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Evaluation of the behavior of a horizontal axis wind turbine subjected to wind loading

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Abstract. Due to the advances in wind energy, it became necessary to better understand the structural and mechanical behavior of wind turbines. This work presents the modeling of the 5 MW baseline wind turbine, developed by the National Renewable Energy Laboratory (NREL) in the USA, considering an onshore structure with 3 blades. Through the SAP2000 structural model, it was obtained the natural frequencies and modes of vibration, while the dynamic response of the structure, when submitted to wind cases as IEC 61400-1, was obtained through the software FAST.

Keywords: wind, turbine, energy, FAST, SAP2000.

1 Introduction

In recent years there has been a global research for forms of renewable energy which could provide less environmental impact as well as guarantee energy for future generations, and this purpose has boosted the advance of research in different areas of the global wind energy field. According to the Global Wind Energy Council [1], wind power could reach nearly 2,000 GW by 2030, supply between 16.7-18.8% of global electricity and help save over 3 billion tons of CO2 emissions annually. The increasing demand for wind energy is also observed in Brazil, where the 10-year Energy Expansion Plan 2029 [2] aims to rise the wind power supply from 9% to 16%.

This scenario leads to an increase in studies of wind power field which focus on the wind turbine, aiming to better understand the structural and mechanical behavior of each component in order to assure safer and quality engineering as well as reducing the wind turbines downtime and mitigating operation and maintenance costs.

This paper aims to evaluate the 5 MW baseline wind turbine developed by the National Renewable Energy Laboratory (NREL), an onshore three-bladed horizontal-axis wind turbine in order to understand its structural behavior when subjected to normal and extreme wind loads. The study was based on the requirements of the International Electrotechnical Commission: IEC 61400 – Part 1 - Wind Turbines Design Requirements.

The wind turbine numerical model will be performed in the software SAP2000 in order to obtain the natural frequencies for the vibration modes. The normal and extreme wind load cases stablished by IEC 61400-1 will be worked out through the FAST, a software provided by NREL, in order to assess the structure behavior.

2 External Environmental Conditions according to IEC 61400-1

According to IEC 61400-1 [3] wind conditions are the primary external conditions affecting structural integrity. The external conditions are subdivided into normal conditions, which concerns the recurrent structural loading, and extreme conditions which considers rare loading including wind shear events, as well as peak wind speeds due to storms and rapid changes in wind speed and direction. This section presents the wind profile model for normal and extreme conditions, which are to be considered for design according to wind turbine classes.

2.1 Wind turbine classes

The wind turbine classes are defined by IEC 61400-1 [3] in terms of wind speed and turbulence parameters as shown in Table 1, where V_{ref} is the reference wind speed average at hub height over 10 minutes; I_{ref} is the expected value of the turbulence intensity at 15 m/s; and A, B and C are categories for higher, medium and lower turbulence characteristics, respectively. The present study considers the analysis of III_C turbine class and is worth mentioning that the design lifetime for wind turbine classes I to III shall be at least 20 years.

Table 1 Basic parameters for wind turbine classes (adopted by IEC 61400-1)

Wind turbine class	I	II	III
V_{ref} (m/s)	50	42.5	37.5
A I_{ref} (-)	0.16		
B I_{ref} (-)	0.14		
C I_{ref} (-)	0.12		

2.2 Wind conditions and requirements

As aforementioned, wind conditions are the primary external conditions affecting structural integrity and so the wind turbine shall be designed to safely withstand the wind conditions defined by the selected wind turbine class. For that, IEC 61400-1 [3] recommends to consider the normal wind condition which will occur frequently during normal operation of a wind turbine as well as the extreme wind conditions, which is accounted for with a wind profile of 1-year or 50-year recurrence period. Additionally, it is recommended to consider the influence of an 8° inclination of the wind mean flow with respect to a horizontal plane.

The turbulence includes random variations in the wind velocity considering the following three vector components: longitudinal which is along the direction of the mean wind velocity, lateral which is normal to the longitudinal direction and in the horizontal plan, and upward which is normal to both acting on the vertical axis.

