Comparison of a Direct Drive Wind Turbine with and without LSS-Coupling Regarding Air Gap Displacement

A Baseer¹, Y He, R Schelenz, A Kari*, B Roscher, G Jacobs
Center for Wind Power Drives, Campus-Boulevard 61, 52074, Germany
*Geislinger GmbH, Hallwanger Landesstrasse 3, 5300 Hallwang / Salzburg, Austria
¹E-mail: abdul.baseer@cwd.rwth-aachen.de

Abstract.
Wind turbines (WT) are highly coupled and complex systems. The dynamic interaction between various components is especially pronounced for multi megawatt wind turbines. As a result, the design process is generally split into several phases. [3]

The first step consists of creating a global aero-elastic model that includes essential dynamics of structural components using the minimum possible number of degrees of freedom (DOFs), with the most important simplifications concerning the drivetrain and rotor nacelle assembly. This approach is not suitable to analyse the generator air gap of a direct drive wind turbine. In this paper a more detailed simulation model is depicted, which calculates realistic deformation of the wind turbine and in particular the displacement between the generator-rotor and generator-stator. For these analysis a detailed multibody simulation (MBS) model of a generic direct drive WT is set up and used to analyse the generator air gap [3].

Several concepts of a direct drive WT are available on the market. One of them includes a coupling between the hub and generator-rotor to decouple the input wind loads from the generator and thus to decrease the impact on the generator air gap deflection [5]. The aim of this paper is to compare such a concept with a conventional concept without coupling.

1. Introduction
The wind turbine (WT) market portfolio can be divided into a gearbox generator combination and a direct driven one. The direct driven WT are either externally excited or equipped with permanent magnets.

The air gap diameter of the generator of a 3-4 MW direct drive WT is about 5 meter. The design of the generator requires a very rigid generator structure and bearing concept to minimize the effect of external and internal loads on the deflection between generator-stator and generator-rotor (air gap), which is in the range of one per mil of the air gap diameter [2]. The deflection, which cause a change in the air gap, reduces the efficiency and increases the loads on the bearings. Additionally, a certain deflection has the result, that a wind turbine is shut down due to the risk of a failure of the generator and consequently an increase in downtime of the WT [3].
To minimize the air gap deflection between the generator-rotor and generator-stator, it is necessary to identify the main factors influencing the generator air gap. The following factors have an influence: gravity, wind loads, magnetic pull, elongation due to centrifugal force, elongation due to heat and manufacturing errors / assembly errors.

In the context of this paper, a direct drive WT without and with a LSS-coupling is compared regarding air gap displacement. The coupling is placed between the hub and generator-rotor (see Figure 5) and is used to decouple the input wind loads from the generator. The comparison focuses on the impact of gravity, magnetic pull and wind load.

2. Modelling

2.1. Modelling approach

For the analysis and comparison of different concepts of direct drive WT, a generic WT model by means of multibody simulation (MBS) is set up. The WT has a rated power of 3.6 MW, a rotor diameter of ~130 m and a hub height of ~115 m [6].

Figure 1 shows the modelling approach of the generic turbine model. To analyze the generator air gap a detailed model is required. Thus, a finite element (FE) model of the generator is set up to calculate the stiffness characteristics of the structure. The rotor blades are modelled in finite element (FE) via an in-house developed rotor blade modelling process. The tower is represented as a Bernoulli beam. In the second step, all the generator structure models and the rotor blades are modally decomposed via the CRAIG-BAMPTON method [1] and integrated into the MBS model as flexible bodies. The deformation of the MBS component model is then compared with the FE model for a static load condition, to identify the required number of eigenmodes to calculate the deflection in the generator accurately [3].

![Diagram of Modelling Process](image)

**Figure 1.** Modelling of a generic direct drive wind turbine [5]

The MBS component model of the generator is extended with the bearing stiffness, coupling stiffness and the magnetic force, to include those impacts on the generator air gap. The bearing stiffness are
calculated with BEARINX and implemented via force elements as one dimensional characteristic curves for radial and axial direction. The air gap force, resulting of the interaction between the generator-stator and generator-rotor, is applied via a linear load-displacement function. Thus, a force is calculated which describes the magnetic pull depending on the displacement between the generator-stator and generator-rotor. The coupling stiffness has been approximated via literature survey. The calculation of different design load cases (DLC) is simulated via co-simulation with MATLAB. For those calculation the AERODYN force element and a SIMULINK PI controller is used [7]. This modelling approach allows to analyze the generator air gap at different DLCs [3].

