Yawing characteristics during slippage of the nacelle of a multi MW wind turbine

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Abstract. High aerodynamic yaw loads coupled with electrical failures in the wind turbine can result to a slippage of the nacelle, due to limited braking capabilities of the yaw system. A slippage on the other hand can lead to a mechanical malfunction of the yaw system. To analyse the yawing characteristics of a wind turbine during nacelle slippage situations, a detailed multibody system model of the yaw system has been developed and incorporated in a multibody system model of a wind turbine based on a 3.3 MW turbine. Extreme load cases which lead to a nacelle slippage have been simulated. The dynamics and loads on different wind turbine components are presented and discussed. First results show minimal load increases of the rotor torque and the bending moments of the blade root sections during slippage but unfavourable rotational speeds of the yaw drives.

1. Introduction to the problem and work objectives
The yaw system of a wind turbine is responsible for turning the nacelle of a horizontal axis wind turbine around the tower axis. The main purpose is to keep the energy capture loss to a minimum. Failure statistics from the Reliawind project [1] show that the yaw system is the mechanical component, contributing second most to the overall downtime of the turbine. Most designs of the wind turbine controller allow power production conditions only for an operative yaw system that is able to keep the rotor plane within a tolerated yaw range to prevent high structural loads. An error in the yaw system therefore leads to a shutdown of the wind turbine. One issue that can lead to a mechanical malfunction of the yaw system is a undesired nacelle movement (yaw slippage) due to high yaw loads. The yaw brakes are designed to hold the nacelle in its azimuthal orientation. The design loads are extracted from the ultimate load strength analysis where the aerodynamics loads acting as torque on the tower top are used. The ultimate strength analysis consists of design load calculations defined by standards like IEC [2] or DNVGL [3]. Extreme load situations that lead to high aerodynamic yaw loads on the yaw system are e.g. power production plus occurrence of a fault, for example a malfunctioning pitch system. It is however common practice and also taken in regard by standards [2, 3] to reduce the yaw systems braking capabilities and tolerate a movement of the nacelle around the tower axis (let the nacelle slip) when the aerodynamic yaw loads are too high. The reduction of the yaw systems braking capabilities is motivated on the one hand to simply reduce cost and maintenance requirements and on the other hand to meet the ever increasing space restriction in
the tower top area [4, 5]. The dynamic behaviour of the wind turbine and the aerodynamic loads during slippage situations are unknown, as these situations are neither tested nor simulated due to damaging risk and increased computing time. The increased computing time mostly results from the additional degree of freedom to analyse nacelle turning movements during these load situations. The typical design process during the load simulations for wind turbines is focused on covering many design cases which can lead to up to 120 load simulations of 10-minute time series each with a time step of 0.01 seconds [6]. Simulations with an additional degree of freedom around the tower axis with added stiffness properties can expand the simulation duration by a multiple of the typically 1:1 real time simulations of standard models [7]. These calculations are too time consuming for wind turbine manufacturers to consider slippage behaviour in their design process. Therefore, the objectives of this work is to simulate load cases based on the standards where the slippage of the nacelle occurs and to discuss the results. The wind turbine model is based on the Nordex N100/3300, a 3.3 MW wind turbine designed for IEC 1A site types.

2. Approach and methods
The yaw system and the 3.3 MW turbine is modelled and analysed with the commercial tools Samcef Wind Turbines (SWT) for aerodynamic simulations and Samcef SFIELD for the detailed multibody system (mbs) model and brake behaviour modelling of the yaw system. The aerodynamic load calculations are based on the Blade Element Momentum theory where the correction formulas for axisymmetric inflow and skewed wake are taken from the methods proposed by the Technical University of Denmark presented in [8].

The mbs model of the wind turbine and the yaw system are illustrated in Figure 1. The nacelle is held by two separate types of brakes, namely the yaw brakes and the mechanical brakes on the yaw drives. Whereas the yaw brakes are modelled directly between the nacelle and the tower, the braking torque of the mechanical brakes of the yaw drives are multiplied by the gear transmission ratio of the pinion/ring gear and the gear of the yaw drives. The braking behaviour of these brakes are modelled after the coulomb model to investigate the influence of stick slip phenomena on the loads and dynamics of the wind turbine. It is considered that the mechanical brakes on the yaw drives are only loaded after the braking torque of the yaw brakes are overcome. This is implemented by defining no braking torque below a rotation speed threshold around zero rpm in the mechanical brake. The friction of the yaw bearing is assumed to be constant.
Similarly to the ultimate load case analysis specified in the IEC 61400-1 standard, extreme loads for the tower top torques have been analysed from different load cases. For the analysis of nacelle slippage only few selected load cases, where a high yaw load is to be expected have been considered. Table 1 shows the design load cases considered in this paper. It should be mentioned that the ultimate load analysis as per IEC 61400-1 considers partial safety factors for the aerodynamic loads of up to 1.35, where the load simulation of the time series presented in this paper does not consider any safety factors.

