wind energy at slow wind speeds contrary to the airfoil shaped blade WT. In order for the Magnus driven WT cylinder blades to be more sensitive to wind, their surfaces are made rough either by using fins or dimples [28]. Notably, making the surfaces of the rotating cylinders rough using sand paper has seen MWT rotor generate higher torque [8 – 10].

Experimental results have proven that surface roughness can be used to improve the performance of MWT up to four times, based on torque production as compared to smooth surfaces. The surface roughness effect is an area which has not been fully explored by researchers. However, it has been proven that rough surface roughness significantly increases torque and reduce the cut-in speed in contrast to smooth surfaces. Figure 4 below shows the torque coefficient versus tip speed ratio of 54.4 x 103 ≤ Re ≤ 108.3 x 103 for three sets of blades rotational speed of 430, 730, and 1030 RPM. According to the figure, there has been an exponential growth as the value of torque coefficient CT increases rapidly as the value of tip speed ratio (TSR) increases.

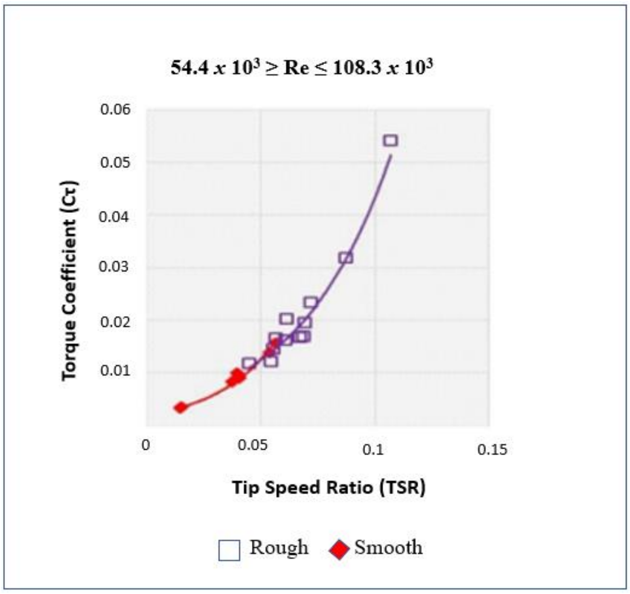

Figure 5: Comparison of torque coefficient with tip speed ratio provided by surface roughness [21]

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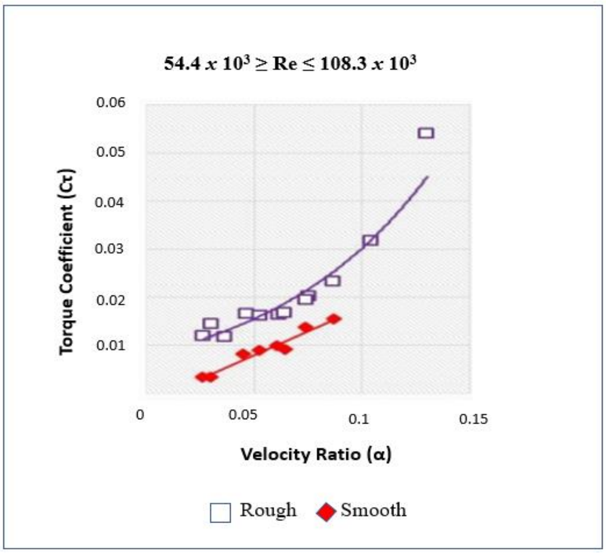

Figure 6: Comparison torque coefficient with velocity ratio provided by surfaces roughness [21]

Smooth surfaces can only produce tip speed ratio of up to 0.06, the smooth and rough surface nearly identical, with torque coefficient ranging from 0.011 to 0.016. Thus, the rough surface had increased the torque coefficient and TSR values in comparison with smooth surface. Figure 5 above shows the torque coefficient versus velocity ratio for smooth surface roughness [21]. According to the figure, the torque coefficient is derived from a single rotating cylinder blade. The figure shows a gradual increase in torque coefficient and an increase in velocity ratio when a rough surface ratio is used. There is a significant improvement of rough surface roughness on the performance of the MWT under the velocity ratio range of 0.02 to 0.08. Present and past experiments have profoundly proven that rough surface roughness provides massive advantages with regards to the performance of the Magnus wind turbines.

