New Drive Train Concept with Multiple High Speed Generator

2016 J. Phys.: Conf. Ser. 753 112001

(http://iopscience.iop.org/1742-6596/753/11/112001)

New Drive Train Concept with Multiple High Speed Generator

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Abstract. In the research project RapidWind (financed by the German Federal Ministry for Economic Affairs and Energy under Grant 0325642) an alternative 6 MW drive train configuration with six high-speed (n = 5000 rpm) permanent magnet synchronous generators for wind turbine generators (WTG) is designed. The gearbox for this drive train concept is assembled with a six fold power split spur gear stage in the first stage, followed by six individual 1 MW geared driven generators. Switchable couplings are developed to connect and disconnect individual geared generators depending on the input power. With this drive train configuration it is possible to improve the efficiency during partial load operation, increasing the energy yield about 1.15 % for an exemplary low-wind site. The focus of this paper is the investigation of the dynamic behavior of this new WTG concept. Due to the high gear ratio the inertia relationship between rotor and generator differs from conventional WT concepts, possibly leading to intensified vibration behavior. Moreover there are switching procedures added, that might also lead to vibration issues.

1. Introduction

So far talking about high-speed applications of electrical machines in the wind energy sector means generators with 1500 - 1800 rpm speed [1]. In the automotive industry the application occurrence of high-speed electric machines (up to 10.000 rpm [2]) increases due to the effect of reducing torque and size and rising power density. Using high-speed generators results therefore in savings of the required cost-intensive magnetic active material. This leads to lower generator investment costs.

These principal advantages can also be used in the wind energy sector. To realize the high-speed for the generator the gearbox needs a higher ratio to transmit the low input speed of the wind turbine rotor to the high-speed generator. Thus the gearbox becomes larger and more complex compared to conventional gearbox configurations. To compensate these disadvantages the wind turbine concept is designed using a multiple generator drive train. The design with multiple equal generators and a gearbox with power split enables the utilization of more identical parts, which are smaller and more lightweight, leading to improvements in production and maintenance. Another advantage is the redundancy in case of a malfunction of one geared generator. Due to the option to cut-off single geared generators by using switchable couplings the efficiency particular during partial load operation [3] can be increased.

2. Objective

Figure 1 illustrates the configuration of the new 6 MW wind turbine drive train with a four-stage gearbox and six 1 MW high-speed generators. The main bearing, which is realized as a fixed-floating roller bearing, and the torque arm suspension of the gearbox are similar to a conventional drive train design. For the proposed drive train six frequency converters are required to individually control the generators. The foci of the project RapidWind are the design of the gearbox concept, the high-speed generators and the development of an operating strategy.

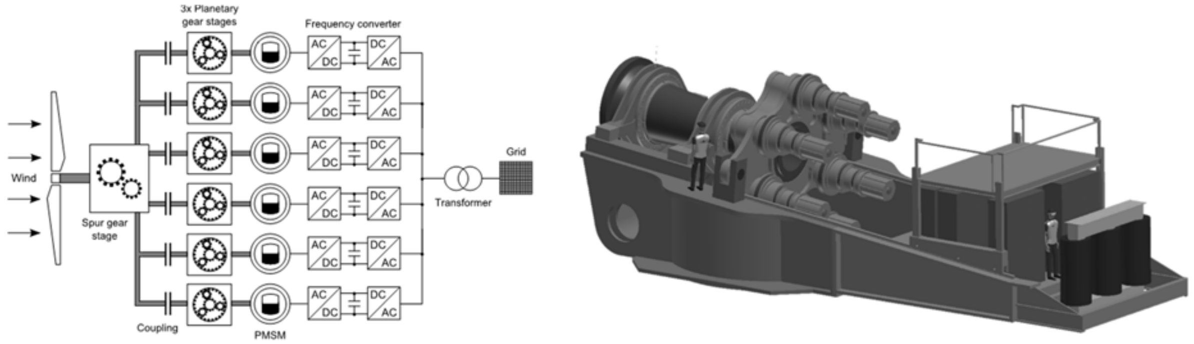
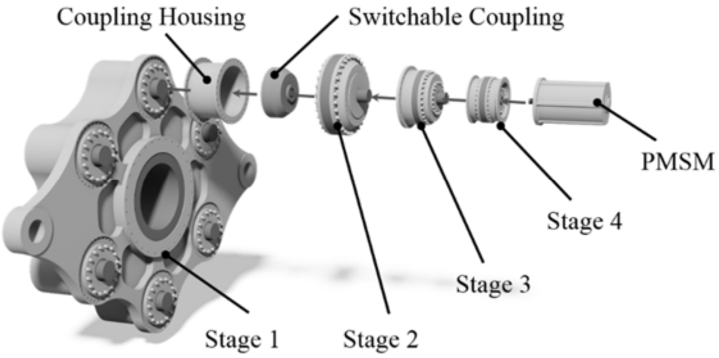


