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5MW AND 2MW NREL WIND TURBINES SIMULATION COMPARISON FOR STEADY LOADING CALCULATIONS

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Abstract. *This paper aims to study the standard behavior of the VSVP (Variable Speed Variable Pitch) NREL 2 MW and NREL 5 MW wind turbines, analyzing and comparing the performance of these turbines in relation to the wind velocity and pitch forces in steady state condition. In this work, a bibliographical revision was elaborated and a computational tool, G.H. Bladed 4.5, was employed in order to analyze the steady state calculations between the two turbines. The results obtained were consistent in the sense of identifying the characteristic pattern of the behavior of the VSVP turbines.*

Keywords: *wind energy, wind turbine, load simulations, steady simulations comparison, GH Bladed.*

1. INTRODUCTION

The numerical modeling of wind turbines is of great importance and has been developed to improve the understanding of the loads which wind turbines are subjected to, allowing the behavior of these workloads to be predicted even before the implantation of these machines into wind farms (GLIS and WEC, 2010; Hassan et al., 2012; Jonkman et al., 2009).

Numerical modeling software, which enable load analysis, depend directly on the number of degrees of freedom (DOF), whose dynamic forces imposed on the turbine components are related to. In this scenario, the choice of the DOF should be as close as possible to a real situation (Jonkman et al., 2009).

Therefore, the GH Bladed 4.5 commercial version software, licensed for Centro de Tecnologias do Gás e Energias Renováveis (CTGAS-ER), and the educational version, licensed for Universidade Federal de Pernambuco (UFPE), were employed in this study. These programs are an integrated set of software that enables performance and loads calculation of wind turbines and their components. They perform calculations in steady and/or transient state, which allow the specification of the turbines parameters, wind data and loading (Hassan et al., 2012; Jonkman et al., 2009).

In addition, wind turbine models of 2 MW and 5 MW, available for studies through the National Renewable Energy Laboratory (NREL), were used for the analysis proposed in this paper.

2. METHODOLOGY

The methodology used is based on the analysis of 9 DOF through the aeroelastic code within the GH Bladed v.4.5 software for both the NREL 2 MW and 5 MW wind turbines to estimate and compare the dynamic responses, the performance and the structural loads of these machines. There are 3 DOF for the turbine's blades, 2 for the drive train, 3 for the nacelle and 1 for the tower.

2.1 Operating Regions of a Variable Speed Wind Turbine

The power curve represented by the **wind speed x power** graph symbolizes the amount of energy that can be extracted from the wind. Variable pitch and velocity wind turbines can be analyzed in four typical operating regions, according to Fig. 1:

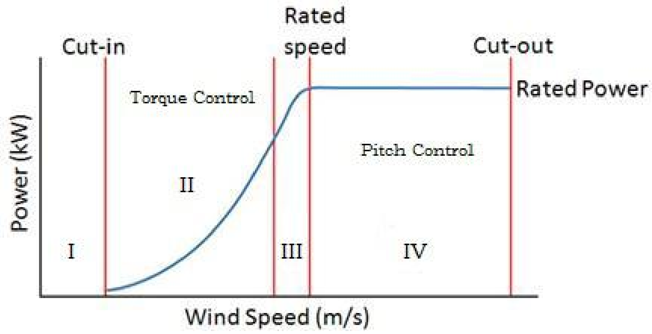

Figure 1. Operating regions of a VSVP wind turbine.

In Region I, where the wind speeds are low, there is no generation of electricity by the wind turbine. In Region II, where the control of the turbine is made through the variation of torque, the higher the wind speed, the greater the power generation. However, any wind speed in this region is below the rated speed of the machine, which is the speed at which the maximum extraction of power occurs. In Region III, considered as a transition region, the slope of the power curve is more accentuated, showing that the wind turbine generates greater amount of energy per variation of wind speed in this part of the graph. Finally, in Region IV, the turbine control system must act by pitch variation rather than by torque to avoid overloading, since the wind reaches higher speeds in this region (Lynn, 2012; Mathew, 2006; Wu et al., 2011). In fact, when the wind speed reaches the cut-out speed of the turbine, it shuts off for safety reasons.