2.2. Generic wind turbine model
The parameters of the generic WT model are shown in Table 1. As it can be seen, the air gap (5 mm) is one per mil of the air gap diameter (5000 mm).

| Parameters generic turbine model | Value | Unit |
|----------------------------------|-------|------|
| Nominal power                    | 3.6   | MW   |
| Nominal speed                    | 12    | rpm  |
| Hub height                       | 115   | m    |
| Rotor diameter                   | 130   | m    |
| Air gap diameter                 | 5000  | mm   |
| Air gap length                   | 1300  | mm   |
| Air gap height                   | 5     | mm   |

The structure model of the generic wind turbine model with LSS-coupling is shown in Figure 2. All considered bodies are elastic bodies except the foundation and the adapters of the coupling. The kingpin has 6 degrees of freedom and is coupled via two force elements representing the bearings with the hub. The stiffness characteristics of the bearings are represented by characteristic curve in all directions including non-linearity and clearance. The rotor blades are coupled with the hub by a rheonomic joint, allowing the blades to pitch. Additionally, a force element is applied between the generator-rotor and generator-stator, to represent the magnetic pull. The bodies of the coupling are rigid and the stiffness between the parts of the coupling are included.

The coupling has 4 DOF including x, α, β and γ (see Figure 5). For those DOF a spring damper is included with stiffness and damping parameters. The model with the coupling needs in total three
bearings. Two bearings to fix the hub with the kingpin and an additional bearing to fix the generator-rotor with the receptacle pin. All the other components are connected over 0 DOF with each other. The topology of the turbine without coupling is the same, only the coupling and the additional bearing between generator-rotor and receptacle pin is missing.

The parameter of the coupling are shown in Table 2. The 1 DOF joint connect the membrane/coupling with the coupling/membrane (see Figure 2). The 4 DOF-Joint connects the adapter/membrane with the membrane/coupling and the coupling/membrane with the membrane/adapter. The total mass of the coupling is around 1.8 ton. The parameters are based on the GEISLINGER COMPOWIND COUPLING, which is designed for $\sim$3 MNm nominal torque [9].

Table 2. Parameters of the coupling

| Joint        | Stiffness | Unit      |
|--------------|-----------|-----------|
| $\alpha$ – 1 DOF-Joint | 3e7       | kNm/rad   |
| $\alpha$ – 4 DOF-Joint | 5e6       | kNm/rad   |
| $\beta$ – 4 DOF-Joint   | 14e3      | kNm/rad   |
| $\gamma$ – 4 DOF-Joint  | 14e3      | kNm/rad   |
| $x$ – 4 DOF-Joint       | 27        | kN/mm     |

3. Results

Figure 3 shows the schematic sketch of the ideal (left) and eccentric (right) position of the generator-rotor. During the ideal position of the generator the air gap is equally distributed over the circumference with $\delta_0 = 5\text{mm}$. The minimum generator air gap is shown in Figure 3 (right) with $\delta_{\text{min}}$.

The minimum air gap can be calculated with Eq. 1, where $e$ represents the eccentric shift. The relative change of the generator air gap can be calculated with Eq. 2. In the paper, the following results are presented as the $\delta\%$, measured at the center of the generator.

\[ \delta_{\text{min}} = \delta_0 - e \] \hspace{1cm} (1)
\[ \delta_0 = \frac{\delta_0 - \delta_{\text{min}}}{\delta_0} \cdot 100 \] \hspace{1cm} (2)

Figure 3. Ideal concentric position of generator-rotor and generator stator (left) eccentric position of generator-rotor to generator-stator (right)
3.1. Impact of magnetic force (direct drive without coupling)

Figure 4 shows a 10 s window out of a 600 s simulation of the displacement in the generator air gap at 12 m/s wind speed and turbulence class A. The distribution of the displacements over 600 s are shown in the histograms.

The blue colored curve in Figure 4 (left) represents the generator model with magnetic force whereas the red curve represents the generator model without magnetic force. It can be seen, that the displacement increases by including the magnetic force in the simulation, due to the additional internal force between the generator-rotor and generator-stator.