Figure 1. Drive Train Configuration.

2.1. Gearbox

The gearbox is assembled with a power split spur gear stage in the first stage and six 1 MW gear trains. Each gear train is built up with three planetary stages in two shaft-mode (drive: planet carrier, driven: sun shaft). With this arrangement the 6 MW input power is split once on the mechanical side. The power summation exclusively takes place on the electrical side. To realize an output speed of 5000 rpm the gear ratio is greater than 1:400. With a total weight of 67 t the gearbox is in a comparable weight range to conventional configurations within this power class. Each of the six 1 MW gear trains has a weight of 4 t whereat each stage has his own housing and can be mounted separately (see Figure 2). Through this modularization of the single stages of the gearbox the weight and probably the cost of the housing increases but the assembly and disassembly of individual gear trains on board of the WTG becomes possible. Cost savings for service and maintenance as well as spare parts are expected.

With the multiple generator concept it becomes possible to switch generators individually on and off during partial load operation of the WTG to increase the energy yield and to reduce the load period of the generators. Switching off a generator leads to an operation of single gear trains without any load. Due to this the risk of roller bearing slip increases which can result in bearing failures. To avoid these load conditions the integration of switchable couplings after the first gear stage is investigated to connect and disconnect an entire 1 MW gear train and generator. To enable a switching procedure fulfilling the requirement of high torque and low coupling wear it is necessary to reduce the relative speed between in- and output to a minimum. This can be realized by ramping the inactive gear trains using the motor-driven generators up to the synchronous speed before the couplings are activated (see chapter 2.3. Operating Strategy). To realize this switching procedure positive fit and dry running frictionally engaged couplings could be designed and integrated in the gearbox.



Stage 1	1 x 43,593 t
Stage 2	6 x 1,726 t
Stage 3	6 x 0,821 t
Stage 4	6 x 0,449 t
Coupling	6 x 0,584 t
Coupling Housing	6 x 0,374 t
PMSM	6 x 0,819 t
System	approx. 72,23 t

Figure 2. Drivetrain Configuration and Weights.

2.2. *Generator*

The six generators of the proposed drive train are designed as synchronous machines with permanent magnet excitation (PMSM). This topology is chosen after an evaluation process based on the Esson power coefficient which is a measure of the performance and utilization of an electrical machine. The Esson coefficient relates the output power that can be obtained from the machine to its volume and speed [4]. In this respect, the chosen PMSM offers the highest power density when compared to other machine types like the electrically excited synchronous machine (EESM) or the induction machine with squirrel cage (SCIM). Furthermore, both the PMSM and the EESM have higher efficiency in the base speed range, with the PMSM being most efficient, since no copper losses occur inside the rotor due to the permanent magnet excitation (see Figure 3). Figure 3 depicts the different ranges of maximum efficiencies of the three types, PMSM, EESM and SCIM where the normalized generator torque is plotted above the normalized generator speed. This is an important advantage for the application as a WTG generator, which generally operates in the base speed range.