2.2 Degrees of Freedom and Deflections of Blades, Hub, Tower and Nacelle

In order to ensure a good analysis, it is necessary to establish the DOF of each component with respect to the various loads scenarios in which the simulations were carried out, so that the dynamic and structural behavior of the blades, tower, nacelle, and the control systems can be analyzed properly.

Figure 2 (a) shows the DOF from one of the wind turbine's blades. The forces F_{XB} (in the X_B axis, perpendicular to the rotor plane), F_{ZB} and F_{YB} act radially, so that M_{XB}, M_{YB} and M_{ZB} act clockwise. Figure 2 (b) illustrates the DOF of a turbine's hub. As can be seen, the forces F_{XN} (acting on the X_N axis, perpendicular to the plane of the rotor), F_{ZN} (perpendicular to X_N) and F_{YN} (acting laterally) operate in such a way that M_{XN}, M_{YN} and M_{ZN} act clockwise (GLIS and WEC, 2010).

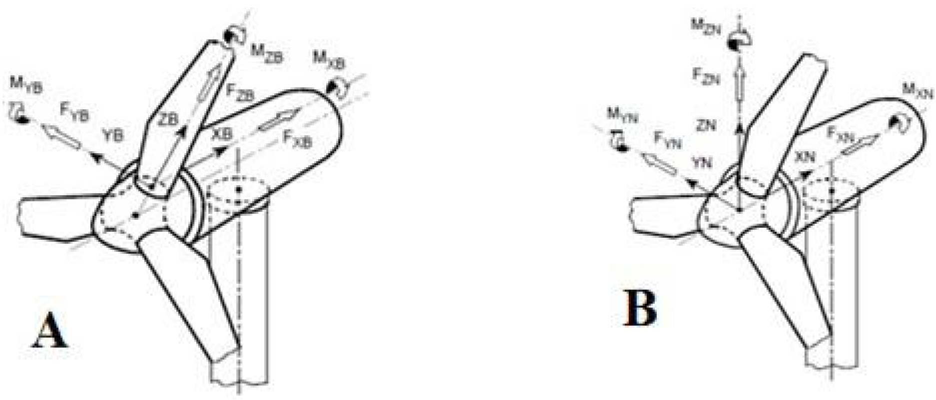

Figure 2. Coordinates system and degrees of freedom (a) located at the root of the blades; (b) located in the cube.

Figure 3 (a) shows the DOF of a turbine's tower base. The forces F_{XF} (in the X_F axis), Z_F (in the direction of the tower axis) and Y_F (acting laterally) are arranged in such a way that M_{XF}, M_{YF} and M_{ZF} act clockwise. Finally, Fig. 3 (b) shows the DOF of a wind turbine's nacelle. The forces F_{XK} (in the direction of the rotor axis), F_{ZK} (vertically in the direction of the tower axis) and F_{YK} act in a way that M_{XK}, M_{YK} and M_{ZK} operate clockwise (GLIS and WEC, 2010).

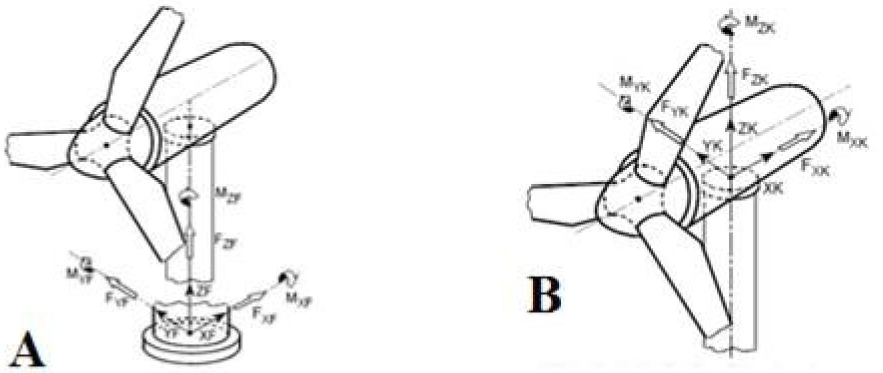

Figure 3. Coordinates system and degrees of freedom (a) located at the base of the tower; (b) located in the nacelle.