According to IEC 61400 [3] the random wind velocity field for the turbulence models shall satisfy:

a. The turbulence standard deviation, σ_1, shall be assumed to be invariant with height. The standard deviation values of the lateral component, σ_2, shall be equal to or greater than $0.7\sigma_1$, while the upward component shall be equal to or greater than $0.5\sigma_1$.

b. The longitudinal turbulence scale parameter, Λ_1, at hub height z shall be given by:

$$\Lambda_1 = \begin{cases} 0.7\mathrm{z} & \mathrm{z} \leq 60\mathrm{m} \\ 42\ \mathrm{m} & \mathrm{z} > 60\mathrm{m} \end{cases} \tag{1}$$

c. The power spectral densities of the three orthogonal components, S1(f), S2(f), and S3(f) shall asymptotically approach the following forms as the frequency in the inertial sub-range increases:

$$S_1(f) = 0.05{\sigma_1}^2(\Lambda_1/\ V_{hub})^{-2/3} f^{-5/3} \tag{2}$$

$$S_2(f) = S_3(f) = \frac{4}{3} S_1(f) \tag{3}$$

d. For the longitudinal velocity component, a recognized model for the coherence shall be applied.

The Kaimal spectrum attends to the above requirements and so will be used in the present study. According to Emil et al. [4] the Kaimal frequency spectrum, $S_K(f)$, is given by the following equation, where $L_{\tilde{V}}$ is the site and altitude dependent turbulence length scale, f is the turbulence frequency, and $\sigma_{\tilde{V}}$ is the standard deviation of wind fluctuations about mean wind speed at hub height.

$$\mathrm{S_K(f)} = \frac{4\ \mathrm{L}_{\tilde{V}}/\mathrm{V_{hub}}}{(1+6\ \mathrm{f}\ \mathrm{L}_{\tilde{V}}/\mathrm{V_{hub}})^{5/3}} {\sigma_{\tilde{V}}}^2 \tag{4}$$

2.2.1 Normal wind profile model (NWP)

In order to define the average vertical wind shear across the rotor, for the wind classes presented above, the normal wind speed profile, V(z), is given by the power law below. The power law exponent, α, is assumed 0,2.

$$V(z) = V_{hub}(z/z_{hub})^{\alpha} \tag{5}$$

2.2.2 Normal turbulence model (NTM)

The value of turbulence standard deviation, σ_1, across the rotor for the normal turbulence model is given by:

$$\sigma_1 = I_{ref}(0.75V_{hub} + b);\; b = 5.6\ m/s \tag{6}$$

2.2.3 Extreme wind speed model (EWM)

The extreme wind speed profile can be steady or a turbulent wind model, established by the reference wind speed, V_{ref}, and a fixed turbulence standard deviation, σ_1. In both cases, steady and turbulent, it is required to consider the extreme wind speed with recurrence periods of 50 years and 1 year, as can be noticed below:

The steady model considers the extreme wind speed with a recurrence period as given below:

$$V_{e50}(z) = 1.4V_{ref}(z/z_{hub})^{0.11} \tag{7}$$

$$V_{e1}(z) = 0.8V_{e50}(z) \tag{8}$$

The turbulent model considers the extreme wind speed with a recurrence period as given below:

$$V_{50}(z) = V_{ref}(z/z_{hub})^{0.11} \tag{9}$$

$$V_1(z) = 0.8V_{e50}(z) \tag{10}$$

The longitudinal turbulence standard deviation shall be given by:

$$\sigma_1 = 0.11V_{hub} \tag{11}$$

For the turbulent extreme wind model, it shall be assumed a yaw misalignment of ± 8º for recurrence periods of 50 years and of ± 20º for a recurrence period of 1 year.

2.2.4 Extreme turbulence model (ETM)

The extreme turbulence model uses the wind profile model from eq. (5) with σ_1, given by:

$$\sigma_1 = c\, I_{ref}\left(0.072\left(\frac{V_{ave}}{c} + 3\right)\left(\frac{V_{hub}}{c} - 4\right) + 10\right);\; c = 2\ m/s \tag{12}$$

3 Model of the analyzed structure

This section shows the main parameters of the onshore wind turbine and its modeling in SAP2000 and FAST.