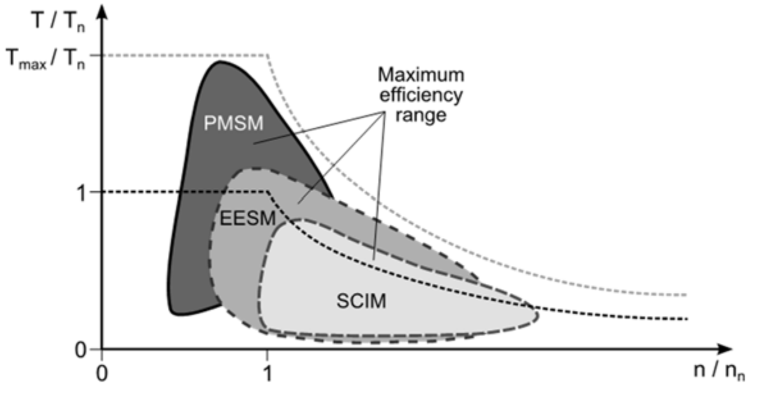


Figure 3. Maximum Efficiency Ranges for Different Electrical Machines [5].

The PMSM is designed with V-shaped buried magnets which minimizes eddy current losses inside the magnets [6]. The machine has a rated power of 1 MW and a rated speed of 5,000 rpm. With an outer stator radius of 240 mm and a total length of 610 mm (including end windings) the resulting design has a total volume of 0.1104 m^3 and thus a power density of 9.06 MW/m^3.

2.3. *Operating Strategy*

The operating strategy for the developed drive train concept is identical to commonly known strategies during start-up and full load using pitch-control. During partial load operation the strategy is to push single drive trains either to rated power or to be disconnected. The range of each operation area (characterized by the number of active generators) depends on the torque characteristics of the generators and is limited by the rated torque. Figure 4 shows the torque-characteristic of the RapidWind concept. The generator rated torque multiples (n*1900Nm) are plotted horizontally and mark the different operation areas. The vertical lines divide the WTGs entire operational area into different load areas. The three main areas are: 1 – idling, 2 – partial load and 3 – rated power. Areas 1.5 and 2.5 are intermediate areas, in which area 1.5 is designed accordingly to [7], whereat the gradient in area 2.5 is designed as steeply rising to rated WTG torque as it is possible without causing massive torque leaps.

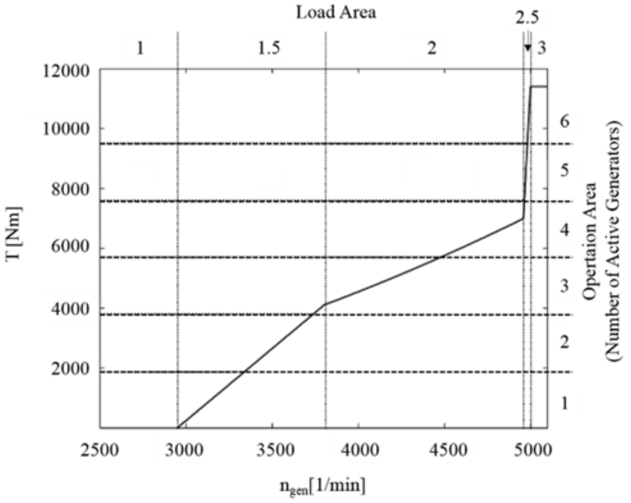


Figure 4. Torque Characteristic.

The load distribution on the gearbox can be designed either symmetrically or asymmetrically, whereat symmetric load distribution means, that all active generators are charged with the same torque and asymmetric load distribution to operate as much active generators at rated power and to load the additional generator with the remaining torque (see Figure 5 left). The torque distribution is designed to be symmetric since this configuration leads to a better combined generator efficiency, calculated with the efficiency characteristic of the designed PMSM generator, than an asymmetric load distribution or an operation without switching procedure can provide (see Figure 5 right).