Figure 4 (right) compares different level of discretization for the representation of the magnetic force in the generator. The magnetic force is simulated with generator discretized in 1, 3 and 5 slices. It can be seen, that the displacement increase with the number of slices. The difference between 1, 3 and 5 slices are negligible small.

3.2. Impact of coupling between hub and generator-rotor

Figure 5 compares the two concepts. On the left side the drivetrain without coupling is shown. This drivetrain has a conventional bearing arrangement as fixed-floating bearing. The fixed bearing consist out of two tapered roller bearings in X-arrangement. The floating bearing is a cylindrical bearing. On the right side the drivetrain with coupling is shown. The coupling is positioned between the hub and generator rotor. This concept needs an additional fixed bearing for the generator-rotor.
Figure 5. Drivetrain without coupling (left) and drivetrain with coupling (right)

Figure 6 shows the airgap displacement summarized for six different wind speeds for normal production DLC and turbulence class A (4m/s, 8m/s, 12m/s, 16m/s, 20m/s and 24m/s). It describes a comparison of the air gap deflection between generator without coupling (red) and generator with coupling (blue). The center displacement shows a huge difference between the two concepts. By using a coupling between the hub and generator-rotor, the displacement with maximum around 20% is all reduced within 3%. By reducing this amount of displacement, it is possible to redesign the generator to decrease the mass and thus the cost of the direct drive WT. Additionally the low displacements in the air gap gives an option to decrease the air gap itself, which leads to lower required active materials like permanent magnets. The disadvantage is the additional required coupling and bearing, which increase the acquisition costs of the wind turbine.

Figure 6. Summarized air gap displacement without and with coupling for 6 different wind speeds
4. Conclusion

This paper describes the modelling effort to set up a MBS model of a direct drive wind turbine. The generic wind turbine model allows to analyze the generator air gap under realistic load condition and includes gravity, magnetic pull and wind loads. The displacements between generator-stator and generator-rotor are analyzed in MBS.

The generic WT model was set up to simulate different DLC according to IEC61400 [8] for evaluation of the maximum displacements at the center of the generator. The simulations of the DLC 1.1 (normal operation) has been performed with a turbulent wind field (class A) at 4, 8, 12, 16, 20, 24 m/s wind speed. The impact of the magnetic force on the air-gap deflection is analyzed for different model depths.

Additionally, a coupling is placed between the generator-rotor and the hub, to see how the loads can be decoupled from the generator and how much the impact is on the air gap deflection [5]. It has been shown, that the use of coupling decrease the maximum air gap deflection from 20% to 3%.

5. References

[1] Craig R R Jr, Bampton M C C: Coupling of Substructures for Dynamic Analysis, In: AIAA Journal, Vol. 6, No. 7, 1968, pp. 1313-1319
[2] McDonald AS, Mueller M: ‘Mechanical design tools for low speed high torque electrical machines’. Proc. 3rd IET Int. Conf. Power Electronics, Machines and Drives, April 2006, Dublin, Ireland, pp. 666–670
[3] Baseer A, Schellenz R, Cardaun M., Duda T, Jacobs G: Study of Direct Drive Turbine Concept with respect to Air Gap Sensitivity by means of Multibody Simulation, In: Conference for Wind Power Drives 2019
[4] Baseer A, Andreani P, Schellenz R, Jacobs G: Generator Air Gap Sensitivity regarding Gravity, Wind Loads and Magnetic Pull of Direct Drive Wind Turbines, In: Offshore WindEurope 2019 in Copenhagen
[5] GE Renewable Energy – Haliade 150-6 MW Offshore Wind Turbine, https://www.ge.com/renewableenergy/wind-energy/turbines/offshore-turbine-haliade
[6] Matzke D, Werkmeister A, Baseer A, Leupold S, Duda T, Rieckhoff B, Berroth J, Schellenz R, Jacobs G: Multibody Simulation in Wind Energy – From Turbine to Detailed Component Load Calculation, 4th Wind and Drivetrain Conference, Hamburg, 2018
[7] Bi L, Schellenz R, Jacobs G: Dynamic simulation of full-scale nacelle test rig with focus on drivetrain response under emulated loads. In: Conference for Wind Power Drives, Aachen (Germany), 2015
[8] IEC 61400 Design requirements of Wind Turbines 2010
[9] Geislinger Compowind Coupling, Lightweight maintenance-free coupling for double digit MNm class, https://www.geislinger.com/en/products/product/compowind-coupling