The main loads acting at the root of the blades, the tower base, the hub center and the nacelle, utilized in the GH Bladed 4.5 software, can be observed in Table 1.

Table 1. Main active loads according to the GH Bladed software.

	Loads	Units	Description
Blade root	M_x bending moment	N.m	Blade deflection perpendicular to the local chord (blade edge)
	M_y bending moment	N.m	Blade deflection parallel to the rotor plane (blade flap)
Hub center	M_x torque	N.m	Total rotor mechanical torque
	M_y moment	N.m	Tilting moment
	M_z moment	N.m	Yaw moment
	F_x force	N	Thrust force
Tower base	M_x bending moment	N.m	Tower deflection in the rotor plane (tower side-to-side)
	M_y bending moment	N.m	Tower deflection out of the rotor plane (tower fore-aft)
Nacelle (yaw bearing)	M_x bending moment	N.m	Nacelle deflection in the rotor plane (nacelle side-to-side)
	M_y bending moment	N.m	Nacelle deflection out of the rotor plane (nacelle fore-aft)

2.3 Simulations and analysis

This section discusses the steady-state simulations of the NREL 5MW turbine. A comparative analysis of its behavior related to the NREL 2MW turbine is made.

2.3.1 Power Curve of NREL 5MW wind turbine

Figure 4 shows the power curve of the 5MW NREL wind turbine, where it is possible to verify that the cut-in and cut-out velocities are respectively 3 m/s and 25 m/s, while the nominal velocity is 11,4 m/s, at which point the generation of electricity is no longer achieved through torque control in the rotor axis; instead, pitch control is required (Fig. 1) and the 5MW nominal generation is maintained from this speed on. This range of velocities represents the analysis scope carried in this study.

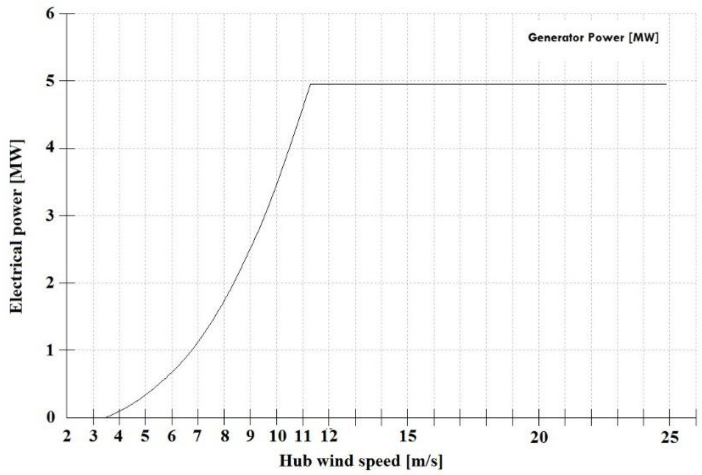

Figure 4. NREL 5 MW wind turbine power curve.

Figure 5 demonstrates that, while the turbine operates in region II (shown in Fig. 1), located between the cut-in speed of 3 m/s and rated speed of 11.4 m/s, the wind speed continues to increase, and a maximum value of 0.6 m of the offset front-rear of the nacelle (Fig. 3(b)) is reached. This displacement tends to stabilize at 0.25 m from 16 m/s to approximately 25 m/s when the cut-out speed is reached.