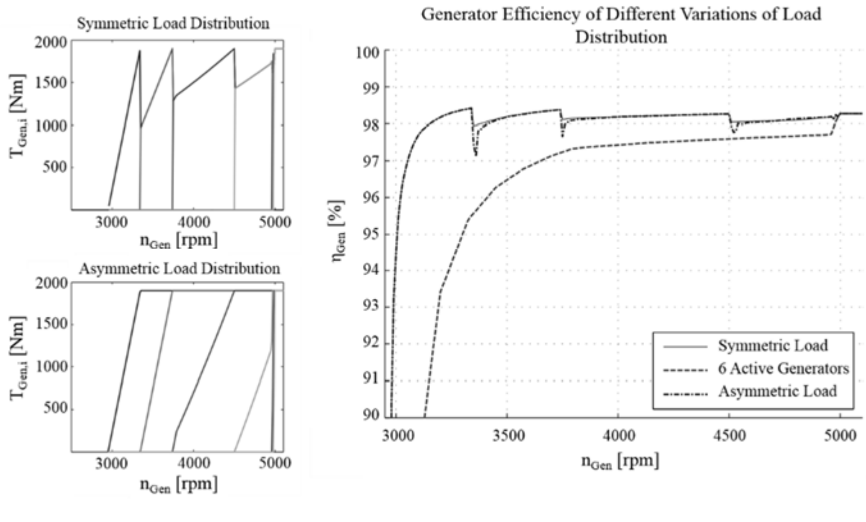


Figure 5. Generator Efficiency of Different Variations of Load Distribution.

In order to reduce the inner loads on the drive train the active generators are selected to be obverse to each other (see Figure 6). Only in operation area one and five the loads do not equalize. However the operation strategy schedules a direct switch from four to six active generators, neglecting the state of five active generators since operation area 5 is only valid in load area 2.5 (see Figure 4) and passed through very quickly. This way one switching procedure can be avoided and the load distribution on the gearbox is optimized simultaneously.

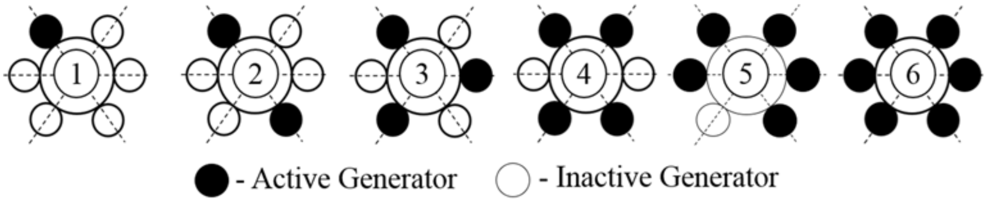


Figure 6. Active and Inactive Generators in the Different Operation Areas.

Through this switching procedure the efficiency during partial load operation can be increased (more than 7 %) [8]. Thus the annual energy yield can be increased. For a low-wind site with a mean wind speed of 5.3 m/s an increase in energy yield during partial load operation of up to 1.2 % is achieved [9]. Figure 7 shows the efficiency of the system “gearbox and generator“ of the RapidWind concept (with and without switching procedure) and of a conventional concept with equal rated power but using one doubly fed induction generator (DFIG) and a gear ratio of about i = 97. The gearbox losses that have been taken into account are calculated load dependent gear losses, bearing losses and seal losses; the load independent gear losses have been estimated according to [10]. It can be determined that especially in the area of partial load the efficiency of the RapidWind concept with switching procedure can be increased compared to the conventional DFIG concept.