As aforementioned this paper uses the 5-MW baseline wind turbine, developed in the American laboratory NREL, and with the geometric parameters presented by Jonkman et al. [5].

3.1 Parameters of the 5-MW baseline wind turbine

The 5-MW baseline wind turbine has a rotor radius of 63 m which considers the blade length and hub diameter. The model considers three blades of 61.5 m long, 2.5° upwind precone and the blade root located at 1.5 m along the pitch axis from the rotor center. The hub has 3 m diameter and 90 m height with a shaft tilt of 5º. The tower top is located at 87.6 m height with a diameter of 3.87 m and 0.019 m thickness while the tower base has 6 m diameter and thickness of 0.027 m.

The tower is made of steel with a Young's modulus of 210 GPa and its effective density is assumed to be 8,500 kg/m3, as recommended by Jonkman et al. [5] in order to account for paint, bolts, welds, and flanges. The blade is composed of LM Glasfiber blade and this study assumed a Young's modulus of 33.5 GPa and effective density of 1,850 kg/m3, based on Burton et al. [6] for similar fiberglass materials.

The wind turbine has three reference speeds that are: the cut-in wind speed, V_{in}, from which the blades start to turn and the electricity starts to be produced; the rated wind speed, V_r, from which the turbine is able to generate electricity at its maximum; and the cut-out wind speed, V_{out}, from which the turbine shuts down to avoid damage.

The table below summarizes the main parameters used in the structural model.

Table 2 Parameters from the 5-MW baseline wind turbine

Parameter	Value
Rating	5 MW
Rotor Orientation, Configuration	Upwind, 3 Blades
Control	Variable Speed, Collective Pitch
Drivetrain	High Speed, Multiple-Stage Gearbox
Rotor, Hub Diameter	126 m, 3 m
Hub Height	90 m
Cut-In, Rated, Cut-Out Wind Speed	3 m/s, 11.4 m/s, 25 m/s
Cut-In, Rated Rotor Speed	6.9 rpm, 12.1 rpm
Overhang, Shaft Tilt, Precone	5 m, 5º, 2.5º
Rotor Mass	110,000 kg
Nacelle Mass	240,000 kg
Tower Mass	347,460 kg
Coordinate Location of overall CM	(-0.2 m, 0.0 m, 64.0 m)

3.2 Structure model on SAP2000

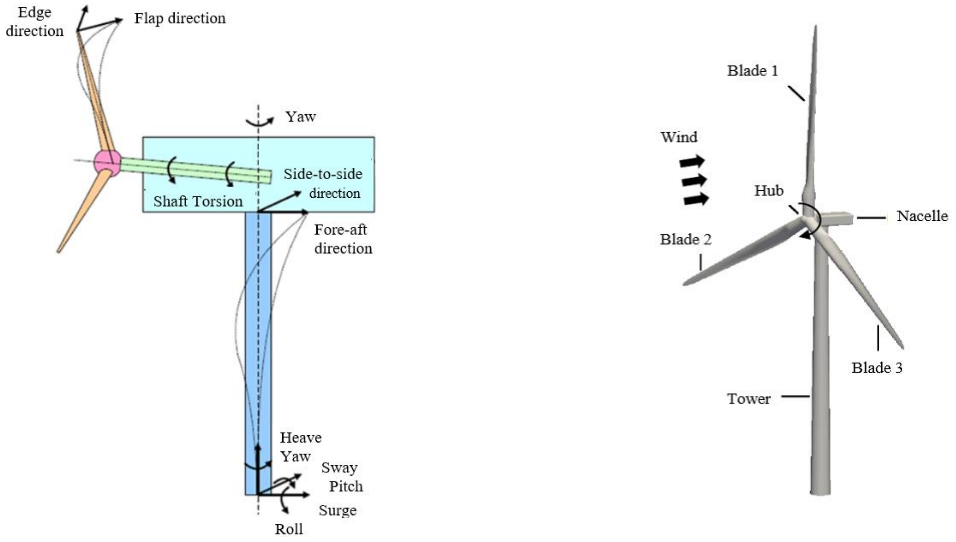
The wind turbine was modeled with beam elements considering the tower as a hollow cylindrical section varying with diameter and thickness from the top to the base, which is considered to be fixed at ground level.