The roughness induced on the blades of the MWT must be controlled otherwise the power generated can be greatly reduced. Roughness induced on the blades by contaminants such as dust affects the performance of the WT leading to less energy production [34]. Experiments were carried out to study the behavior of turbulent flow over HAWT under different roughness heights [35]. The governing equations that help in solving the physical problem that the experiment was aiming to solve were conservation of momentum equations (Navier-Stokes equations) and continuity [36]. Since the blades of the turbine are rotating, a steady-state approximation is applied which transforms the equations of the fluid motion to frame that is moving thus enabling steady state solution to be achieved. By use of this technique, computation time is reduced as compared to where computation is done through moving mesh.

i.Governing equations

The Navier-Stokes equation in steady state is expressed as follows [37] [38]: -

$$\nabla_{\vec{u}} = 0 \qquad \text{(Eq.1)}$$

$$\nabla \cdot (\rho \vec{u}\vec{u}) = -\nabla p + \nabla \cdot (\tau) \qquad \text{(Eq.2)}$$

Where: -

ρ is the density of air

U is the fluid velocity vector

p is the static pressure

τ is the shear stress tensor and its equation is defined as below:

$$\tau = \mu\left[(\nabla\vec{u} + \nabla\vec{u}^T) - \frac{2}{3}\nabla \cdot \vec{u}I\right] \qquad \text{(Eq.3)}$$

Where: -

μ is the dynamic viscosity, I is the unit tensor while the second term found on the right of the equation is the effect of volume dilation.

ii.Turbulence Modelling

In order to execute the turbulent simulation that is caused by the roughness of the surface, the most common model employed is known as the RANS-based turbulence model [39]. This model is simulated by mainly decomposing the Reynold's number [40]. Notably, there is no specific turbulence model that has been accepted internationally for being more superior to the others. According to a simulation conducted by Bouhelal et al., it is advisable to employ k - ε (RNG) turbulence model on rotating flows since the model incorporates the effect caused by swirl on turbulence [41] [42]. This model was by means of statistical technique known as renormalization group theory [43]. In order to establish a relationship between the mean velocity gradient and the Reynold's stresses, the model was based on the Boussinesq hypothesis [44] [45]. It is important to note that the region where high wind speed flow is separated, all the RANS model experience difficulty while solving the full separated flows [46]. There are several factors that impact on the modeling of a win turbine. This paper will concentrate on the lift, drag and frictional torque experienced onspinning cylinders.

C. *Lift, drag and Frictional Torque experienced on spinning cylinders*

In 1925, Reid [15] conducted experimental studies on rotating cylinders whereby he used smooth cylinders that were spinning in the leading edge of wings. Reid reported that when he employed different Reynolds's number at various rotational speed ranges up to 3600 rpm, then the lift force of the wing increased drastically. More discoveries governing the lift force on the cylindrical body such as the boundary layer theory was discovered. Glauert [16] discovered the boundary layer theory occurring over rotating circular cylinders in 1957. Major revelation about the computational solutions over the rotating cylinders were made in 1983 by Ingham [17] who conducted the study in order to assess the viscous effects that a rotating body experiences during rotation.

Mittal and Bhaskar [18] attempted to study the 2 dimensionless incompressible flow and its behavior over a circular cylinder at Re 200. The duo used a dimensionless spin ratio which varied in value in the range of 0 - 5. At a spin ratio ω'<1.91, vortex shedding was experienced. Turbine spin ratio refers to the ratio between the wind speed and the speed of the tips of the wind turbine blades.

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If the rotor of the wind turbine spins too slowly, most of the wind will pass straight through the gap between the blades. Throughout the higher spinning rates, the researchers experienced a steady flow except where the spin ratio fell in the range where the flow registered was unstable. Whenever the circular cylinders were rotated at high rates, the lift coefficient were very large. However, as the spinning rates of the cylinders increased, the consumption power to spin the cylinders also increased. Vorticity is usually created on the surface of the solid cylinder in every viscous but steady flow. Notably, it is diffused and converted as noticed.

At ω'= 2, Prandtl [23] noted that the equilibrium state was approached. Therefore, as the equilibrium limit is reached, no substantial increase in the lift is experienced on the circular cylinder despite spinning at higher rates [23]. Prandtl [23] further noted that the value of the maximum achievable lift is. However, experimental research and numerical observations made by Tokumaru and Dimotakis [19] revealed that there is no limit to lift experienced by solid cylindrical surfaces. Moreover, they noted that the lift is subject to rotational speeds and aspect ratios. Therefore, at higher aspect ratios and higher rotational speeds respectively an extension on the lift due to unsteady effects was observed. Following the experiments carried out by Tokumaru P, Dimotakis (1991) and Badalamenti, C. and Prince (2008), [19, 20] and the numerical results deduced out of the research, it was suggested that the practical range upon which Magnus effect can be effectively used is 2<ω'<4where ω' is Dimensionless Spin ratio.