Design situation of the design load case (DLC) category 2: power production plus occurrence of fault are mostly responsible for high aerodynamic yaw loads as it couples turbulent wind conditions with high yaw errors or pitch deviation of the blades to each other. Faults in the control or protection system of the wind turbine can also result from malfunctions in the instruments or the mechanical systems of the wind turbine. In this paper the DLC 2.2 is considered, where the fault is a malfunctioning pitch of one pitch system during shut-down procedure of the wind turbine. The shut down is initialized by the controller to prevent critical structure loads due to high rotational speeds.
Table 1. Abbreviated load cases taken from IEC 61400-1 [2].

| Design situation | DLC | Wind conditions     | Other conditions                                           | Type of analysis | Partial safety factors |
|------------------|-----|---------------------|------------------------------------------------------------|------------------|-----------------------|
| 2) Power production plus occurrence of fault | 2.2 NTM | $V_{in} \leq V_{hub} \leq V_{out}$ | Protection system or preceding internal electrical fault | U               | A                     |

3. Results
Figure 2 illustrates the boundary wind and turbine conditions of the DLC 2.2. The wind is turbulent with a mean wind speed of 12 m/s and a mean yaw error of 14°. The turbulence of the longitudinal and lateral wind components are specified according to the wind turbine class A for higher turbulence characteristics, as defined in the standards. The wind turbine has a reference rotor speed of 14.3 rpm. As illustrated the rotor speed increases for 50 seconds until the shut-down procedure is initiated and the pitch angles change to 90°. During the shut-down, a fault in one pitch system leads to a pitch-stuck at an angle of 4.78°.

![Graphs](image.png)

**Figure 2.** Time series of a 120s simulation from DLC 2.2. Graphs of the wind speed and direction relatively to the nacelle and rotations speed of the low speed shaft. Graph on the lower right showing the pitch struck of pitch 1 at 4.78° and 50s.

The resulting loads on the wind turbine are illustrated in Figure 3. The time series of the loads and dynamics of the wind turbine model with the detailed yaw system model are compared.
with the time series of the same wind turbine model and a fixed DOF around the tower axis to illustrate the difference during nacelle slippage.

The pitch stuck of one blade during the shutdown procedure leads to an aerodynamic imbalance of the rotor and thus results in a high yaw load. Figure 3 illustrates that the tower top torque reaches a value of around 8000 kNm for the fixed model. The total braking torque of the yaw system is designed to withstand a yaw load of around 6000 kNm. Thus the aerodynamic yaw load overcomes the braking torque of the yaw system and the nacelle begins to slip at 50s.

A reduction of 9.78% of the extreme tower top value is observed compared to the fixed model as the transferred yaw loads on the tower top are limited to the total braking torque of the yaw system. Higher yawing loads result in the acceleration of the nacelle rotor system. It should be mentioned that the acceleration of the nacelle is considerably decreased by the yaw drives themselves, due to the inertia moment of the yaw drives coupled with the high transmission ratio of the gears. A peak at 6000 kNm and a sudden drop to 4500 kNm is observed due to the braking behaviour, changing from static to the lower kinetic friction.

The flap-wise bending torque on the blade root section and the torque in the low speed shaft have been illustrated to analyse the influence of gyroscopic forces during nacelle slippage. As can be seen in the second time series of figure 3 the flap-wise bending torque for both models are nearly identical with only a slight increase of 0.19% in the extreme value. It is assumed that the influence on the flap-wise bending moments due to the gyroscopic forces are negligible compared to the aerodynamic thrust acting on the rotor blade sections.

The third time series illustrate the low speed shaft torque where an increase of 5.86% of the maximum value is observed compared to the model with the fixed yaw model.
Figure 3. Simulation results from DLC 2.2. Time series comparing the loads for a yaw model with fixed degree of freedom (DOF) around the tower axis and a detailed yaw model which begins to slip due to high aerodynamic yawing moments.

During nacelle slippage the nacelle rotates by 3.35° which results in a nacelle yawing speed of 4.89 °/s (see Figure 4). Figure 2 illustrates that the nacelle rotation leads to a higher yaw misalignment. As the transmission ratio between the ring gear and the motor is around 10,000 the rotation speed of the yaw drive motors reaches a maximum value of around 9000.00 rpm.
To quantify the influence of the aerodynamic loads and the gyroscopic forces on the flapwise bending moments on the rotor root section a separate simulation without aerodynamic loads has been conducted. The mbs model of the wind turbine has been run with pre-set rotor rotation speed and nacelle movement, extracted from the prior simulation of DLC 2.2, ignoring any aerodynamic loads. The difference in the flapwise bending torque is shown in Figure 5.

As can be seen in Figure 5, the minimum flapwise bending moment due to gyroscopic forces (inertia and gravity loads) occurs 5 seconds after the minimum of the aerodynamic loads is reached at 50 seconds. Meaning that the gyroscopic forces doesn't add any value to the absolute minimum flapwise bending torque. Other simulations with different starting rotor angles have been conducted with similar results.
Figure 5. Simulation results from DLC 2.2. Comparison between aerodynamic and gyroscopic flapwise bending torque during nacelle slippage.

4. Conclusion
To analyse the yawing characteristics during slippage of the nacelle of a multi MW wind turbine, load simulations have been conducted by means of a mbs model of the wind turbine. A detailed mbs model of the yaw system has been implemented and calculation with the design load case 2.2 of the IEC 61400-1 standard has been conducted. Time series of the results has been shown and discussed.

The tower top torque is limited to the braking torque of the yaw system but if nacelle slippage occurs the rotor torque and the bending moments of the blade root sections are increased. The acceleration of the nacelle rotation is decreased by the high moment of inertia of the whole rotor nacelle structure and the yaw drives. The influence of nacelle slippage on the rotor torque and the bending moments of the blade root sections are not considered crucial for their respective design. For the analysed load case, the influence of the gyroscopic effects on the fore-aft bending moments on the rotor blade root section during the slippage situation of the nacelle are small compared to the aerodynamic loads. During the nacelle slippage the angular velocity is around 5-10 times higher than the reference yawing speed which leads to equally increased rotational speeds of the yaw drives. The loads are calculated without any partial safety factors usually considered for ultimate load case analysis. The rotation speeds of the drives are unfavourable and their impact on the structural integrity of the yaw drive has to be considered.

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