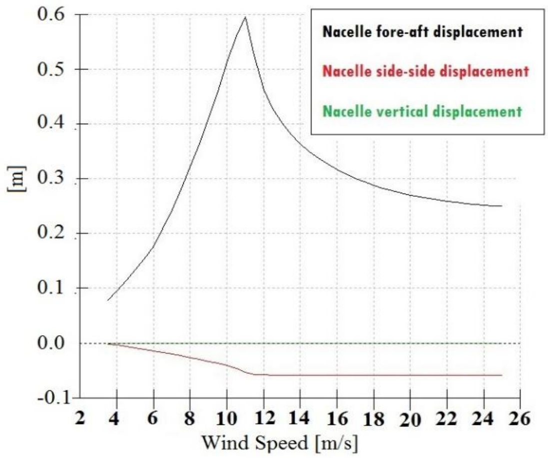

Figure 5. Front, lateral and vertical displacements of the 5 MW wind turbine's nacelle.

The maximum displacement occurs when the transition speed between region II and IV is achieved. The control system ceases to operate by torque control to extract maximum power from the low velocity wind and secures the production by controlling the blades through pitch control.This avoids overloads due to dynamic loads of higher intensity coming from the higher speed winds, guaranteeing better quality in the generated electricity and also ensuring a longer life of the turbine and its components.

Regarding lateral displacement, which occurs along the Y axis, as the wind speed increases from 3 m/s to 11.4 m/s, it increases in absolute values. After the nominal velocity is reached, the lateral displacement does not undergo any behavior change, stabilizing at -0.06m, once the rotational direction of the rotor and the blades design causes the lateral displacement to occur in this direction. Finally, it can be noted that wind speed velocity variations in the 11.4 m/s - 25 m/s range do not cause lateral displacement. Moreover, the turbine is a balanced system, whose mass helps to prevent vertical displacement in the Z axis.

2.3.2 Low speed shaft and high speed shaft torque analysis

Figure 6 shows the behavior of the low speed (LSS) and high speed (HSS) axes in relation to the torque generated in each of the axes by the increasing wind.

In the figure, it is possible to verify that the torque generated in the two axes is practically linear at wind speeds around 10 m/s; however, there is a considerable torque increase for a small variation of the wind speed at wind speeds between 10 and 11.4 m/s. Then, when the nominal velocity of 11.4 m/s is reached, the control system starts to act through pitch control (Fig. 5), keeping the torque constant even at higher wind speeds, setting the electricity generated at 5MW. When the torque remains constant, the control system keeps the power coefficient high.

The low torque generated in HSS is compensated for by the high wind speed due to the ratio of 97: 1 in the gearbox (Jonkman et al., 2009), which corresponds to each revolution movement of the LSS axis multiplying to 97 in the HSS axis. When the turbine is operating in the Region IV, the power generated, the generator torque and the rotor speed reach their maximum values.

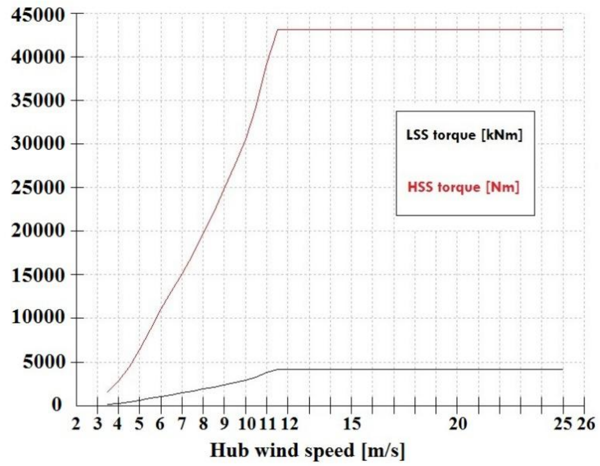

Figure 6. Torque acting on the Low Speed Shaft (LSS) and High Speed Shaft (HSS) in the NREL 5 MW wind turbine.

