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A Comprehensive Review of Wind Turbine Modeling for Addressing Energy Challenges in Nigeria and South Africa in the 4IR Context

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Abstract

Wind energy is a promising renewable energy source that can contribute to addressing the energy challenges faced by countries such as Nigeria and South Africa. Wind turbine modeling has emerged as a critical tool for optimizing the design, operation, and maintenance of wind turbines, as well as for integrating wind energy into the power grid. This approach can potentially enhance the performance and reliability of wind turbines, increase their energy production, and reduce their environmental impact. The review examines various wind turbine modeling approaches and techniques. It also discusses these modeling approaches' strengths and limitations and highlights their potential applications in addressing energy challenges in Nigeria and South Africa. Overall, this comprehensive review provides valuable insights into the potential for wind turbine modeling to address energy challenges in Nigeria and South Africa. It provided a thorough analysis of the current state of wind turbine modeling technology and highlighted areas for further research and development.

Keywords: Wind energy. Renewable energy. Wind turbine modelling. 4IR. Nigeria. South Africa.

1. Introduction

As the world continues to face significant energy challenges, many countries are exploring the potential of renewable and alternative energy sources to meet their energy demands (Dioha *et al.*, 2021; Egieya *et al.*, 2022; Ewim *et al.*, 2022; Ewim *et al.*, 2023; Hoogwijk & Graus, 2008; Ntuli *et al.*, 2022). Wind energy, in particular, has emerged as a popular solution due to its low environmental impact and cost-effectiveness (Abbas *et al.*, 2020). However, the efficient and reliable operation of wind turbines is essential to ensure the widespread adoption of wind energy. One of the critical tools that can be used to optimize wind turbine design and operation is wind turbine modeling (Bianchi *et al.*, 2007). Wind turbine modeling involves creating computer models that simulate the behavior of wind turbines under different wind conditions. These models can be used to optimize the design of wind turbines, improve their efficiency, and reduce their costs. In this context, the fourth industrial revolution (4IR) presents a unique opportunity to develop more advanced wind turbine models using machine learning, artificial intelligence, and big data analytics.

Nigeria and South Africa are two of the largest economies in Africa and face significant energy challenges. Nigeria has a population of over 200 million people and an energy demand that is growing at a rate of 5% per year (Okafor, 2012). However, the country's energy sector faces several challenges, including a lack of investment, an aging infrastructure, and a dependence on fossil fuels (Ohunakin *et al.*, 2014). As a result, Nigeria's energy sector is struggling to meet the country's energy demands, with frequent power outages and load shedding affecting businesses and households. Similarly, South Africa's energy sector also faces challenges, including a lack of investment, an aging infrastructure, and environmental concerns (Andrade *et al.*, 2020; Ewim *et al.*, 2023). The country's energy demand is expected to grow by 2.5% annually until 2040, with a significant portion of this demand being met by renewable energy sources (Rennkamp *et al.*, 2017). However, a lack of investment and regulatory uncertainty has hindered the adoption of renewable energy sources, including wind energy.

Wind energy has emerged as a promising solution to the energy challenges faced by Nigeria and South Africa. Both countries have significant wind energy potential, with Nigeria having an estimated wind energy potential of 15 GW and South Africa having an estimated wind energy potential of 10.5 GW (Akinbami *et al.*, 2021; Andrade *et al.*, 2020; Edkins *et al.*, 2010; Ohunakin *et al.*, 2014). Furthermore, wind energy has several advantages over traditional sources of energy, including low greenhouse gas emissions, low operating costs, and a low environmental impact. In recent years, both Nigeria and South Africa have made significant strides in developing their wind energy sectors. Nigeria has set a target of generating 30% of the country's energy from renewable sources by 2030, with wind energy expected to play a significant role in achieving this target (Bamisile *et al.*, 2020; Okafor, 2012). Similarly, South Africa has set a target of generating 18 GW of renewable energy by 2030, with wind energy expected to contribute significantly to this target (Edkins *et al.*, 2010; Rennkamp *et al.*, 2017).

According to literature, one of the key challenges facing the widespread adoption of wind energy is the efficient and reliable operation of wind turbines (Amano, 2017). Wind turbines are complex systems affected by various factors, including wind speed, wind direction, and turbine design. Wind turbine modeling can play a critical role in optimizing wind turbine design and operation to improve the efficiency and reliability of wind turbines (Menezes *et al.*, 2018). Wind turbine models can simulate the behavior of wind turbines under different wind conditions, allowing researchers and engineers to test different designs and optimize their performance. By using wind turbine modeling, engineers can identify potential issues with wind turbine design and operation and develop solutions to improve the efficiency and reliability of wind turbines (Manwell *et al.*, 2010; Slootweg *et al.*, 2003). There are several types of wind turbine models, including aerodynamic, structural, and control system models (Hansen *et al.*, 2006). Aerodynamic models simulate airflow over wind turbine blades and can be used to optimize blade design to maximize energy production (Hansen & Aagaard Madsen, 2011). Structural models simulate the behavior of wind turbine structures. They can be used to optimize the design of wind turbine towers and foundations. Control system models simulate the behavior of wind turbine control systems and can be used to optimize the operation of wind turbines in different wind conditions (Navarrete *et al.*, 2019).

The fourth industrial revolution (4IR) presents a unique opportunity to develop more advanced wind turbine models using machine learning, artificial intelligence, and big data analytics. These technologies can be used to develop more accurate and efficient wind turbine models that can simulate the behavior of wind turbines under a wide range of wind conditions (Ayentimi & Burgess, 2019). By using machine learning algorithms, wind turbine models can learn from historical data to predict future wind conditions and optimize wind turbine operation. Artificial intelligence (AI) can also be used to develop more accurate wind turbine models by analyzing large amounts of data from different sources, including sensors and weather forecasts. AI can identify patterns in the data and develop predictive models that can optimize wind turbine design and operation. Big data analytics can also identify potential wind turbine design and operation issues by analyzing data from multiple sources (Lee & He, 2021). In addition, the Internet of Things (IoT) can monitor wind turbines in real-time, allowing engineers to detect potential issues and optimize wind turbine operation. IoT sensors can be installed on wind turbines to collect data on wind speed, wind direction, and other factors affecting wind turbine performance (Sudarshan *et al.*, 2020; Teimourian *et al.*, 2022). This data can then be analyzed in real-time using machine learning and AI algorithms to optimize wind turbine operation.

In conclusion, wind turbine modeling presents a significant opportunity to optimize wind turbine design and operation and improve the efficiency and reliability of wind turbines. By using wind turbine modeling, engineers can identify potential issues with wind turbine design and operation and develop solutions to improve their performance. In the context of 4IR, the potential of wind turbine modeling can be further enhanced by using machine learning, AI, and big data analytics to develop more accurate and efficient wind turbine models. In Nigeria and South Africa, wind energy has significant potential to address the energy challenges faced by these countries, and the development of advanced wind turbine models using 4IR technologies can play a critical role in realizing this potential. This review aims to explore the role of wind turbine modeling in optimizing wind turbine design and operation. It also discusses the potential of 4IR technologies to improve wind turbine modeling and the benefits and applications of wind turbine modeling in solving Nigeria and South Africa's energy problems in the context of 4IR.

2. Wind Turbine

A wind turbine is a device that converts the kinetic energy of wind into electrical energy (Shahariar & Hasan, 2014). The turbine consists of several components: blades, rotor, gearbox, generator, and tower (Liu, 2013). The blades are the primary components responsible for capturing the wind's energy and converting it into rotational energy. Wind turbine blades are typically made of lightweight materials such as fiberglass or carbon fiber. They are designed to be aerodynamic to maximize energy capture from the wind. The blades are attached to the rotor, which is connected to the gearbox and generator. The generator converts the rotational energy of the blades into electrical energy that can be used to power homes, businesses, and other electrical devices (Chaudhuri *et al.*, 2022).

The design and construction of wind turbine blades are critical factors in a wind turbine's overall performance and efficiency. The blades' length, shape, and curvature are carefully optimized to maximize energy capture while minimizing noise and vibration. Different blade designs are used for different types of wind turbines, with larger blades generally used for larger turbines. This section will discuss various aspects related to wind turbine blades such as blade modeling, structural dynamics, types and effects of vibrations, and the importance of monitoring vibrations in wind turbine blades.