However, according to the researchers, this could only be achieved within Reynolds flow region of 4 × 104< Re < 6.6 × 105. When the dimensionless spin ratio is within the range of 2 to 4, the drag coefficient value remains at the lowest possible values [19]. Notably, the linear increase of the lift force on the cylinders rotating at different speeds is usually halted in the event that centrifugal forces across the blade occur. When the Naiver-Stokes equations was simulated at high spin rates, the computational evidence were generated which supported development of instabilities and definite violations from the maximum lift at high Reynolds numbers [21]. During the fluid flow around a cylinder, the parameters that are measured include the magnitude of the drag and lift, and the frictional torque [18]. Viscous fluid flow that occurs around cylindrical objects is characterized by two factors: the spinning ratio and the Reynolds Number[19].

The lift and drag experienced on the wind turbine blades largely affect the performance of the turbine. In order to improve the turbine efficiency, there is need to reduce the ratio of drag coefficient (CD) to lift coefficient (CL) [47]. Additionally, in order for the cylindrical blades to rotate less noisy as compared to the convectional types WT, [48] proposes that the WT be designed to utilize centrifugal forces.

D. Improving the Efficiency of Magnus Wind Turbines

One of the most effective mechanisms of improving the efficiency of MWT is through increasing the rotational speed of the wind blades using steering aerofoils surrounding the blades. Factors such as the influence of power output, wind speed, air density, and the blade radius have a profound effect on the efficiency of wind turbines. Enhancing the wind power involves increasing the electricity generated from the wind. There is need for wind turbines to be positioned in areas with a lot of wind on a regular basis, more important than the intermittent wind.

The wind speed determines the amount of electricity generated by a turbine. Higher wind speeds generate more power because stronger winds allow the blades to rotate faster. The faster rotation of the turbines leads to more mechanical power, thus more electrical power is generated. The figure 6 below shows the relationship between the wind speed and the power for a typical wind turbine [22]. Magnus wind turbines are specifically designed to operate at a range of wind speeds. The limits of the range are referred to as the cut-out and cut-in speed. The cut-in speed is referred to as the point at which the wind turbine generates power. Power output increases cubically with regards to the wind speed at the range between the cut-in speed and the rated speed.

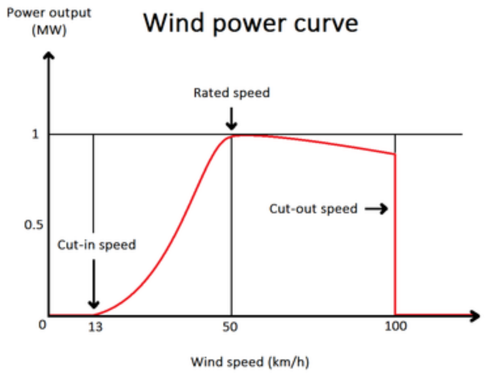

Figure 7: Power Curve for 1 MW wind turbine in comparison to the wind speed [22]

At the cut-in speed, the turbine must be shut down to prevent damaging the equipment. Both the cut-in and cut-out speeds relate to turbine design and size and are decided prior to the construction of the turbine. Further, power output is related to the local air density, which is primarily a function of altitude, temperature, and pressure. Dense air often exerts more pressure on rotors resulting into higher power output. The design of the turbine emphasizes on the maximization of the rotor blade radius to maximize the power output [22]. Larger turbine blades facilitate the turbine to capture more of the wind kinetic energy thus moving more air through the rotors. On the other hand, larger blades require more space and higher wind speeds to operate. As a rule, for the MWT, the turbines are spaced out at 4 times the rotor diameter. The distance avoids the interference between the turbines, which is known to decrease the power output.

Wind turbines are optimized by considering wind speed, swept area and air density in terms of local area conditions to extract maximum power. The output power of a wind turbine is directly proportional to cube of wind speed, air density and swept area of the blades. The larger the diameter of its blades the more power can be extracted from the wind. The figures 7 and 8 below shows that the power output is directly proportional to the wind speed [24].

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The available power in the wind is directly proportional to the air density. An increase in the air density results into a corresponding increase in the available power. The air density is a function of both temperature and the air pressure. An increase in the elevation (altitude) results in a decrease in both pressure and temperature. Therefore, the changes in elevation/altitude has a profound effect on the power generated due to changes in the air density [24].