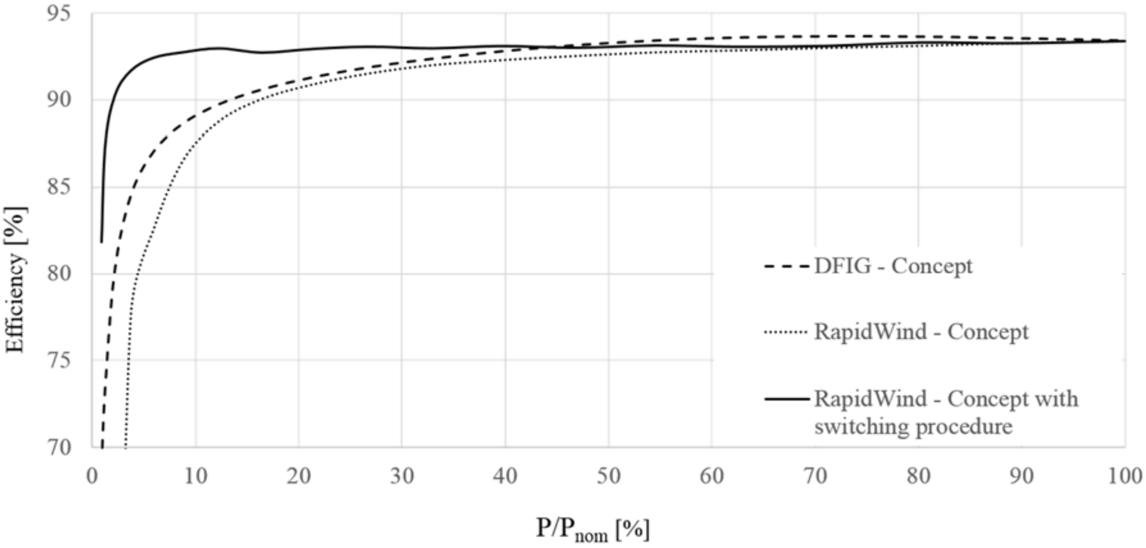


Figure 7. Efficiency – Gearbox + Generator.

3. Approach and Methods

To examine the dynamic behavior a MBS (Multi Body Simulation) model has been built up. The first stage model consists of rigid bodies but includes a flexible wind turbine rotor (used from the C6x126-model [11], see Figure 8) and flexible shafts. The shafts are designed as Timoshenko beam elements. These elements are shear-soft which means that deformations caused by shear stresses can be taken into account. The gear contacts are modeled with a teeth damping calculated according to [11]. The wind loads are simulated using NREL AERODYN v13 as it is described in [12]. First calculations show a good accordance between the calculated teeth forces and the design loads. During the continuing project work the model will be supplemented with further flexible bodies, e.g. the planet carriers, the gearbox housing or the main frame.

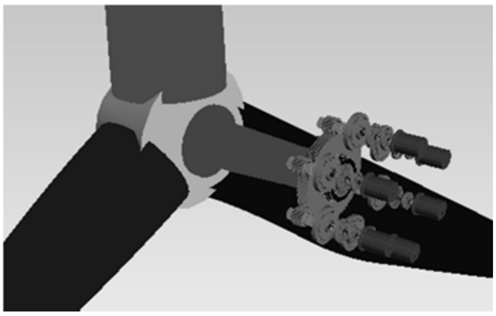


Figure 8. Model of the Drive Train Concept Including the Flexible Rotor.

The rotor has been designed based on the blade element momentum theory referring to a Sandia-publication [13] and the UpWind project [14]. The blades have been created in regard to the Eigenfrequencies in turn and lay direction analog to the approach in [15]. To examine the operational behavior of the entire RapidWind concept a co-simulation between the operational strategy and the MBS model has been installed.

4. Results

To examine the vibrational behavior of the MBS model a speed run up (without using the operational strategy) of the pre-loaded drive train has been performed as a synthetic load case. Thereby the generator speed has been given as control signal and constantly increased up to rated speed (5000 rpm). Figure 9 depicts the difference between the calculated generator speed and the control signal (delta n_gen) during this run up. It can be seen that there are two vibration areas visible, in which the vibration at n_gen = 4200 rpm is more distinctive than the other at 2125 rpm generator speed.