2.1. Blade Modeling

Wind turbine blade dynamics have necessitated numerous literature studies into it. Blades have been generally considered and analyzed as Euler Bernoulli beams (Jokar *et al.*, 2020). Some studies have considered modeling the blade based on its structural dynamics, while few others have considered the aerodynamics aspect. Otero and Ponta (2010) conducted a numerical simulation of a blade by aiming to capture its complex features by developing a code based on the VABS technique. VABS, also known as the generalized Timoshenko theory, was used to determine the blade's extension, torsion, and shear stresses in two directions. Larsen and Nielsen (2006) performed a structural non-linear dynamics analysis on an analytical wind turbine blade model that is based on the Euler-Bernoulli beam theory.

Li *et al.* (2016) developed an equivalent transformation green function and differential equations to achieve a dynamic analysis of a HAWT blade. This equation was used to get the mode shapes, the natural frequencies, and the system. Hodges and Dowell (1974) developed two linear equations of motion using two methods, the Newtonian method and Hamilton's principle method. These methods were able to develop the dynamic response and aeroelastic stability of a helicopter rotor blade. Kallesøe (2007), using Hodges-Dowell's partial differential equation of blade motion, investigated a blade rotating without influence from the tower and mechanical factors. The blade was allowed to undergo varying rotor speed, pitch action, and neoconservative forces. Baumgart (2002) derived a mathematical model for a WT blade of length 19 m. An experimental test was conducted in order to validate the mathematical model results.

2.2. Structural Dynamics

In the structural dynamics modeling of operating WT blades, it is usually modeled as a rotating cantilever beam. Two main types of beams are usually used, namely the Timoshenko beam and the Euler-Bernoulli beam. Between the two beams, the most commonly used in determining the dynamic structural analysis of a WT blade that is considered a thin and slender structure is the Euler-Bernoulli beam (Larsen & Nielsen, 2006). The Euler-Bernoulli beam theory does not consider shear deformation or rotary inertia as the Timoshenko beam does; it instead focuses on the lateral displacement and assumes the beam is rigid. It is important to note that both beam theories' vibration modes and natural frequencies are similar when considering slender structures (Zohoor & Kakavand, 2012).

The wind turbine blade is made up of a finite number of elements that are connected together. Finite element method (FEM) is used in determining the structural dynamics of the blade. It involves the discretization of the blade deflection along the blade length. FEM can be used to perform dynamic analysis for both the aerodynamic model and the structural model of the blade (Ju & Sun, 2017). In this study, modal analysis is used to extract the structure's mode shapes and natural frequencies. This is important during design since a system that operates close to its natural frequencies may show high amplitudes for any given level of excitation, thereby making it unstable. Similar studies on modal analysis have shown different methods used to present results. Pandey *et al.* (1991) determined and situated the damage of a cantileversupported beam structure by introducing a new parameter called curvature mode shape. FEA was used to determine the mode shapes.

Deyuan *et al.* (2004) performed a simulation analysis on a 600 kW blade using a method known as the vibration modal analysis method to examine the essential factors of the natural frequencies. Vibrational modal analysis is a method used to perform and understand the natural frequency, mode shapes, and dynamic characteristics. Sellami *et al.* (2016) used modal analysis to investigate two different blade models to know the differences in dynamic characteristics.

2.3. Vibration In Wind Turbine Blade

Vibration happens when oscillations occur around an equilibrium point. This oscillatory motion tends to repeat itself at intervals. Oscillations might be of two types: random oscillation, such as tire movement on a rough unsmooth road, and periodic oscillation, as is the case with a pendulum bob. Vibration involves the interface between kinetic energy and potential energy (Ajayi *et al.*, 2017), and hence for a system to vibrate, there must be a transfer of its potential energy to kinetic energy and vice versa. In general, the vibratory system consists of three components: those that store potential energy, those that store kinetic energy and those that are responsible for steady loss of energy (Rao, 1995).

A typical wind turbine is made up of three uniform blades rotating and connected to an annular tower. Wind turbine mechanical vibrations are harmful to living things and can potentially be destructive to the environment. The most significant of all mechanical vibrations in the wind turbine is the blade vibration, as it is the first part that comes in contact with the wind. Therefore, it is central that in the design of turbine blades, the suppression of vibration is taken into deliberation. It also affects the power generation of the overall wind turbine. With the increase in wind turbine size, the blades are more prominent and more flexible and therefore are more prone to vibration. This vibration is caused by the interaction of the blade with the tower and the wind dynamic (Ahlström, 2006). The wind turbine tower and the blade undergo dynamic interaction during operation Staino *et al.* (2012); hence in the design of the wind turbine blade, it is vital to consider the dynamic behavior.

Vibration is mainly important to a wind turbine because they operate in unsteady conditions, leading to a vibrating response. In order to forestall the effects of vibrations that result in fatigue and failure, vibration and its effect must be catered for in the design of turbines. The reduction of wind turbine blade vibration is important (Ju & Sun, 2014). Due to their flexibility, they can be subjected to vibrations when the wind, and other external forces act on them. Studies have shown that about 35% of wind turbines have vibrations due to the rotor blade. These vibrations exceed the normal limits, causing unusual structural loads, adverse start-up conditions, and increased wear (Ju & Sun, 2014). There are two primary sources of rotor imbalance: mass imbalance because of inhomogeneous mass distributions and this is because of inaccuracies during manufacturing or water inclusions in the texture of the blade. The second main cause of rotor imbalance is aerodynamic imbalances, and this occurs when there is an error in the blade pitch angle or a change in the profile of the blade (Ju & Sun, 2014).

2.4.Presentation of Natural Frequency

Natural frequency in rotating structures like wind turbines generates exciting forces, which are then conveyed to the fixed structure. The structure operates at frequencies that are integer multiples of the rotating structure. When designing a wind turbine, resonance must be avoided. Resonance occurs when the forcing frequency or exciting equals or almost equals one of the structure's natural frequencies (Burton *et al.*, 2011). In structural dynamics analysis, the structural resonance is identified and then ensured that it is far away from any of the natural frequencies or rotor harmonics (Sullivan, 1982).

There are two ways to present natural frequency data. They are namely:-

1. The Campbell diagram: - a graph of natural frequencies versus the rotor speed is plotted. With the help of a set of a straight lines from the origin, a relationship is formed between the rotor speed and the exciting frequencies (Sullivan, 1982). With the help of a Campbell diagram, resonance can be determined and avoided in the initial design of the turbine. Figure 1 is an example of what a Campbell diagram looks like.

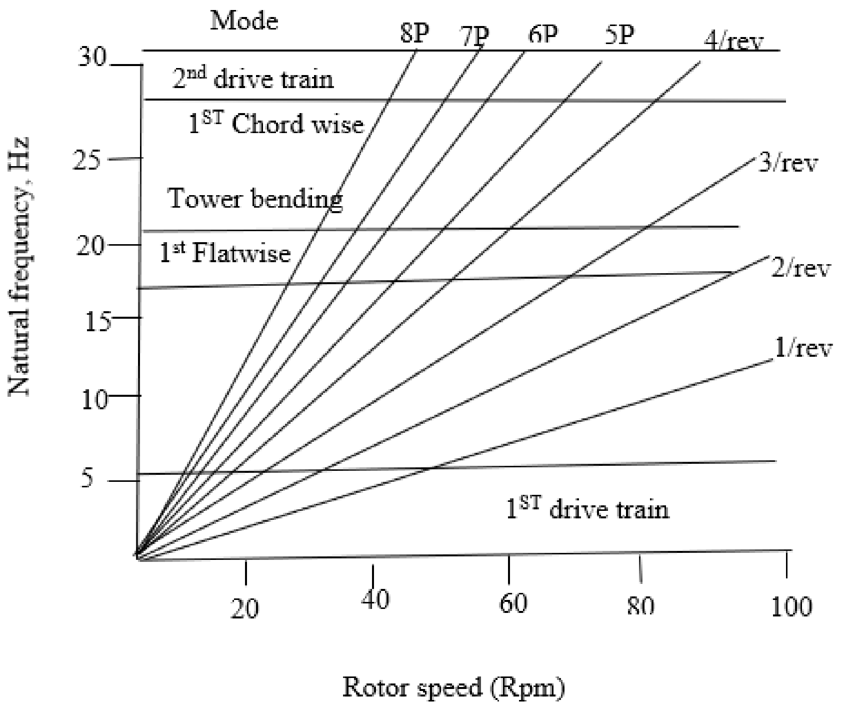

Figure 1 - Example of a Campbell diagram (Sullivan, 1982).