The nacelle, the hub and the top of the tower are connected to the shaft through a rigid link. For modeling the nacelle and hub, a mass element located in the center of mass of both equipment was used, considering the masses and mass moments of inertia presented by Jonkman et al. [5].

For modeling the blades, beam elements with a generic section were used, where the blade edge and flap inertia properties were applied according to the element divisions and properties used by Jonkman et al. [5].

3.3 Structure model in FAST

For modeling the structure in FAST, the software main code calls aero-servo-elastic subcodes, that is, the simulation considers: the wind speed in the Inflowind code obtained through the TurbSim; the aerodynamic force calculations in the Aerodyn code; the performance of control systems in the Servodyn code; and the dynamic structural response in the Elastodyn code. According to Jonkman [7], the aerodynamic and structural response to wind-inflow conditions is determined in time and the forces and deflections of the structural members are obtained.



(a) (b)

Figure 1. The NREL 5 MW wind turbine modeled on FAST: Degrees of freedom and vibration mode directions (a) and three-dimensional model of the turbine (b) (adapted from Teotônio [8]; Liu et al [9])

4 Results and discussions

This section shows the results obtained through SAP2000, presenting the structure natural frequencies and modes of vibration; and through FAST, presenting forces, displacements and main frequencies to which the structure is subjected when the wind load is applied according to IEC 61400- 1.

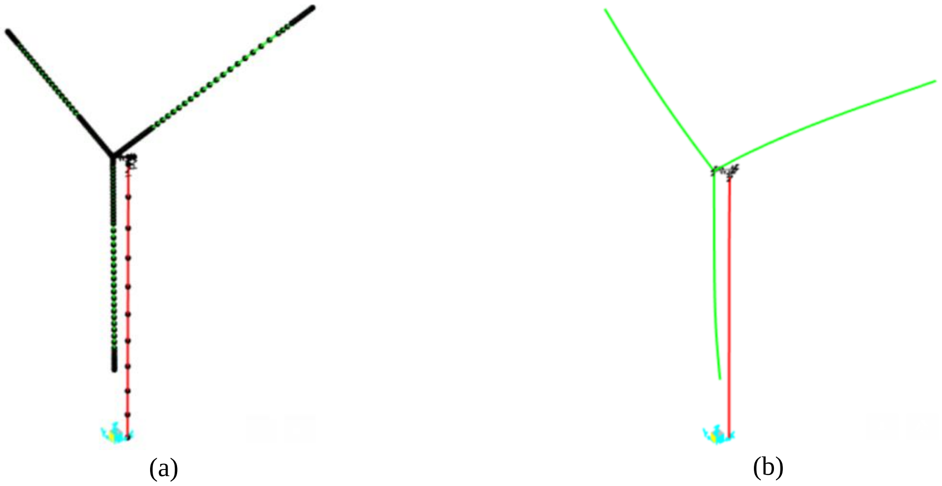
4.1 Structural model in SAP2000

Through the modal analysis it was obtained the natural frequencies of the wind turbine. In order to validate the model, it was compared the obtained values with the ones presented by Jonkman [5] as given below.

Table 3 Structure natural frequencies in Hertz and modes of vibration

Mode	Jonkman [5]	Present work SAP2000	%	Mode description
1	0,312	0,315	-0.96%	1st tower side-to-side
2	0.324	0.317	2.16%	1st tower fore-aft
3	0.6205	0.638	-2.82%	1st blade asymmetric flapwise yaw
4	0.6664	0.679	-1.89%	1st blade asymmetric edgewise surge
5	0.6675	0.703	-5.32%	1st blade asymmetric flapwise pitch
6	0.6693	1.146	-71.22%	1st blade collective flap
7	1.0793	1.189	10.16%	1st blade asymmetric edgewise pitch
8	1.0898	1.258	-15.43%	1st blade asymmetric edgewise yaw
9	1.9337	1.644	14.98%	2nd blade asymmetric flapwise yaw
10	1.9223	1.922	0.02%	2nd blade asymmetric flapwise pitch
11	2.0205	1.931	4.43%	2nd blade collective flap

As shown in Table 3, the wind turbine natural frequencies obtained through SAP2000 presented a good correlation with the values found by Jonkman [5]. Most of the frequency percentage difference is acceptable, especially for the first natural frequencies. An exception is observed for mode 6, however, it can be disregarded, because even with the high percentage, the absolute difference between frequencies is low and differs in decimal order. Hence, it is feasible to state that the model is calibrated and validated.