Figure 8: Effect of wind speed in power output (1.65 MW)

Figure 9: Effect of air density in power output (1.65 MW)

Swept area

The power captured by the turbine from wind depends of the swept area. The larger the area results into more energy being captured from wind [30]. In order to increase the power generated by the MWT, it is important to increase the sizes of the blade thus increasing the swept area of the MWT [31]. Notably, Sing and Li & Chen opines that the high-power output is achieved through increasing the torque and rpm of the turbine by varying the pitch angle [31] [32].

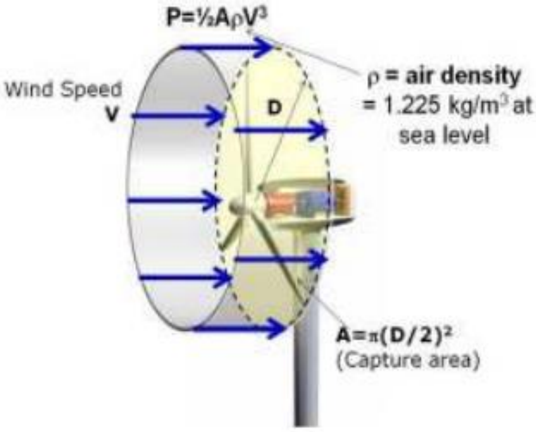

Figure 10: Wind Turbine Model defining the swept area by rotating blades

According to Burton et al., power production from WT can be calculated as follows: -

$$Power\ (watts) = \frac{\rho A v^3}{2} \qquad \text{(Eq.4)}$$

Where:

$\boldsymbol{\rho}$= Air density (Kg/m³)

$\boldsymbol{A}$= Swept area of the wind turbine rotor (m²)

$\boldsymbol{V}$= Wind Speed (m/s)

$$Air\ Density\ (\rho) = \frac{M \cdot P}{8{\cdot}314T} \qquad \text{(Eq.5)}$$

Where:

$\boldsymbol{M}$=Molecular weight of air (g/mol)

$\boldsymbol{P}$=Atmospheric pressure (KPa)

$\boldsymbol{T}$=Temperature (K)

$$M = 28.964 - (RH) \qquad \text{(Eq.6)}$$

Where:

$\boldsymbol{M}$=Molecular weight of air (g/mol)

$\boldsymbol{RH}$=Relative humidity, expressed as a decimal

$$\boldsymbol{Air\ Density\ (\rho)} = \frac{[28.964 - 0.253(RH)]\,P}{8{\cdot}314T} \qquad \textbf{(Eq.7)}$$

$$P_T = C_P \cdot \frac{\rho A v^3}{2} \qquad \textbf{(Eq.8)}$$

Where:

$\boldsymbol{P_T}$=Power extracted by wind turbine (watts)

$\boldsymbol{C_P}$=Coefficient of performance

$\boldsymbol{\rho}$= Air density (Kg/m³)

$\boldsymbol{A}$= Swept area of the wind turbine rotor (m²)

$\boldsymbol{V}$= Wind Speed (m/s)

III. CONCLUSION

This paper strives to explain the past history of wind turbine information. The paper describes various research work as far as the operation of the wind turbine is concerned. The previous works of wind simulation is described. The results of the study of simulation of the WT are discussed and the most accurate ones outlined as per the previous works. In most of the previous works, researchers have exploited the field of wind turbine when the blades are aero foil. The results of the simulation of WT with aero foil shaped blades have been outstanding. Notably, there are researchers who concentrate on the computational simulation of the Magnus wind turbine. The paper outlines the simulation of the Magnus WT using different types of models from the RANs model to LESs model. Other researchers have gone a notch higher to compare the results collected after simulation is done with different models, inflow conditions, different arrangement and position of the wind turbines within the wind tunnel model [10]. Also, simulations software have been analyzed and expounded on from OpenFOAM, ANSYS etc. and their outcome results compared.

Some of the parameters that have been monitored by different researchers include the coefficient of power, thrust coefficient, wake development among others [21]. The review paper facilitated the understanding of the factors affecting the efficiency of the MWT while simultaneously addressing critical issues such as drag and surface roughness effects which are considered fundamental factors for efficiency. Research into the factors affecting the efficiency of Magnus wind turbine is not conclusive, especially with regards to the effects of drag and surface roughness. Researchers should maximize their research on mechanisms of increasing performance and power of Magnus wind turbines.

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