Design and Analysis of Wind Mill for Efficient Energy Production

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ABSTRACT

Wind energy is always treated as the environmental pollution free, hazardless and one of the best and free renewable energy resource for generation of electric power. The main aim of the design and analysis is "to produce current using multi generator and single rotor". The multi-generator addresses potential challenges: dimension, cost effectiveness and reliability. The two electromagnetic induction generators are desired to share the single shaft through straight bevel gears. These poles of the two generators will be changed as alternate to parallel. The Construction, working, parts of windmill; materials are discussed detailed in this paper. It is known fact that the speed at which a wind turbine rotates must be controlled for efficient power generation and to keep the turbine components within designed speed and torque limits. The centrifugal force on the spinning blades increases as the square of the rotation speed, which makes this structure sensitive to over speed. This paper discusses about the design procedure of gears, gear life and wind turbine rotors. The output current is stored in series of battery to appliances through converter and step up transformer are also to be designed.

Keywords: *Design & analysis, wind turbine, multi generator, electro-magnetic induction, windmill.*

1. INTRODUCTION

Since the Arab oi1 embargo, we have seen increasing emphasis placed on energy and its conservation. President Carter, in his speeches of April 18th and 20th of 1977, called the energy situation "the greatest challenge that our country will face during our life time". It is the opinion of the author that wind turbine can play a significant role in meeting this challenge. Both small and large machines have the potential for relatively low cost production; even without the advantages of mass production they offer one of the cheapest means o f producing solar electricity available today. The problem of energy storage will not be dealt with in this report, although it is felt it can be handled in many parts of the country because hydro electric dams and underground gas formations suitable for compressed air storage are abundant in many windy areas. It is an important fact that is not widely appreciated, that the amount of wind energy available on an annual basis is as large as the average energy flux of sunlight in many regions. The average wind power on the Great Plains over the course of a year i s over 200 watts / M^2 . In a low gap in the Rocky Mountains near Medicine Bow i n southern Wyoming, for instance, the annual average wind speed is 21miles (34 km) per hour and the energy flux is 500 watts / M^2. In the next few years more effort and attention will be focused on conservation and developing new sources o f energy than the combined efforts in this area during the past 50 years of relatively plentiful and inexpensive energy.

The power that can be extracted from the wind is primarily driven by two factors, the size of the cross sectional area that is being used to capture the wind and the velocity of the captured wind. It is well documented that as rotor size increases the power captured from the wind increases proportional to swept area. This has led to the ever-increasing size and subsequent power output of the standard three bladed turbine designs. One can also increase the power capture by increasing the velocity of the wind at the rotor plane, where it reacts on the blade. This typically necessitates the need of a location in high wind areas and has led to the development of higher towers. An alternative approach, investigated in the present study, is to modify the local wind stream to achieve higher velocities. As is well known, a turbine's power output has a linear relationship with the area of a given turbine, but a cubic relationship with wind speed **[1]**. This makes incremental differences in wind speed significant and the idea of accelerated wind stems from the exploration of such a potential increase. Accelerated wind encompasses a broad range of concepts, each with the same fundamental goal, namely to increase the velocity at the rotor plane and draw more energy out of the wind. Generally, a structure is situated near the rotor to accelerate the wind, such that it reaches peak velocity at the rotor plane. An example of this is a diffuser structure that surrounds the turbine blades, resulting in a Diffuser Augmented Wind Turbine (DAWT). A DAWT's structure lowers the pressure downstream of the blades to draw a greater mass of air through the rotor plane and thus generate more power than a similarly sized HAWT (Horizontal Axis Wind Turbine) [**2-4].**