2. Mod-1 method: - This method involves the use of a table to present the information. The method involves the presentation of each individual revolution frequency in a tabulated column. The resonance that shows the integer multiples of the rotor speed is indicated in the figure below as areas that should be avoided (Sullivan, 1982). Figure 2 is an example of the natural frequency method.

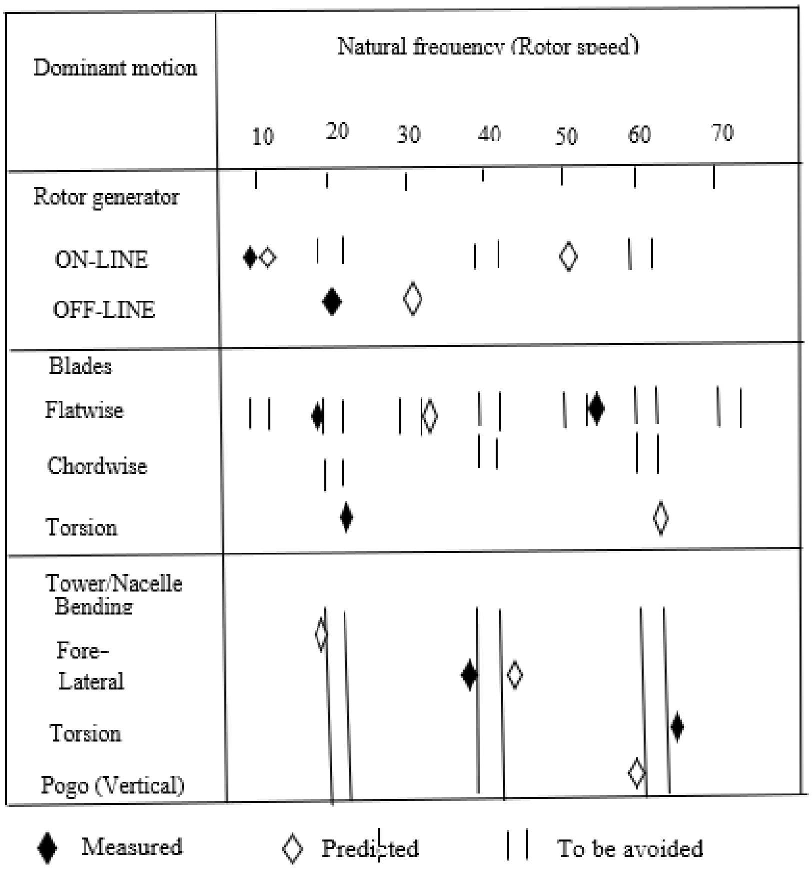

Figure 2 - Natural frequency method (Sullivan, 1982).

2.5. Types Of Wind Turbine Vibration

Research focuses on the WT blade dynamic behavior, and its interaction between the blades only started during the last few years proposed that for a WT blade, the various deflections are divided into;

a) Lateral translations, which comprise of edgewise and flap-wise vibration
b) Chord rotation occurs around the blade's longitudinal axis.

Two key vibration types are associated with turbine blades, edgewise and flap-wise. Edgewise vibrations tend to occur in the rotational plane of the blades, while flap-wise vibrations occur outside of the rotational plane of the blade. Flap-wise vibration tends to have a more devastating effect on the wind turbine blade as it can lead to the collusion of the blade with the tower. Figure 3 gives a detailed description of the direction of flap-wise vibration and edgewise vibration of a typical WT blade.

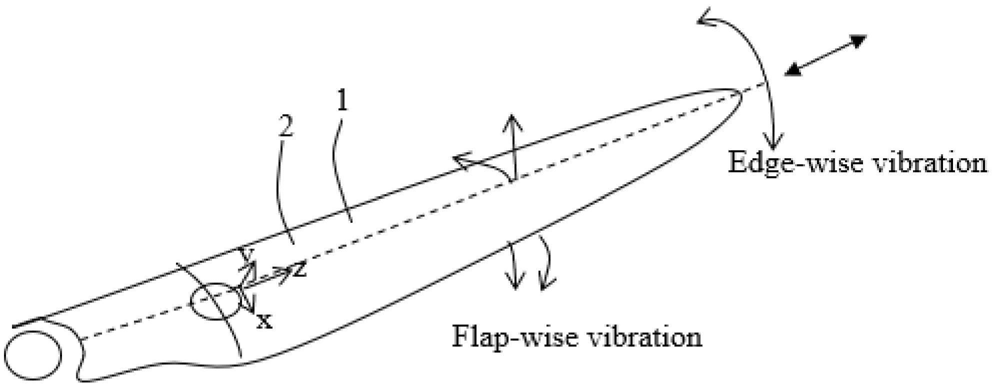

Figure 3 - Flap-wise and Edgewise vibration

Flap-wise vibration is comparable in nature to fluttering; this can be seen in aircraft wings. In some rare cases, flap-wise vibration in the WT has led to the collusion of the WT blade with the tower leading to catastrophic failure. Ronold and Larsen (2000) studied blade failure in flap-wise bending throughout standard operating situations of the turbine. Murtagh *et al.* (2005) conducted a study on the flap-wise bending of WT blades and went further to analyze their dynamic interface with the tower. Rotor imbalance is also known to be a significant cause of vibration. Studies have shown that about 35% of wind turbine's vibrations are caused by rotor imbalance. This rotor imbalance can cause vibration caused turn off, adverse start-up conditions, increased wear, and unusual structural loads (Ju & Sun, 2014). Two main causes of rotor imbalance are known namely mass imbalance and aerodynamic imbalance. Table 1 presents the causes of the two different rotor imbalances.

2.6. Wind Turbine Blade Vibration Monitoring

Several studies have devised different ways to suppress blade vibrations and their effects. In order to tackle the problem of increased vibration that occurs in the WT blade, emphasis must be on the design of the blade. It was determined that when blade tower interaction was included, there was a significant increase in the maximum blade displacement. Staino *et al.* (2012) studied edgewise vibration and its effect on sizeable multi-megawatt wind turbines. Edgewise vibrations, in this case, occur with low aerodynamic damping. Large amplitude cyclic oscillations significantly lead to a shortened lifespan of the components of the WT and may also cause structural damage or failures.

Table 1 - Causes of rotor imbalance (Ju & Sun, 2014).

Mass imbalance	Aerodynamic imbalance
i. Large blade repair	Different blade angles.
ii. Inclusions of fluid in the rotor blades	Profile deviations from the geometry
iii. Different static moments inside a blade can also cause mass imbalance.	Leading edge damage on the rotor could also lead to aerodynamic imbalance
iv. Rotor division error	Cone angle error.

Ju and Sun (2014) proposed the input-shaping method. This technique was used to reduce the flap-wise vibration of a WT blade by reducing the blade pitch angle. The Lagrange method was used to develop a model. The model created is validated using software from NREL known as the future automotive systems technology simulator (FASTSim). FASTSim is a computer-aided engineering tool known for its ability to simulate wind turbines' coupled dynamic response.

Maldonado *et al.* (2010) demonstrated the possibility of using synthetic jet actuators to improve the performance of WT blades. This technique involved altering the flow of air around the blade so that the flow separation was reduced. Depending on the Reynolds number and the angle of attack, during separation, the airflow over the WT blade was partially or fully reattached. At the end, that led to a reduction in the blade vibration. Subsequently, smart turbine blades were being developed to reduce blade loads.

Arrigan *et al.* (2011) conducted a study on the natural frequency variation of a wind turbine blade that occur because of centrifugal stiffening and then analyzed the potential of using semi-active tuned mass dampers (STMDs) to decrease vibrations in the flap-wise direction with varying parameters in the wind turbine. Simulations were later carried out numerically to verify the STMDs method's efficiency.