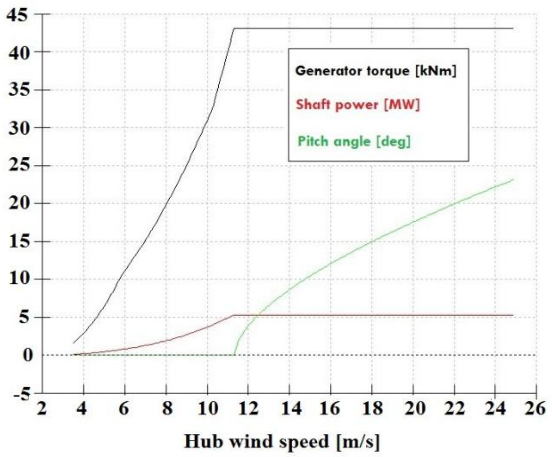

Figure 7. Electricity generation and variation of the torque and pitch angle for the NREL 5 MW wind turbine.

The higher the wind speed above 11.4 m/s, the greater the variation in the pitch angle to keep the turbine within the projected nominal values (Fig. 7).

2.3.3 Blades and tower degrees of freedom

Before the nominal velocity (11.4 m/s) is reached, the power generation prioritizes the maximum wind energy extraction, increasing the bending moments (M_X and M_Y) and the torsor moment (M_Z) at the blade root, the moment of the total bending (M_{XY}) in a given position along the blade, and the torque at the base of the tower (M_Y). These moments reach their maximum values as soon as the nominal operation speed is achieved (Fig. 8).

For wind speeds greater than 11.4 m/s, the pitch control system acts to relieve stresses and to limit the rated power. The system stabilizes at a wind speed close to 25 m/s. If this speed is exceeded, the turbine is switched off due to safety measures.

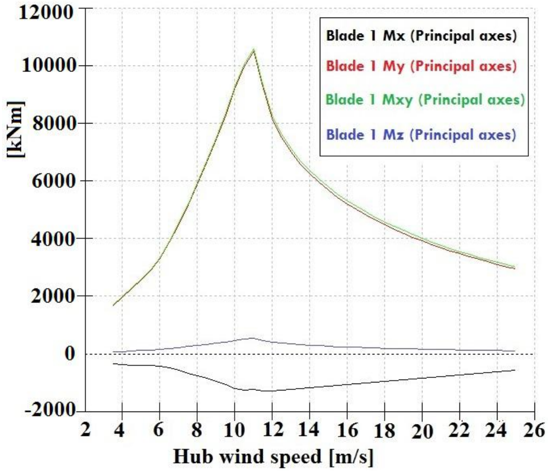

Figure 8. Moments acting on the blade's root in the NREL 5 MW wind turbine.

The way the moments act in the tower and in the blades is similar, increasing as the wind speed reaches 11.4 m/s, and remaining stable for speeds above this value (Fig. 9). Moreover, while the turbine operates in Region II, the rotor speed increases; in regions III and IV, the rotor speed remains constant (Fig. 10).

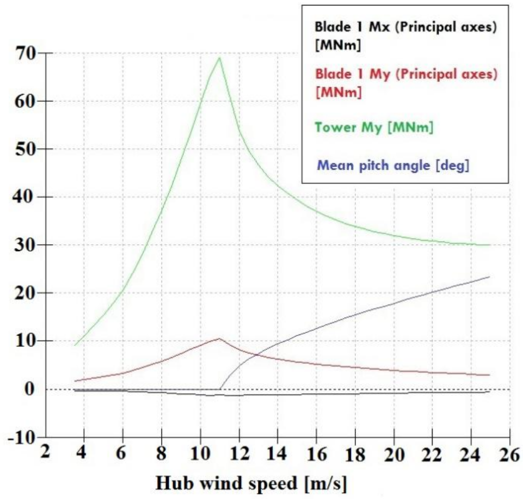

Figure 9. Moments acting on the blades and the tower related to the pitch angle in the NREL 5 MW wind turbine.