This study explored the benefit of situating a cylindrical structure next to a turbine in order to increase the velocity upstream, and at, the rotor plane. Similar concepts have been previously explored. Duffy **[5]** performed wind tunnel studies to analyze various geometries of a toroidal accelerator rotor platform (TARP) to accelerate the wind. The TARP is conceptualized as an add-on attachment to grain silos, water towers or as standalone structures. A prototype was built and briefly tested in Belgium. This concept was extended to (WARP^{TM}) Wind Amplified Rotor Platform **[6]**, consisting of a number of stacked TARP modules; however a viable commercial product does not exist today. A numerical and experimental design investigation of such an accelerator device was performed in the current investigation. The geometrical effects of the cylindrical "accelerator platform" and the implications of accelerated wind on rotor blade design are studied. Initially, various cylindrical geometries, including straight cylindrical and toroidal platform shapes, were looked at both numerically and experimentally. Several different physical models were used in order to develop a better understanding of what is required to accurately predict power output. The highest level of fidelity utilized actuator disc models. The actuator disc model results were then used to generate the design target thrust coefficient for the rotors. Initially, an open rotor, blade element momentum (BEM) design strategy, as noted by Glauert **[7]**, was optimized for a rotor plane velocity of 2/3 of the free-stream velocity. The Computational Fluid Dynamics (CFD) analysis, however, indicated that a target reduction of the free-stream velocity by 1/3 was not the best speed at the rotor plane velocity for a location adjacent to a cylinder. Hence a strategy was employed to utilize the predicted optimum rotor pressure drops from CFD, in the presence of the cylinder at the rotor plane, to design the optimized blades using the BEM code. The speed at which a wind turbine rotates must be controlled for efficient power generation and to keep the turbine components within designed speed and torque limits. The centrifugal force on the spinning blades increases as the square of the rotation speed, which makes this structure sensitive to over speed. The design procedure of load applied on wind turbine structure, gear life and rotors are discussed.

2. WIND TURBINE DESIGN CHALLENGES

As wind turbines (WTs) are used to convert energy from the wind into electrical energy, the amount of generated electricity depends mainly on the rotation speed of the wind turbine (WT), the wind resource and the aerodynamic design **[8].** A WT comprises three main parts, which are the rotor, nacelle and tower. The wind turbine tower (WTT) elevates the rotor and the nacelle above ground level to a minimum height, which corresponds to the diameter of the rotor. This ensures that the blades do not collide with the ground. The maximum height is limited by cost, as well as by challenges of installation. However, these constraints are constantly evolving along with scientific and technological advances and innovations. The first WTTs had a lattice design, whereas cylindrical or conical tubular WTTs built out of steel or concrete are now the most used designs **[9]**. The criterion for selecting a design depends often on the natural frequency of vibration, the wind resource, aesthetic considerations and the proposed installation site. Currently, WTTs are subjected to great stress, due to the various dynamic loads that these are required to sustain during operation. The main dynamic loads are the interaction of the wind with the rotor and tower **[10]** and the weight of both the nacelle and rotor. The weight of the latter, which is located at the top of the tower, causes instabilities in the structure, and its natural frequency is greater than that of a building of the same height. The effect of earthquakes on WTs should also be considered. A WT located at sea will also be subjected to wave and sea current loads on its supports and WTTs. The effects of the wind, which become less turbulent but more intense as WTT height increases, must also be considered.

2.1 Types of Wind Turbine loads

Although wind loads acting on a WT mainly comprise two types, that acting on the turbine and those acting on the tower, wind are unpredictable by nature and exerts thrust on the structure in various directions and at different intensities.

2.1.1. Wind modelling: Due to the disperse and random characteristics of the wind, the only way of accurately estimating the adequate area of land for the installation of a wind farm is to analyze wind measurements recorded by weather stations via statistical methods. For this purpose, wind estimation methods have been developed. The oldest of these is the Fisher Tippet method (1928) [**11**], which were modified by Jenkins on in 1955 by generalized Fisher-Tippet formulas into a single equation. This equation is known as Generalized Distribution of Extreme Values [**12**]. Fernandez [**13**] made an important contribution by writing a historical review of the evolution of wind estimation methods. There are three types of distribution for the above-mentioned analysis: Type I or Gumbel distribution; Type II or Frechet distribution; and, Type III or Weibull distribution. The selection of some of these distributions has been the subject of intense debate in the scientific community. Today, several researchers prefer an adjustment towards a Type I distribution. However, Mayne [**14**] states that this type of distribution is adjusted satisfactorily in 'well-behaved' climates, namely places with little variability in events that produce extreme winds. A Type III distribution minimizes asymptotic behavior errors in the distribution, and although it does not work well for tropical areas, the data can be conditioned to use this method in those areas. It is clear that a general and detailed method for estimating the dynamic behavior of the wind is not yet available.

2.1.2. Average wind speed. In the development of wind energy projects, a database obtained from weather stations and compilation of at least one year of wind behavior records is indispensable. This data is obtained from weather stations located in the selected area and then processed and analyzed using various statistical methods. One of the most outstanding methods is the Weibull distribution, which is recommended by the International Electrotechnical Commission's (IEC).