Vibration-based SHM is often used in structural damage identification. The method involves studying the response of the structure dynamically. This response is then measured and recorded by a variety of instruments, namely strain sensors such as accelerometers. Certain damage-sensitive features are extracted in the process of using this method, they include; damping, mode shapes, resonant frequencies, natural frequencies and other dynamic sensor signal features (Doebling *et al.*, 1998). The process of extracting features in the vibration-based SHM involves two techniques largely used: the EMA and the OMA used in structural dynamics. Several other methods employed which fall under the SHM include ultrasonic guided wave inspection (Ebrahimkhanlou *et al.*, 2016), acoustic emission (Grosse & Ohtsu, 2008), vibration testing (Ou *et al.*, 2017), and thermal imaging (Henneke *et al.*, 1979). It should be noted that the SHM is a contact method.

This method is also used in model validation and model updating in other applications like mechanical systems and aerospace (Ewins, 1984; Niezrecki *et al.*, 2014). Identification of changes in the structure's dynamic behavior is recorded with the help of a sensor system, which plays a key role in the approaches used in EMA and OMA (Montalvao *et al.*, 2006). Sensors usually used in vibration-based SHM are accelerometers, which are precise with high spatial resolution but usually do induce less mass-loading effect, but when compared to displacement and velocity sensors, they do not.

In 2018, Sarrafi *et al.* (2018) suggested a non-contact method, which involves using PME to detect vibration-based damage in a WT blade. During the work, image sequences were recorded and then extracted by the use of PME. This extracted video recording was then used to conduct damage identification of the WT blade. In addition to using the PME method, video magnification was also used to perform operational modal analysis, and resultant modal shapes and resonant frequencies were extracted. Other non-contact methods include laser vibrometers and digital video cameras, combining image and video processing algorithms. Although laser scanning vibrometers are known to be expensive, they can record the structural response and, in the process, avoid the effects of mass-loading and do not also tamper with the structural stiffness (Castellini *et al.*, 2006; Stanbridge & Ewins, 1999). Digital video cameras, image, and video processing algorithms are cheaper in comparison to laser vibrometers and can be utilized in strain and modal analysis (Busca *et al.*, 2014; Cheli *et al.*, 2013; Mazzoleni & Zappa, 2012).

2.7. Effect of Blade Vibration/ Deflection on Power Output

Gloe and Jauch (2017) analyzed the dynamics of an E30 wind turbine. They discovered that there is small power available when the wind is at resonance speed. Wind turbine components like the blade are vulnerable to vibrations and excitations in a wide frequency range. When the frequency caused by the external excitations of the wind turbine is close to the eigenfrequencies of any of the WT components, it limits the WT's ability to support power in the grid (Gloe & Jauch, 2017).

In designing the external geometry of a WT blade, the main aims are to maximize the extraction of power and structural efficiency. The maximization of power includes maximizing the AEP and the minimization of the COE produced. Ahlström (2006) researched on the design of WT blades that more lighter and flexible and their impact on the structural load and power output. Large blade deflections occurred because of the increase in the flexibility of the blade. This blade deflection led to a significant drop in both the production of power and the structural loads.

Larsen *et al.* (2004) did work on blade deflection using HAWC. HAWC is a useful tool in investigating the effects of large deflections on power production and loads. HAWC is an aeroelastic code used to predict the load response for a HAWT in the time domain. It was determined that there was a drop in power production as deflection increased. It also determined that with the increase in deflection, there is a change in frequencies when a rotor is excited. They concluded that there is a change in frequency for a rotor at a standstill when excited by white noise.

Xudong *et al.* (2009) optimized the blade based on the BEM theory and an aeroelastic code to reduce the COE. The AEP and the rotor blade cost ratio were calculated to achieve this aim. The overall aim of the model optimization was to reduce the COE. The COE is obtained from the AEP and the rotor cost. The design variables utilized in this study were the relative thickness, twist angle, and chord. Aerodynamic and structural optimization methods is a popular method that has been used in previous studies to date. Benini and Toffolo (2002) introduced a technique that involves the optimization of the WT blade. Two algorithms were used, namely the multi-objective evolutionary algorithm and the BEM theory. The two methods were coupled to arrive at the best objective, a trade-off between AEP and COE.

2.8.Modeling Optimal Wind Turbine Hub Height

The wind turbine hub height is a critical factor in the efficiency of wind turbines. The hub height affects both the amount of energy generated and the operating costs associated with turbines. To optimize these factors, determining the optimal hub height is essential. Wind turbine design needs to optimize the ratio between energy production and operating costs. To determine this ratio, it’s important to analyze the effects of wind turbine hub height on power output. By simulating different heights, engineers can identify the ideal height for maximum efficiency. There are many factors that must be considered when modeling an optimal hub height. These include wind speed, turbulence, local topography, and terrain roughness.

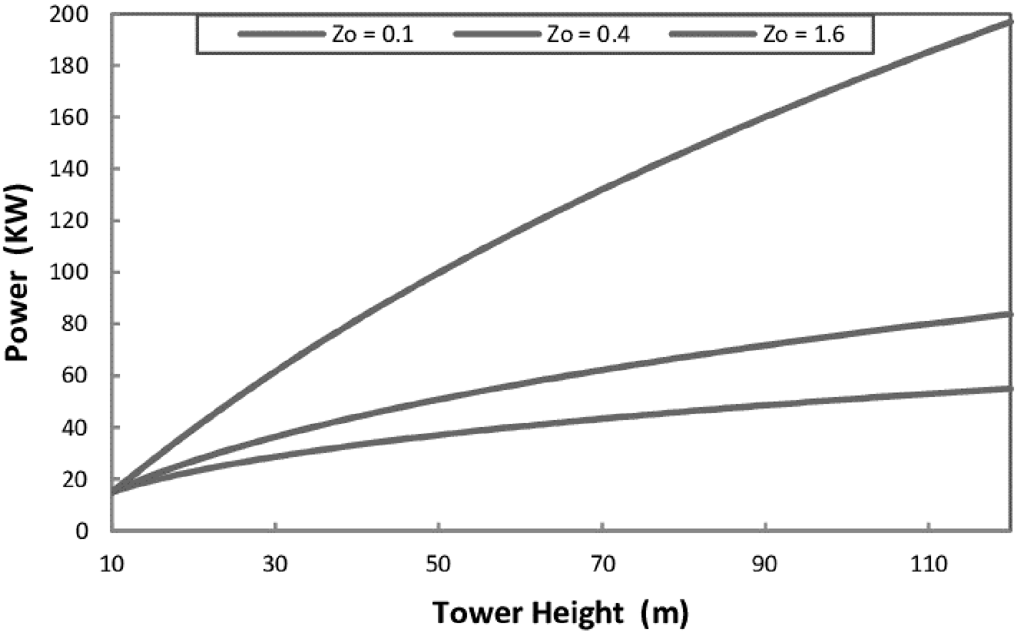

Figure 4: Evaluation of factors affecting wind turbine output power (El-Ahmar *et al.*, 2017)

Eric Lantz *et al.* (Lantz *et al.*, 2019) emphasize the fact that the quality of the wind as an energy resource is significantly improved with the height above ground. Wind speed increases with height, and as such, higher wind turbine hub height translates to improvements in wind turbine capacity factor. Nevertheless, increase in hub height introduces new constraints that need to be me for viable deployment, such as adequate tower design to withstand extreme conditions during turbine life, minimization of mass that directly impacts material costs, labor costs and logistics costs, remarkably so. Engineers will typically implement turbine tower design considerations similar to requirements for tall buildings and towers. Narjisse *et al.* (Narjisse & Khamlichi) using computational fluid dynamics to evaluate wind speed height distribution and examine the dependence of the performance of a wind turbine on the characteristics of the airflow, in addition to conditions associated with the atmospheric boundary layer (ABL). Making a decision with proper consideration of the various competing factors relating to tubine hub height is a challenge and different approaches have been develeoped. Talini *et al.* (Talinli *et al.*, 2011) highlight a methodology, fuzzy analytic hierarchy process (FAHP) that can be used on each factor to determine the weight of fuzziness of its attributes.