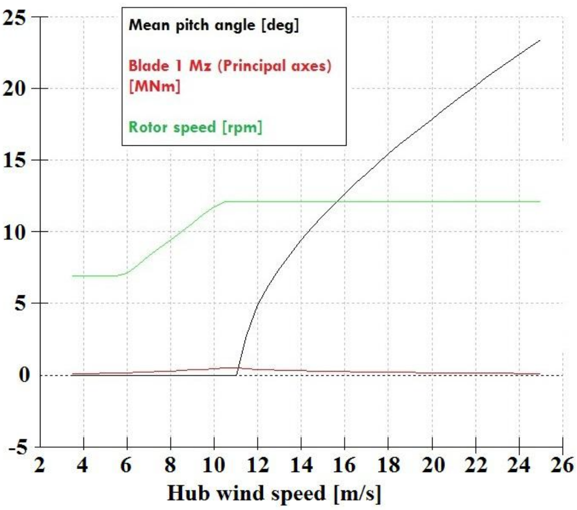

Figure 10. Rotor speed, pitch angle and torque acting on the blades in the NREL 5MW wind turbine.

3. RESULTS

For the NREL 2 MW wind turbine simulation, the same steady state analysis methodology for the 5 MW was carried out. Both turbines main characteristics were compared in the following.

3.1 Comparisons between the performances of the NREL 5MW and 2MW wind turbines

It is possible to verify that the behavior of both VSVP turbines is similar, although the dimensions of their components, such as the blades lengths and profiles, the diameter of the rotor and the tower, the height of the hub, shafts and other internal components are different due to the rated power of the project to which they were developed.

In this sense, the nacelle displacements in region II, as in the 5MW turbine, also increases. Furthermore, when the nominal speed is reached, the control system stops acting by torque and starts to act through the variation of the pitch angle. The 2 MW and 5 MW wind turbines lateral displacements are similar owing to the rotor movement in a clockwise direction and the design of the blades. No vertical movement was detected (Fig. 11).

Figures 12 and 13 show that the torque increases as the wind speed increases until the rated speed is reached. Then, it stabilizes for higher wind speeds. As a result of the pitch control, the torque, rotor speed and turbine power are limited by nominal design values in region IV.

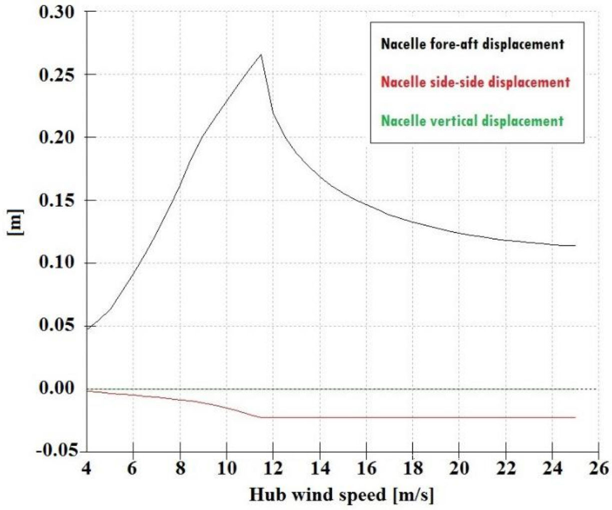

Figure 11. Nacelle’s front, lateral and vertical displacements for the NREL 2MW wind turbine.

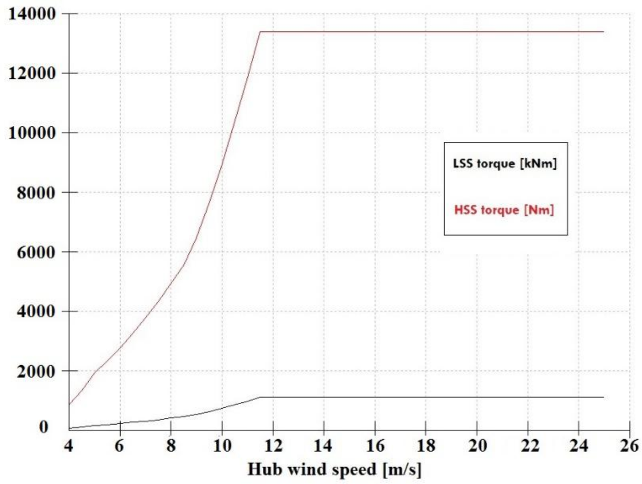

Figure 12. Low-speed (LSS) and high-speed (HSS) axes for the NREL 2MW wind turbine.