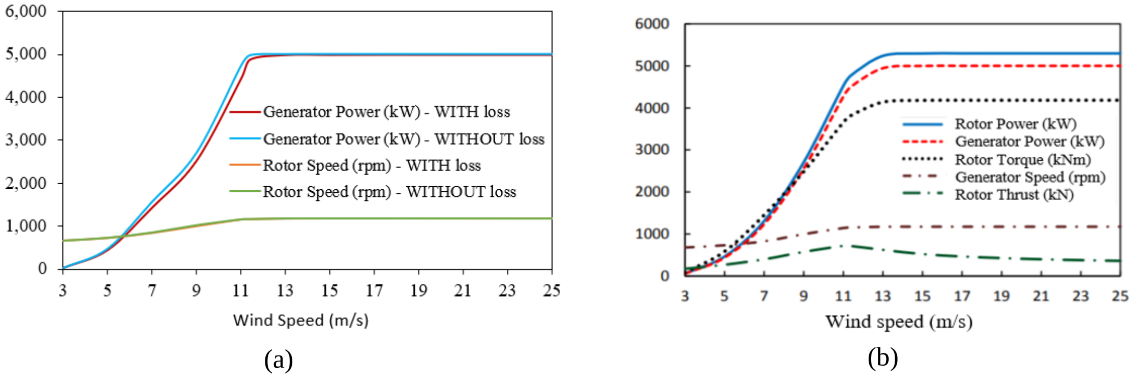
(a) (b)

Figure 2. The NREL 5 MW wind turbine modeled on SAP 2000: three-dimensional model with beam element (a) and the fist blade collective flap mode of vibration (b)

As per ASCE 7-05 [10] the structure is classified as dynamically sensitive, or “flexible”, if its fundamental natural frequency is less than 1 Hz. Since the wind turbine is within this range, as can be noticed in Table 3, the structure is dynamically sensitive and so it is necessary to dynamically evaluate it to avoid the occurrence of the resonance phenomenon. For this reason, the natural frequencies obtained herein will be compared with the excitation frequencies of the structure due to wind loads, obtained through FAST.

4.2 Structural model in FAST

The results obtained through FAST, Figure 3 (a), show that for wind speeds above the rated speed (11.4 m/s), the turbine reaches its maximum power capacity, that is, 5,000 kW. This value converges to the one presented by Jonkman [5], as per section 3.1. Additionally, the generator power curve is similar to the one presented by Teotônio [8], while carrying out the studies for the same turbine, as presented in Figure 3 (b). Hence, the model is validated.

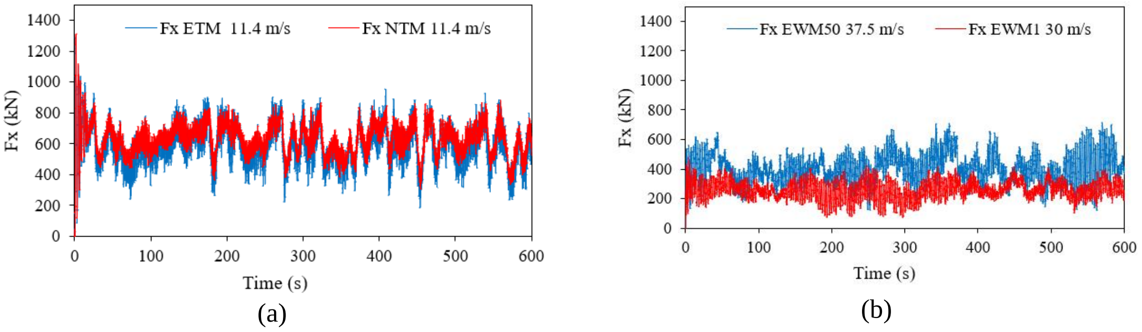


(a) (b)

Figure 3. Wind turbine curves obtained through FAST: present work (a); another study for the same turbine (b) (by author; adapted from Teotônio [8])

Additionally, Figure 3 (a) shows that the reduction in generator power is not significant when considering losses at the hub and blade tip. Resembling the real wind flow over a surface, losses were considered in this study.