3. Wind Turbine Blade Structural Dynamics

During operation, the WT blade experiences large structural dynamic loads that tend to change with time; some of the loads include aerodynamic, gravitational, and inertia loads. It is, therefore, crucial that the WT blade model precisely predict the structure's response when subjected to dynamic and static loads (Griffith, 2009).

Wind turbine blade structural dynamics are critical. Structural dynamics models are essential for the WT turbine's entire system and substructures. The most important structural dynamic analysis type is modal analysis. Modal testing is a method used to understand the characteristic of a structure like the natural vibration. It is also used to determine the structural dynamics model. Modal analysis helps to obtain the natural frequencies of the structure. The natural frequency is the frequency at which the structure will naturally vibrate.

3.1. Wind Turbine Blade Loads

WT blades are an essential part of the system that comes in contact with the wind. It is the main component that captures wind loads and converts them to the mechanical rotation of the generator rotor. Some of the crucial components of the WT include the blades, generator, shaft, bearings, and gearbox.

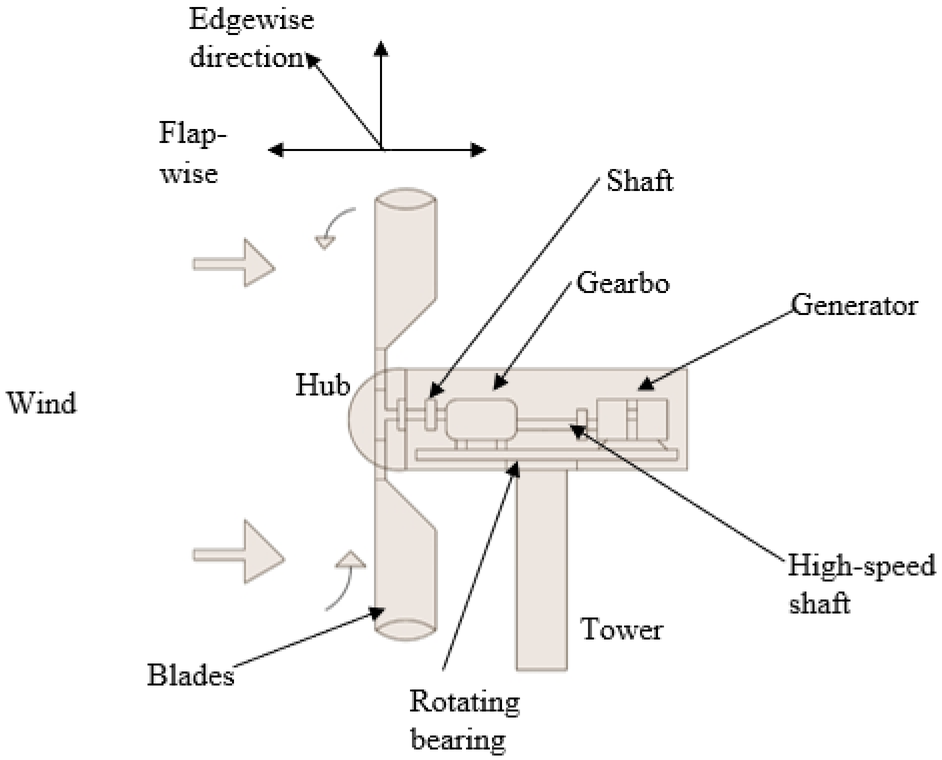

Figure 4 - Wind turbine and its major components.

Figure 4 above details some of the significant components of a WT. In this study, the component of particular concern and analysis is the blade with certain boundary conditions from the bearing inputted. Theoretical development will be limited to the dynamic behavior of the blades. In the WT blade operation, two deflections are of key interest namely; lateral translations, which include flap-wise and edgewise deflection, and chord rotation, which is when the WT blade operates around its longitudinal axis (Hau, 2013).

Wind turbine blade loads are usually affected by three main sources namely (Hansen, 2008):-

1. Inertial loading
2. Gravitational loading
3. Aerodynamic loading

Inertial loading: - occurs when the wind turbine blade is accelerated or decelerated. This might occur when the rotor blade accelerates due to increased wind speeds or brakes due to internal friction forces. Other forces that may act on the blade because of inertial loading includes centrifugal forces, Coriolis, and gyroscopic moment. Steady loads are produced during inertia loading as a result of constant wind speed and centrifugal forces acting on the blade as a result of rotation.

A force dF will act on a small area of the blade in the rotational direction. Figure 5 shows the force acting on a small section of one blade.

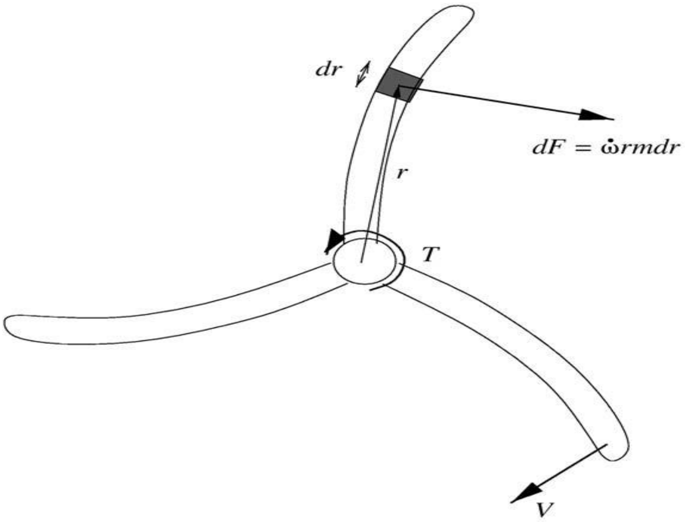

Figure 5 - Braking rotor induced load (Hansen, 2008)

The elemental force dF on one blade is given as:

$$dF = \dot{\omega}rmdr \quad 1$$

Where m is blade mass, r is the element radial position, dr is the elemental length as given in figure 3.2.

$\dot{\omega} = \frac{d\omega}{dt}$ is the acceleration which can be obtained from the braking torque T given by

$$T = I\frac{d\omega}{dt} \quad 2$$

I is the mass moment of inertia.

For three-bladed WT, the final value obtained from equation 3.1 is to be multiplied by three, which gives a formula

$$dF = 3(\dot{\omega}rmdr) \quad 3$$

Gravitational loading: - This is a loading that occurs due to the earth's gravitational field. Because of the earth's gravity, there is sinusoidal loading that occurs on the WT blade. (Hansen 2008.). The result of the gravitational loading is felt more along the edgewise direction. Because of the gravity on the blade, periodic loads arise. Other factors that contribute to periodic loads are vertical wind, the velocity of yaw, crosswind error in yaw) and tower shadow (Rao, 2011) (Rao 2011). These periodic loads are also known as cyclic loading, which occurs because of rotor rotation.

In Fig. 6, on the WT blade top and bottom, there is a cyclic loading during rotation due to gravitational forces. Position 1 shows that at the bottom side of the blade, it experiences compressive stress, whereas, at the top side, it experiences tensile stress. When the same blade moves to position 2, the sides exchange the nature of the stresses. Between these two positions, it can be observed that the magnitudes continually change from compressive to tensile stress and at the vertical position. The top and bottom sides experience no stress due to gravitation. Gravitational loading is more dominant and seen on the edgewise bending moment. It is responsible for sinusoidal rotor loading with a frequency corresponding to the number of revolutions in one second (1P).