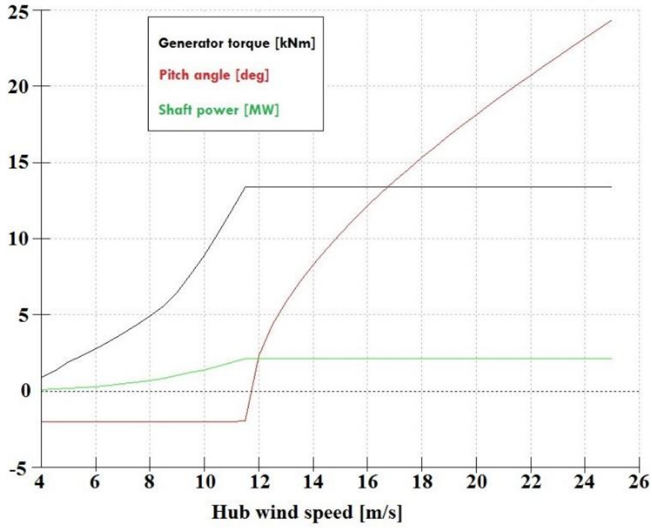

Figure 13. Electricity generation, pitch angle variation and actuating torque on the generator in the NREL 2MW wind turbine.

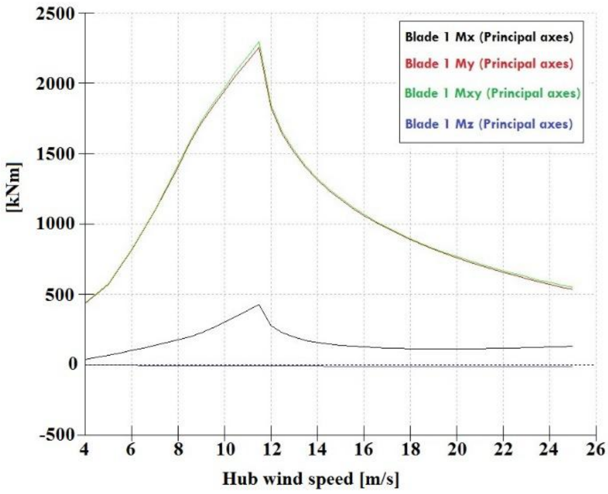

Figure 14. Moments acting on the blade's root in the NREL 2MW wind turbine.

A comparison between Fig. 14 and Fig. 8 shows that, in both turbines, the moments M_{xy} and M_y acting at the root of the blades present the same pattern, with a peak load during the rated speed (11,4m/s). M_z values remained close to 0 (zero) in both turbines, increasing up to the rated speed, reducing afterwards. On the other hand, in the 5 MW turbine, the M_x torque reached maximum values close to 2000 kNm, reducing gradually as the wind speed increased, stabilizing near 200 kNm, while it remained almost zero in the 2 MW wind turbine due to the design of its blades.

As in Fig. 9, Fig. 15 shows a similar behavior of the moments acting at the base of both towers, reaching its maximum peak at 11.4m/s and reducing as soon as the pitch control is activated, which, as already mentioned, maintains the power generation stable, relieving loads and stresses on the turbine as the wind speed increases. This feature clearly exhibits the main characteristic of the VSVP turbines.

Figure 16 results are directly related to the blades design. A comparison with Fig. 10 shows that the rotor speed and the mean pitch angle are different for both turbines, although the curves may be similar: the 5 MW turbine starts-off at a speed near to 7 rpm with 0 pitch angle, while the 2 MW wind turbine starts-off at 10 rpm with a pitch angle of 2°. Relatively to the moments acting at the base of the blade, in the 5 MW turbine, the values are close to zero, while it is possible to perceive a peak of approximately 14 MNm in a wind speed of 25m/s in the 2 MW wind turbine. This feature demonstrates that the variation of the pitch angle on the 5MW turbine is able to better prevent load incidents in the blades as the wind speed increases. In the 2 MW wind turbine, for small variations of the wind speed, the moments acting in the blade change sharply, whereas in the 5MW turbine these changes are much smoother, leading to greater efficiency in the control of the pitch angle.