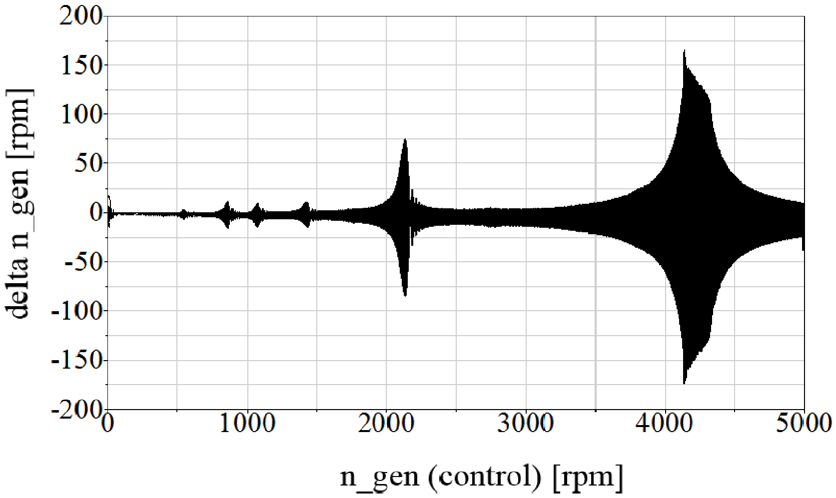


Figure 9. Difference between Generator Control Signal and Calculated Generator Speed During Run-Up from 0 rpm to Rated Speed (5000 rpm).

To determine the cause for this more intense vibration a Campbell-Diagram has been generated, taking the systems Eigenfrequencies (horizontal lines) and the excitations (lines though origin) like the gear meshing frequencies and the speeds of the different stages into account (see Figure 10). In every intersection of an Eigenfrequency-line and an excitation-line there are vibrational reactions possible. The vibration shown in Figure 9 can be lead back to the intersection of the first torsional Eigenfrequencies of the gearbox and the gear meshing frequency of the spur gear stage (stage 1), marked in Figure 10.