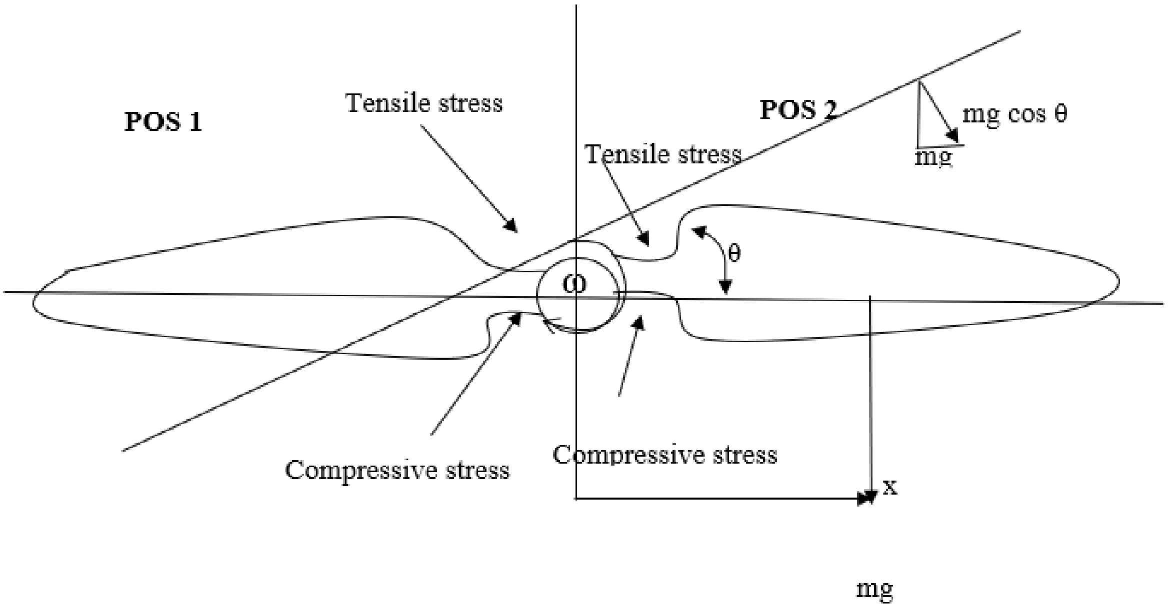

Figure 6 - Gravitational loading

The gravitational pull on the blade because of its weight is given as

$$w = mg\cos\theta \tag{4}$$

Where w is the weight, m is the mass of the blade, g is the gravity due to acceleration, and θ is the local pitch angle.

Taking a moment around x, the edgewise bending moment force is hence given as

$$M_x^{edge} = \rho\, A\, g(L-x)\frac{(L-x)}{2} \tag{5}$$

Where ρ is air density, A is the blade cross-sectional area, and L is the blade length.

Aerodynamic loading: - occurs when there is a flow of air past the wind turbine blades and usually occurs in a flap-wise direction. Stochastic load is usually generated during aerodynamic loading, which occurs when there are random variations in wind speed. This results in correspondingly random aerodynamic forces on the WT blade. Transient loads may also occur because of a rapid change in operating conditions, such as a sudden wind gust and wind direction change. Transient loads typically die out after a certain duration. Two vital forces are involved in aerodynamic load generation, namely, lift and drag. Lift occurs because of uneven pressure acting on both sides of the airfoil, while drag occurs when viscous forces acting on the outer surface of the airfoil (Hansen, 2008). As shown in Fig 7, in defining the lift and drag per unit length, it is necessary to determine the coefficient of lift and drag first.

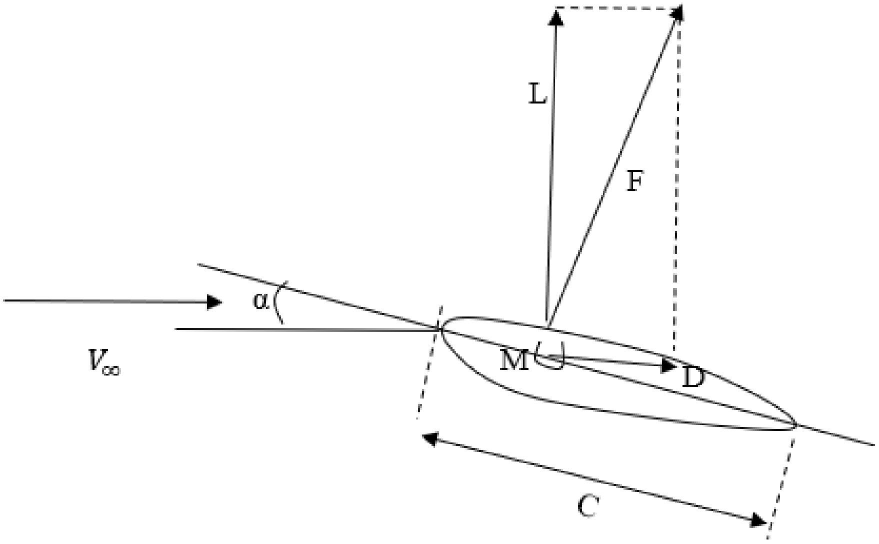

Figure 7 - Lift and Drag

Lift per unit length is given as

$$L = \frac{1}{2}\rho V_{rel}^2 c C_l \quad 6$$

Drag per unit length is

$$D = \frac{1}{2}\rho V_{rel}^2 c C_D \quad 7$$

Were C_l and C_d is coefficient of lift and coefficient of drag, respectively, ρ is the air density, V is air velocity, and c is the length of the airfoil.

Wind velocity on the rotor is

$$V = V_\infty(1 - a) \quad 8$$

Wind velocity as a result of the rotation of the blade is

$$V = \Omega r(1 + a') \quad 9$$

Ω is the angular velocity.

3.2. Wind Turbine Blade Stress

In determining the stress on a WT blade, it is essential to note that the wind turbine blade can be modelled as a cantilever beam hence the simple beam theory can also be applied. A cross-section of the airfoil is shown in Figure 8.

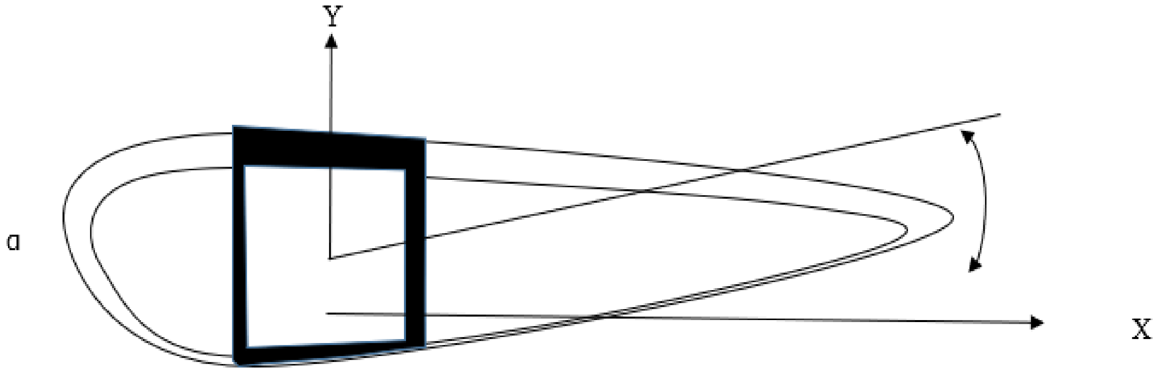

Figure 8 - Cross-section of an airfoil

The stress in the cross-section x,y is given as

$$\sigma_{(x,y)} = E_{(x,y)}\left(\frac{M_1}{EI_1}y - \frac{M_2}{EI_2}x + \frac{N}{EA}\right) \qquad 10$$

N is the normal force acting on the shaded X-section above, E is defined as the modulus of elasticity, I is a different moment of inertia, and M is a different bending moment;

$$M_1 = M_y \cos\alpha - M_z \sin\alpha \text{ And}$$

$$M_2 = M_y \sin\alpha + M_z \cos\alpha$$

If the external loadings p_y and p_z are known along the blade, the shear forces T_z and T_y can be calculated as

$$\frac{dT_z}{d_x} = -p_z(x) + m(x)\ddot{u}_z(x) \qquad 11$$

$$\frac{dT_y}{dx} = -p_y(x) + m(x)\ddot{u}_y(x) \qquad 12$$

$$\frac{dM_y}{dx} = T_z; \frac{dM_z}{dx} = -T_y \qquad 13$$

3.3. Local Load and Relative Velocity on the Blade

For a force acting on a WT blade, the drag and lift projected in the normal and tangential directions to the rotational plane are given as