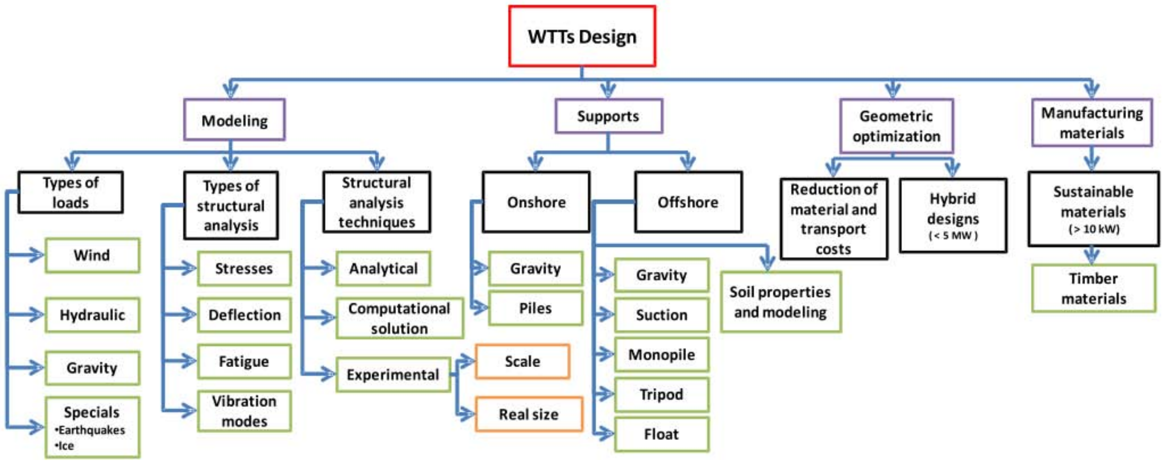

Figure 1: Classification of the main parameters involved in the design of WTTs.

2.1.3. Blades pitch angles to 90: As seen in **Fig. 2**, as an additional safety measure, a WT places its blades in feathered position when it is parked to ensure that blades are not in angle of attack position, which would cause the turbine to stall [**15]**. Under this condition, the drag coefficient of the blade tends to decrease drastically, whereas the level of thrust force on the rotor axis is very low compared to the force exerted were the WT to be in operation. On the other hand, IEC 61400 – 1recommends that the calculations for the design and resistance of the structure take into account a situation in which there are extreme winds and the blades are in feathered position. Some studies have applied these recommendations and ensured that their calculations take extreme winds into account, and real wind speeds caused by hurricanes (between 30 and 50 m/s) [**16**].

***2.1.4. Blades in angle of attack**:* If an error in the orientation mechanism of the blades occurs, a WT remains in angle of attack mode, which means that the drag coefficient CD maintains a higher value compared to the value of CD at 90 ◦ . As studies on this extreme case have not been found, it is recommended that the calculations required to analyze the behavior of the structure are carried out in order to compare the results with data from WTs that have collapsed after exposure to hurricanes. Thus, It is highly important to take additional design considerations into account.

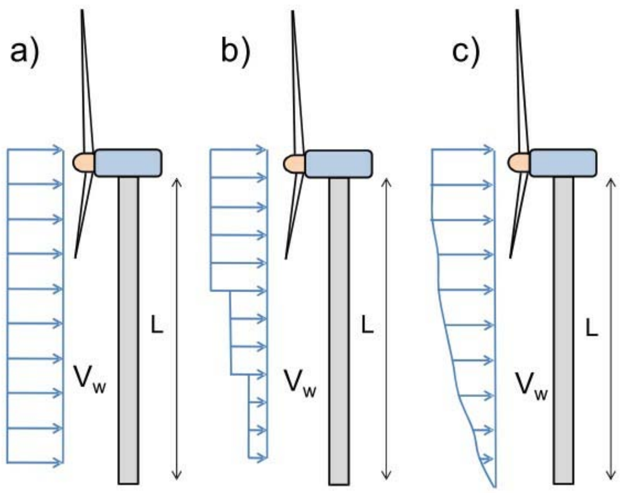

Figure 2: Wind load models for a WTT

2.1.5. Thrust force of the wind on the tower: The simplest model for wind force on a tubular tower considers the diameter of the tower as constant from base to top, and the vertical profile of the wind is deemed as uniformly distributed [**17-18**], as observed in **Fig. 2(a)**. Another model used to facilitate calculations is to divide the tower into sections and obtain the thrust force via the sum for each section [**19–21**], as observed in **Fig. 2(b)**. If the curvature of the vertical profile of the wind is considered, the mathematical model is approximated to the real behavior of the structure [**22–24**], as seen in **Fig. 2(c)**, obtaining

3. DEFLECTION ANALYSIS

WTTs are designed to withstand various loads that cause buckling, deflections, and vibrations in the system.