According to IEC 61400-1 [3], the turbine is on energy production mode when the normal (NTM) and turbulent (ETM) wind conditions occur. However, the turbine is on unavailability mode, when there are gusts or winds with a recurrence period of 1 year (EWM1) and 50 years (EWM50), and so the turbine rotor is stopped through the pitch control system. Since the turbine is parked, it is feasible to understand that forces and displacements in the parked structure will be lower when compared to the power generation mode. This fact can be seen through the Table 4, which shows the main forces withstood by the structure, that is, the peak shear force at the base of the tower in the wind direction (Fx), the moment caused by this force (My), as well as the displacement at the blade tip in the wind direction (dBx) and at the top of the tower (dTx). Figure 4 shows the shear force at the tower base over time.



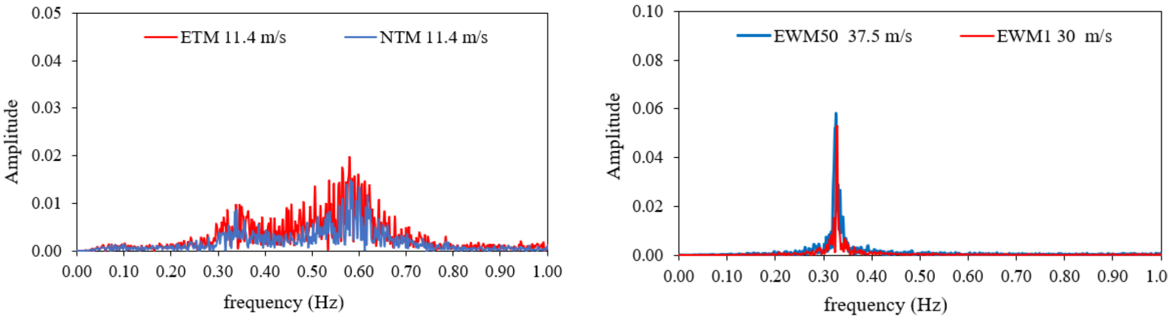
(a) (b)

Figure 4. Shear forces at the tower base for energy production mode (a) and for the unavailability mode (b)

Table 4 Main forces and displacement withstood by the wind turbine – peak values

Wind Model	Wind Speed (m/s)	Fx (kN)	My (kNm)	dBx (m)	dTx (m)
NTM	11.4	883.00	76,970	7.19	0.47
ETM	11.4	953.20	80,610	7.40	0.48
EWM1	30.0	420.00	22,640	1.04	0.11
EWM50	37.5	713.00	52,680	1.74	0.33

The maximum displacement of the blade tip in the wind direction, dBx = 7.19 m (NTM) and 7.40 m (ETM), are quite high values, which justify the caution regarding the turbine design in order to avoid the blades to collide on the tower. Accidents of this nature have already occurred triggered by nacelle tilt and loose bolts, for example.



(a)

(b)

Figure 5. Acceleration frequency spectra at the tower top for energy production (a) and for unavailability (b)

The predominant excitation frequencies in the tower are 0.34 and 0.58 for the energy production mode, Figure 5 (a), and 0.32 for the unavailability mode, Figure 5 (b). Comparing these values with those presented in Table 3, it is observed that the tower excitation frequencies obtained in FAST are close to the first, second and third natural frequencies of the structure. This is a point of attention in order to avoid resonance.

5 Conclusions

The results obtained for the 5MW baseline wind turbine showed that the reduction in generator power is not significant when considering losses at the hub and blade tip. For the turbine on unavailability mode, the forces and displacements in the parked structure are lower when compared to the power generation mode. The maximum displacement of the blade tip in the wind direction, about 7.40 m, needs to be carefully addressed during the turbine design to avoid the blades to collide on the tower.

Due to the wind load causing excitation frequencies close to natural frequencies, it is important to consider resonance as a point of attention in the wind turbine design and operation.

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