The normal direction is given as

$$\mathrm{P_N = Lcos_\phi + Dsin_\phi} \qquad 14$$

While the tangential direction is given as

$$P_T = L\sin_\phi - D\cos_\phi \tag{15}$$

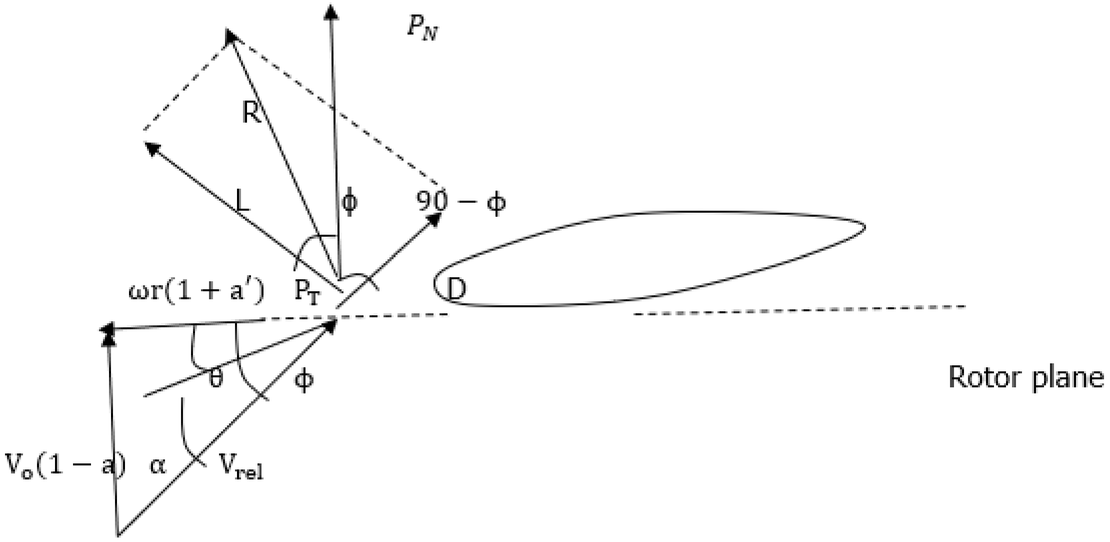

Figure 9 - Local load and relative velocity on the blade.

The coefficient of the normal force is

$$C_n = C_l\cos\phi + C_d\sin\phi \tag{16}$$

In addition, the coefficient of tangential force is

$$C_t = C_l\sin\phi - C_d\cos\phi \tag{17}$$

For relative velocity V_{rel} , this is the addition of the axial velocity $V_o(1-a)$ and the tangential velocity $wr(1+a')$ in fig. 9 above.

$\theta =$ Local pitch of the blade, this is the combination of pitch angle, θ_p, and the blade β. α is the angle of attack.

Angle of attack $\alpha = \phi - \theta$

ϕ is the angle between the relative velocity and the rotational plane.

$$\mathrm{Tan}\phi = \frac{(1-a)V_0}{(1+a)\omega r} \tag{18}$$

3.4. Determination of WT Blade Excitations and Resonances

Resonance occurs when a forcing or exciting frequency of a structure is equal or nearly equal to one of the natural frequencies (Burton *et al.*, 2011). At these resonant frequencies, the response amplitudes of the concerned part are severely amplified, with the result that they cause catastrophic failure if the operation is sustained at that excitation frequency. Therefore, it is imperative that the WT system operates close to resonant frequencies and should be avoided or kept to an absolute minimum at all times. For a three-bladed WT, the vibrations are excited by 3f, and the 3f and its multiples excite vibration in the tower (Krenk *et al.*, 2012).

$$f_{3n} = 3nf\ (n = 1,2,3,4 \ldots.) \tag{19}$$

The introduction of damping into the system reduces the response amplitudes with the result that resonance occurs at what is called damped natural frequencies. The mathematical formula for the calculation of the WT blade damped natural frequency is expressed as

$$\omega_d = \omega\sqrt{1-\zeta^2} \qquad 20$$

Where ω is the natural frequency, and ζ is the damping ratio.

$$\omega = \sqrt{\frac{k}{m}} \qquad 21$$

$$\zeta = \frac{c}{2\sqrt{mk}} \qquad 22$$

Where k is the spring constant of the blade and m is the mass.

Damping helps reduce the blade's vibration amplitude during variable and turbulent wind situations. In turn, it helps reduce the blade's ability to generate a resonant response. For a rotating blade, the frequency exciting the structure is usually the integer multiple of the rotor speed.

3.5. Wind Power Output

Wind power is defined as the total accessible energy per unit of time. The wind power is converted into mechanical-rotational energy of the wind turbine rotor. For a HAWT, the wind turbine output depends on its rotor speed and the turbine size. The WT output is restricted by Betz's limit; Betz's restricts the coefficient of power to 59.3%. Figure 10 is a view of a HAWT.

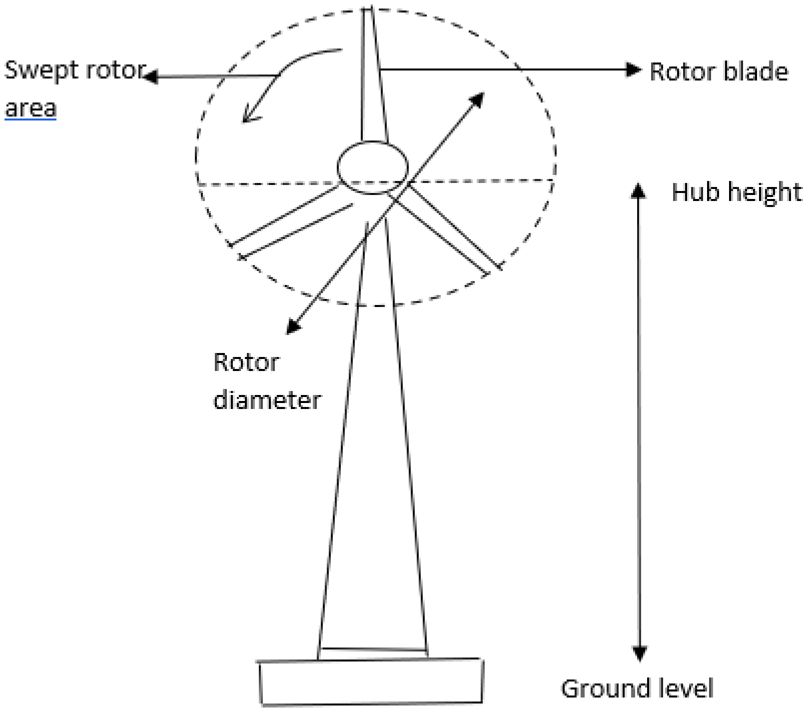

Figure 10 - HAWT

Designers of WT have ensured that they can approach the Betz limit efficiency. Modern small-scale standalone turbines are beginning to gradually reach this limit (Dayan, 2006). Modern wind turbines that are manufactured now have higher power output ratings that range from 250 W to 1.65 mW. For small-scale WT, the average annual wind speed by which is can generate electricity is 4 m/s (Anderson *et al.*, 2015). The available power in the wind is directly proportional to the cube of the wind speed. Therefore, to achieve a power by the factor of eight, the wind speed should be doubled (Mollasalehi *et al.*, 2014).

The Wind speed of an area is a critical factor in projecting the performance of the turbine; this is an important assessment before the siting and construction of a wind turbine system. In Fig. 11, the cut-in wind speed of a WT is shown to be the minimum wind speed at which the blades of the turbine start to rotate after overcoming friction. The cut-out wind speed is regarded as the wind speed at which the WT blade stops rotating to avoid damage to the system due to dangerously high winds. Not all turbines have a well-defined cut-out speed.