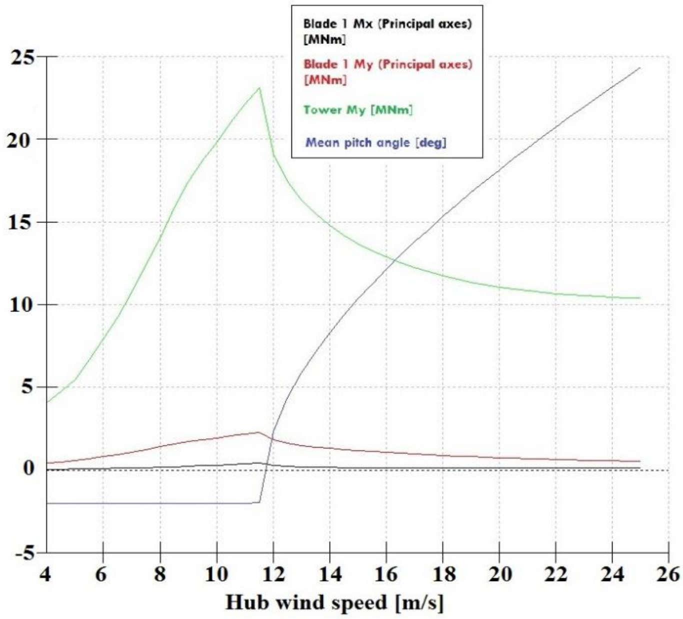

Figure 15. Moments acting on the tower and blade, and pitch angle for the NREL 2MW wind turbine.

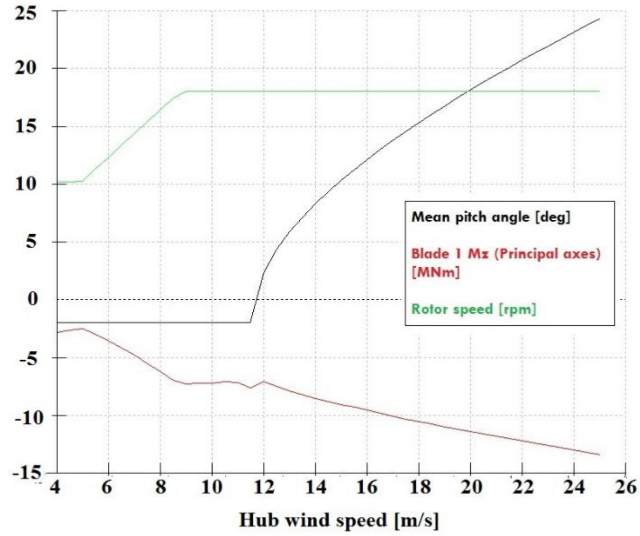

Figure 16. Rotor speed, pitch angle and torque acting on the blade in the NREL 2MW wind turbine.

4. CONCLUSIONS

In this work, the behavior of the NREL 5MW wind turbine with variable speed and pitch was simulated in steady state, using the G.H. Bladed 4.5 software. The behavior of the turbine and its different components were analyzed and compared with the NREL 2MW turbine presented in the educational version of the program.

The pitch system has proved to be important in relieving the excess loads to which the turbines are subjected when the wind speed exceeds the rated speed of the turbine as well as in the constant electricity generation in each equipment.

It was verified that it is a characteristic of the VSVP wind turbines to experience the peak loads around the nominal velocity when the control system stops acting through torque control and starts to act by the control of the pitch angle. In addition, there is a similar pattern in the behavior of the two turbines, even though they differ in design dimensions. On the other hand, the main difference lies in the magnitude of their results, since the standard, as already mentioned, is similar.

The results obtained in this work were satisfactory in order to identify the characteristic behaviors of the VSVP turbines.

5. ACKNOWLEDGEMENTS

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