3.1. Deflection due to wind

Deflection in the towers is determined by the lateral load values caused by the wind and the weight of the structure. These loads will cause the displacement of the tower, but this shift will be avoided by fixing the tower to the foundations in the base. However, displacement may occur at the top of the tower, causing curvature, as observed in **Fig. 3**. When deflection is small, this curvature effect will not cause the tower to break. However, deflections can cause more damage to the structure if the load conditions surpass the elastic limit of the material. The deflection caused by this load is given in **Eq. (1)**. Feliciano [**17**] developed an analytical model to calculate the maximum deflections of a 5 MW WT characterized by the National Renewable Energy Laboratory (NREL). The obtained results show a displacement of up to 80 cm at the top of the tower. Huo [**25**] considered seismic effects in deflection analysis conducted on a 1.2 MW WT, obtaining up to 120 cm displacement. This data which is very critical to predicting possible failure via overturning or fracture.

$$\delta_r = F_R L^3 / 3EI \qquad (1)$$

where F_R is the load on the rotor, L is the height of the tower and E is the elasticity modulus of the material. The wind load over the length of the tower is a non-uniform distributed load. This will cause a lower level of displacement compared the load on the rotor. Some designs have opted to linearize the load of the vertical profile of the wind to an average uniformly distributed load in order to simplify calculations, although at the cost of precision in the design. The distributed linear load is converted into a point load FT located at the tower's centre of gravity. Therefore, the displacement of the tower due to wind load is given in **Eq. (2)**.

$$\delta_t = 5F_T L^3 / 48EI \qquad (2)$$

Once both displacements have been determined, these are added and their total value must be lower than 2% of the length of the tower, in order to prevent the failure of the foundations and the tower from tipping over.

3.2. Buckling analysis

The buckling of the tower is caused by the mass of the nacelle and rotor, especially if the load is not found at its centre of gravity. To avoid the occurrence of this phenomenon, it is necessary to increase the structure's stiffness. Therefore, the load that can be borne by a cylindrical thin-section tower is given by **Eq. (3)**.

$$P_{cr} = \pi^2 EI / 4L^2 \qquad (3)$$

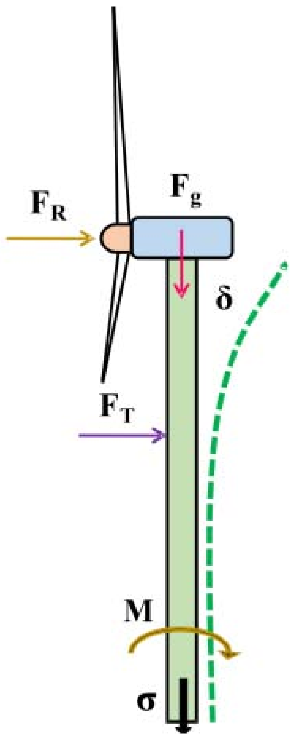

Figure 3: Loads and forces exerted on WTT

3.3. Fatigue analysis

A static calculation is not sufficient to determine the structural behavior of the tower in the long term, as these static steel structures are designed to last more than 100 years [**26**]. It is important that research regarding fatigue is conducted to avoid structural failures in the tower.

The phenomenon of fatigue is of particular importance in structural design, given that the number of load cycles sustained during the structure is useful life is in the order of 106 cycles. This was show by Hsu [**27]**, where dynamic structures have been designed to last for more than 20 years, according to the building code for structures, ISO 2394. A material's resistance to fatigue is determined based on its fatigue curve, in relation to the number of load cycles required to cause the breakage of the material, whose value is estimated in **Eq. (4)**.

$$log_{10}^{N_{eq}} = log_{10}^{a} - m_{S-N}\, log_{10}\left(\Delta\sigma_{eq}\left(\frac{t_f}{t_{ref}}\right)^{K_T}\right) \tag{4}$$

where Neq is the number of fatigue cycles, $m_{S\text{-}N}$ is the negative slope for the S – N curve, tref is the tower reference thickness, K_T is its thickness exponent, and t_f is the thickness by means of which a fracture can be produced. Fatigue can occur in a WTT due to different factors, such as turbulence, cyclical loads and variation in wind direction. For these factors, a range of equivalent forces $\Delta\sigma_{eq}$ is used, comprising the sum of the forces on the structure, mainly caused by the wind $\Delta\sigma_{wind}$ and the action of waves $\Delta\sigma_{wave}$, and is denoted by **Eq. (5)**.

