Investigation of Modelling Depths for an Electromechanical Simulation of a Direct-Drive Generator Considering Parasitic Airgap Forces and External Loads

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Abstract. This paper shows a multiphysical simulation approach for direct - drive generators, including electromagnetic force calculations and multibody simulation. The objective of this method is to determine the airgap width distribution of the generator during operation.

In this investigation different modelling depths of the electromechanical model are discussed. Especially the modelling of the electromagnetic force application and integration of flexible structural elements is discussed.

1. Introduction

Renewable energy production must become competitive to fossil and nuclear energy sources. One way to achieve this is to keep maintenance and investment costs as low as possible. Therefore, novel and efficient simulation models are needed for improving the turbine’s design. This paper shows an electromechanical simulation method for direct-drive generators, including the parasitic electromagnetic forces in the airgap of the generator in a multi-body simulation model. These parasitic forces aim to close the airgap resulting in a fatal turbine damage. To prevent collision of rotor and stator, the drivetrain is designed very stiff [1], which leads to an increased use of material. Most of recent research regarding direct-drive design addresses the matter of airgap stability, e.g. incorporating flexible couplings between hub and generator.[7] However, an accurate determination method of the airgap width distribution during operation is needed, which can lead to a reduction in the use of materials and thus be cost-reducing. [2]

2. Modelling Approach

Figure 1 shows the approach for the electromechanical simulation. First the geometry of the stator and rotor tooth and slots are modeled by permeance functions by means of conformal mapping [3]. This step is a preprocessor step and can be calculated in advance independently of the other simulations steps. After that a lumped parameter model of the generator calculates
the ideal flux density distribution from the excitation voltage. The ideal flux density multiplied with the permeance functions of rotor and stator results in the airgap flux density distribution.

![Diagram of the electromagnetic model](image)

**Figure 1: Approach for hybrid electromechanical simulation of a direct-drive generator.**

From the airgap flux density distribution the Maxwell stresses on the airgap surface can be calculated, which results in tangential, radial and axial electromagnetic force densities [4]. The results of this electromagnetic model are handed over to force-elements in a multibody simulation (MBS) model of the turbine, which can also apply mechanical rotor loads and weight forces on the structural components of the generator. These forces, either mechanical or electromagnetic, result in a displacement of rotor and stator or lead to deformation in the structural elements of the turbine. Consequently the airgap permeance changes, which will be accounted in the electromagnetic field calculation iteratively. [2]
Figure 2: Bending moment application and resulting radial airgap forces.

Figure 2 shows the flexible MBS model of the generator. The applied bending moment on the rotor hub, causes a tilting of the generator rotor, which leads to a non-uniform airgap with the smallest space between stator and rotor on the bottom. The corresponding radial airgap forces are shown to the right, it can be seen that the forces near the smallest airgap width are much larger, resulting in the so called unbalanced magnetic pull [5], which will lead to increased loads on the generator structure.

3. Magnetic Force Application

As the electromagnetic forces do not act on discrete points on the airgap surface, rather being continuously distributed in the airgap, the force elements need to be discretized for the MBS [2]. In conclusion there exist different level of abstraction (modelling depth) with a corresponding calculation time. A simple method for discretization is shown in Figure 3.

For modelling generator tilting, the corresponding force elements are distributed axial on the permanent magnets. To investigate the model behaviour, the number of electromagnetic force elements on the permanent magnets were differed in axial direction, see Figure

4. This leads to a change in deformation and movement of the generator rotor due to bending moments at the turbine hub.

With different level of abstraction the results for the airgap widths distribution will change. This is shown in Figure 5, where modelling depth 1 considers just one force element on the
rotor and stator structure per permanent magnet. Modelling depth 2 includes the parasitic airgap forces, by applying three force elements per magnet on the structure. Modelling Depth 3 considers the force distribution of five force-elements per magnet. As a central result, it should be noted that the additional loads caused by magnetic forces are in a significant range. For the most detailed possible consideration of the air gap width in generators, these should be taken into account in simulations.

![Graph showing normalized airgap width distribution](image)

**Figure 5:** Resulting airgap width distribution due to extreme bending loads, modelled with different levels of abstraction of electromagnetic force excitation.
4. Structural Modelling

Figure 2 shows the drivetrain structure of the direct-drive generator as a 3D multibody model. The pivot is connected via a pressfit with the flange of the support structure, which in turn is attached to the foundation structure. The stator of the generator is also attached to the support structure while the rotor is connected to the hub, which transmits the torque from the rotor blades to the rotor.

For modeling the (mechanical) drivetrain with a sufficient level of abstraction, the major components of the direct-drive structure are either modeled rigid or as flexible bodies.

**Bearing Stiffness**

In the first step the bearings are modelled by spring systems (see Figure 6), with its behavior calculated by the commonly used tool BEARINX [6]. This allows the hub and rotor structure to move in all degrees of freedom according to the respective displacement of the bearing structure.

**Flexible Pivot**

In the next step the model is extended by a flexible pivot structure (see Figure 7). Therefore the pivot structure modal order is reduced via Finite Element Method.

**Flexible Rotor**

The model is extended by a flexible rotor support structure (Figure 8). This support structure carries the permanent magnets of the generator and is directly exposed to the Maxwell stresses.

**Flexible Stator**

Furthermore the MBS model is extended by a flexible stator structure (Figure 9). The stator windings of the generator are inserted in the stator structure. However these are not included in the model as they have no influence on the stator radial stiffness behavior.

Figure 10 shows the influence of the mechanical modeling depths on the airgap width distribution. It can be seen, that the addition of the flexibility of the pivot has the biggest influence on the airgap width. However each additional modelling depths has an influence on the airgap width distribution.
Figure 10: Resulting airgap width distribution due to normal bending loads, modelled with different levels of abstraction of electromagnetic force excitation.

Depending on the objective of the simulation model, different modelling approach are sufficient. In the case of fundamental design studies of the drivetrain behaviour (e.g. to ensure that the airgap clearance is maintained during turbine operation) modelling depth 2 seems sufficient.

On the other hand, if the objective of the model is to simulate the drivetrain in higher frequency domains with focus on local force distribution and deformation (e.g. to model the acoustic behaviour of the drivetrain) a higher modelling depths is recommended.

5. Conclusion

This investigation shows a modeling approach for direct-drive generators, considering the interaction of electromagnetic airgap forces and external loads. During this research a sensitivity analysis of the structural components and modeling depths of the electromagnetic force excitation were conducted.

It is shown that the axial distribution of electromagnetic force-elements influences the airgap width distribution. The biggest deviation in airgap width change is between the modeling with one force-element per magnet compared with three force-elements per magnet. Still the results between the model with five and the model with three force-elements per magnet differ significantly. For a design estimation, also considering model design effort, the modeling approach with three magnets seems sufficient, as it models rotor tilting in a more realistic way compared to one force-element, but leads to valuable results.
Furthermore it is shown, that the different ways of modeling the structural components have an influence on the airgap width distribution. Even though all modeling depths have an influence on the airgap width distribution, it can be stated, that the flexibility of the pivot has the biggest influence on the airgap width and should always be modelled as a flexible structure. For investigating the fundamental behavior of the airgap width during operation a flexible model of the pivot leads to sufficient results. However if local forces are of interest a more detailed model is recommended.

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