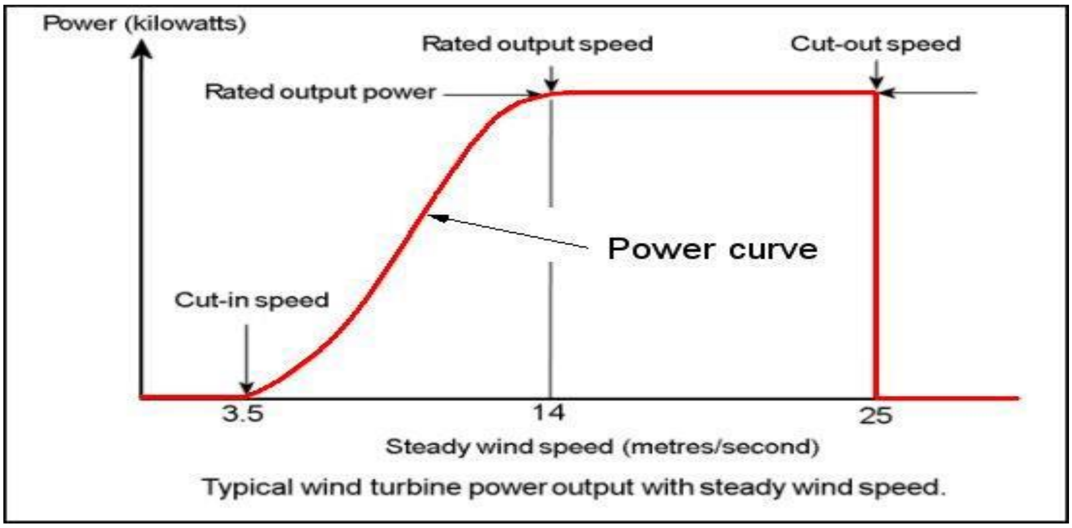

Figure 11 - Wind turbine power output with steady wind speed.

The power curve is the steady power brought by the WT; it is a function of a stable wind speed between the cut-in and cut-out speeds. In order to install a 10 kW WT system that can power up to twelve households, it will cost between ZAR355, 000 - ZAR496, 000 in South Africa. In Nigeria that same 10 KW WT will cost 4,110,000 NGN – 12,330,000 NGN. Depending on the availability of the wind, in one year, the turbine will produce power between the ranges of 10,000 to 18,000 kWh. The turbine of this range should sit on a tower of height 30 m tall. The height of the tower enables it to be above the turbulence, such as surrounding buildings and trees. The velocity of wind increases the higher the altitude hence improving turbine performance.

3.6. Wind Power Output Calculation

The KE per unit time/power of the flow expression Ackermann and Söder (2000) gives the wind power as P that flows at a wind speed, V, around blade area A.

$$P = \frac{1}{2}\rho A V^3 \tag{23}$$

Where

ρ = Density of air

A = cross-sectional area of flowing air

V = speed of wind

Betz in 1926, argued that the power available in the wind cannot be extracted completely by the WT and hence postulated a theoretical optimum to get the most out of the power from the wind and reduce the velocity. It was given as

$$\mathrm{P_{Betz}} = \frac{1}{2}\rho \mathrm{AV^3 C_{P.Betz}} = \frac{1}{2}\rho \mathrm{AV^3} 0.59 \qquad 24$$

Hence using Betz, 59.3% of the power in the wind could be extracted and used by the WT.

3.7. Annual Energy Production

If a wind turbine is to be installed, knowing the annual energy output at the particular installation site is important in assessing the economic feasibility. Two probability density functions are mostly used in determining annual energy production. The Weibull distribution and the Rayleigh distribution are given as

The Rayleigh distribution is represented by mean velocity only and is given as,

$$h_R(V_o) = \frac{\pi}{2}\frac{V_o}{V^2}\, exp\left(-\frac{\pi}{4}(\frac{V_o}{V})^2\right) \qquad 25$$

For the Weibull distribution

$$h_w(V_o) = \frac{k}{A}(\frac{V_o}{A})^{k-1} exp\left(-(\frac{V_o}{A})^k\right) \qquad 26$$

Where k = form factor and A= scaling factor. Both of these factors are obtained from meteorological data around the area of local siting.

The Weibull distribution is the most commonly used.

The total AEP can be determined by:

$$AEP = \sum_{i=1}^{N-1}\frac{1}{2}\left(P(V_{i+1}) + P(V_i)\right)\cdot f(V_i < V_0 < V_{i+1})\cdot 8760. \qquad 27$$

4. Benefits and Applications 4IR to WT modeling

Wind turbine modeling has many benefits and applications in solving energy problems in Nigeria and South Africa, particularly in the context of the Fourth Industrial Revolution (4IR). 4IR technologies provide a number of advantages that can raise the effectiveness and performance of wind turbines, here a some of the benefits and application of using 4IR in wind turbine modelling:

1. Predictive maintenance: Using 4IR technology like predictive analysis, it is possible to fortell when maintenance on wind turbine will be necessary. This may aid lowering maintenance expenses and downtime, as well as lengthening the life of the the wind turbine. Wind turbine modeling can also help predict the amount of energy that can be produced from wind turbines, allowing for optimization of wind energy production. This can be particularly helpful in areas with variable wind patterns, as it can help maximize energy output while minimizing downtime (Black *et al.*, 2021)

2. Enhanced accuracy and precision: Models for wind turbines that are accurate and precise can be created using 4IR technologies like machine learning and artificial intelligence. These models can forecast how wind turbines will perform in various climatic scenarios, which can be used to improve their efficiency and design (Ukoba *et al.,* 2023)
3. Improved energy yield: by focasting the ideal blade angle and changing it in real-time based on wind conditions, 4IR technologies can aid in maximizing the energy production of wind turbines. This could aid in boosting energy production and enhancing wind turbines general efficiency. It can also be used to reduce energy cost; Wind energy is often more cost-effective than traditional fossil fuel-based energy sources, and wind turbine modeling can help reduce the costs of wind energy even further. By optimizing wind turbine systems and predicting energy output, it is also possible to reduce the costs of energy production and distribution (Munteanu *et al.,* 2008)
4. Real-time monitoring and control: The performance of wind turbines may be tracked in real-time using 4IR technologies like the Internet of Things (IoT). This can aid in early problem identification and resolution, minimizing downtime and enhancing wind turbine dependability (Mhlanga, 2023)
5. Reducing carbon emissions and energy cost: Wind energy is also more environmentally friendly than traditional energy sources, as it produces no carbon emissions. By using wind turbine modeling to increase the efficiency of wind energy production, it is possible to reduce carbon emissions and combat climate change. Wind energy is often more cost-effective than traditional fossil fuel-based energy sources, and wind turbine modeling can help reduce the costs of wind energy even further. By optimizing wind turbine systems and predicting energy output, it is possible to reduce the costs of energy production and distribution.
6. Increasing energy access: Wind energy can be used to provide energy access to areas that are off-grid or underserved by traditional energy sources. By using wind turbine modeling to optimize wind energy production, it is possible to increase energy access and improve the quality of life for people living in these areas.

Overall, wind turbine modeling has many potential applications in solving energy problems in Nigeria and South Africa. By increasing the efficiency of wind energy production, it is possible to reduce energy costs, reduce carbon emissions, and increase energy access, all of which are crucial in the context of 4IR.

5. Recommendations

To effectively address the energy challenges that Nigeria and South Africa are facing, it is recommended that policymakers and researchers prioritize the development and implementation of wind energy technologies. Utilizing advanced wind turbine modeling techniques can help these countries achieve a more reliable power supply, reduce carbon emissions, and meet the increasing demand for electricity. Wind energy has the potential to promote sustainable economic growth, energy security, and environmental protection. The 4IR context also provides an opportunity to leverage technological advancements in wind turbine modeling and integrate them with digital infrastructure to improve energy efficiency and reliability. Therefore, it is crucial that industry, government, and academia collaborate to successfully implement wind turbine modeling technologies in the context of the 4IR.

6. Conclusion

Wind energy is gaining popularity as a sustainable and clean energy source, which has led to a growing interest in developing more advanced and efficient wind turbine blade designs. However, it is also crucial to investigate the potential of wind energy to address the energy challenges faced by Nigeria and South Africa, the two largest economies in Africa. In conclusion, this study provided an overview of the different types of loads that act on wind turbine (WT) blades and the relevant theory for their determination. The calculation of stresses on the blade, velocity, and relative velocity on the blade, as well as the determination of WT blade excitation and resonance were also discussed. The reduction of damping into the system to reduce amplitude was highlighted, and the importance of identifying the frequency and speed at which the blade resonates to improve its vibration behavior was emphasized. This study also noted that the power output of a WT is primarily dependent on its size and wind speed, with a maximum generation of 59.3% (Betz limit). Furthermore, the calculation of annual energy production was highlighted, and the potential for wind turbine modeling to address energy challenges in Nigeria and South Africa was discussed, providing valuable insights for future research.

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