$$\Delta\sigma_{eq} = \sqrt{\Delta\sigma_{wind}^2 + \Delta\sigma_{wave}^2} \tag{5}$$

3.4. Analysis of vibration and resonance

A structure is designed based on tests of its natural frequency, and is made to not coincide with other frequencies causing resonance, such as spinning of the rotor. Kim [**28**] implemented a frequency analysis for a 5 MW offshore WT, finding that the first frequency of the vibration mode is 0.290 Hz and is located between the rotation frequencies of the rotor
and the vibration frequency of the blades. Kim concludes that, while WTs with broad foundations have similar frequency behaviors, it is necessary to perform vibration studies for each specific structure.

Ahmad [**29**] used accelerometers in a Nordex N43 WT, finding higher vibration modes ranging from 0.701 to 17.96 Hz for the first and eighth modes, respectively. Resonance is an effect that tends to increase the amplitude of the tower's movements, due to the nature of wind or by spinning of the rotor. The most important modes of vibration in the tower are the first and second modes and lateral bending [**30**], given that these most closely resemble the modes of vibration of the rotor and the movement of the passing blades. For the first mode, the value for the natural frequency of vibration is calculated in **Eq.** (**6**).

$$\omega_1 = \frac{3.516}{L^2}\sqrt{\frac{EI}{m_T}} \tag{6}$$

where m_T is the value for the total mass of the structure. The value for the natural frequency of the vibration of the tower must not coincide with another frequency close to the first natural frequency that could cause resonance in the structure.

For example, **Table 1** presents the natural frequencies of a 5 MW conical tower [**31**]. For this particular case, the tower was designed to ensure that its natural frequencies are distanced from the other natural frequencies produced by the movement of the blades, and the rotation of the rotor and drive train.

Table 1: Natural frequencies of a 5 MW WT

Description	Frequency (Hz)
1st Tower Fore-Aft	**0.3240**
1st Tower side to side	**0.3120**
1st Drivetrain torsion	0.6205
1st Blade Asymmetric Flapwise yaw	0.6664
1st Blade Asymmetric Flapwise pitch	0.6675
2nd Tower Fore-Aft	**2.9003**
2nd Tower side to side	**2.9361**
2nd Blade Asymmetric Flapwise yaw	1.9337
2nd Blade Asymmetric Flapwise pitch	1.9223

Fig. 4 presents the types of structural analysis that have been most studied over the last five years, where the most common research topic involved performance of vibration modes under different environmental conditions in order to ascertain the dynamic behavior of the structure.

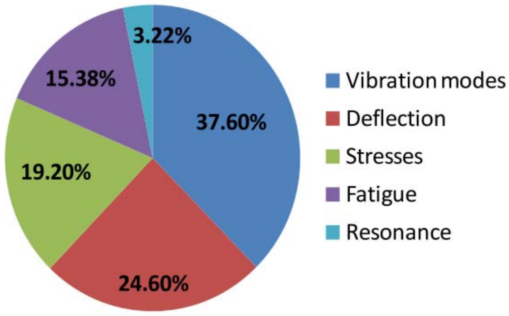

Figure 4: Types of analysis most used for WTTs.

The second most common research topics have studied the deflections exerted on the towers. Other topics include structure resonance and material fatigue, the limitations of which involve the electronic instrumentation of the WT. Such instrumentation requires large economic investment, a high level of computing power, and access to a WT and a wind farm. This last activity mentioned can be a difficult task, sometimes impossible.

4. CONCLUSION

A design methodology was established to develop a wind turbine rotor for use in a flow field accelerated by a cylindrical structure. Several important conclusions can be made as a result of this study.

- A comparison of the ribbed and straight cylinders CFD calculations indicated that without the rotors present, the ribbed configuration produces a higher velocity at the intended rotor plane. The reverse was observed from the wind tunnel experiments.
- Accounting for the presence of the rotors in the calculations reverses this result. The primary reason for this is that the cylindrical platform allows a greater expansion of the rotor wake indicating a lower downstream velocity and a consequential greater power extraction from the flow.
- The optimized thrust coefficient for the rotor in the accelerated flow stream is lower than that of an open rotor. This implies a lower free stream axial induction factor is required than the traditionally accepted optimum target value of 1/3.
- As the axial induction factor is lower for the accelerated flow field conditions than that of an ideal open rotor, a different design strategy is required to optimize the rotor power output than that used for a typical open rotor. In the present case, the pressure drop across the rotor was the criterion of choice.

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