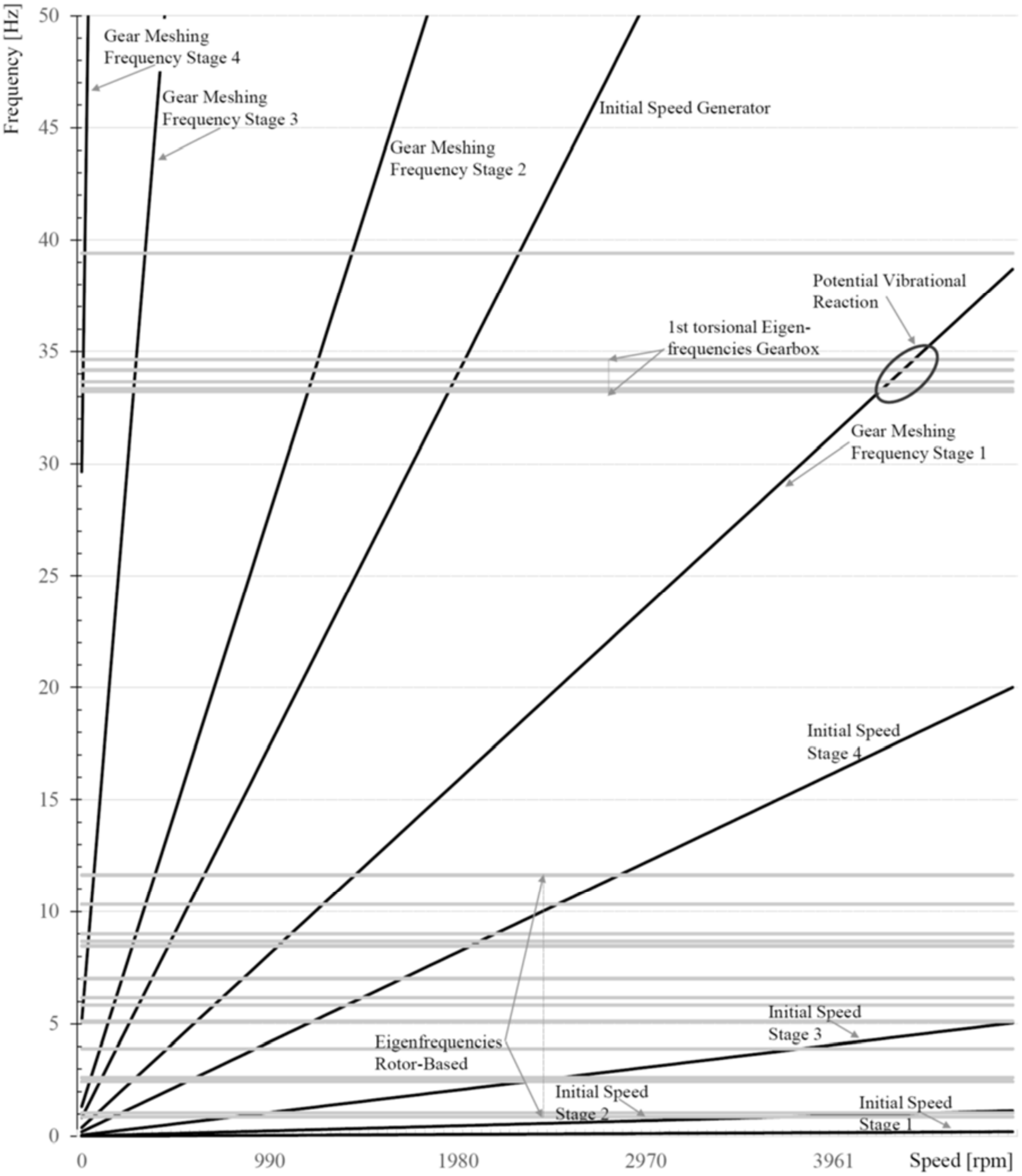


Figure 10. Campbell-Diagram of the Entire RapidWind Concept.

4.1. Behavior During Coupling Procedure

To evaluate the behavior of the drive train during the coupling procedure, a start-up at 4.5 m/s wind speed with a later increase of the wind speed up to 6 m/s has been executed (see Figure 11). Figure 12 shows the torque of generator 1, that is active from the beginning on and generator 4 that is switched on when the wind speed rises. It can be seen that the torque is distributed equally on both active generators. Figure 13 shows the speed of generator 1 and generator 4. It can be seen that both generators operate at the same speed after the activation of generator 4. Figure 14 shows the generator speeds during the coupling procedure in detail.

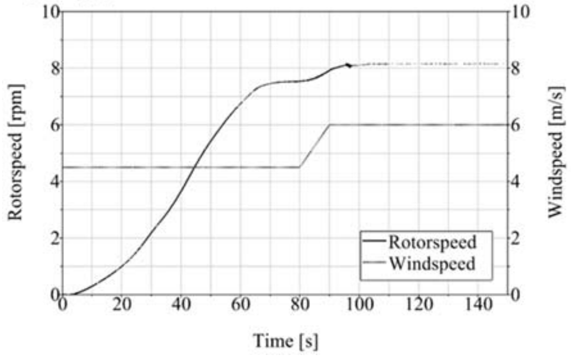


Figure 11. Wind Speed and Rotor Speed.

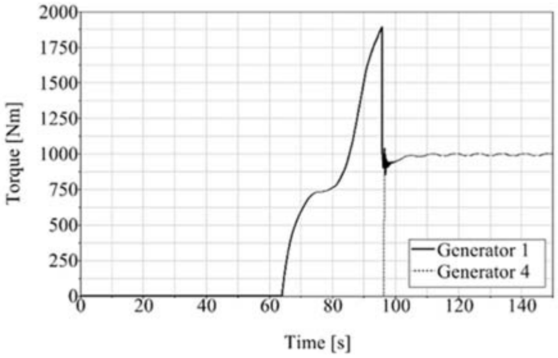


Figure 12. Generator Torque of Generator 1 and 4 with Coupling Procedure.

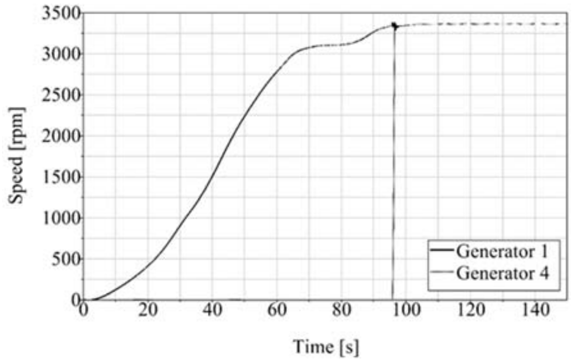


Figure 13. Generator Speed of Generator 1 and 4 with Coupling Procedure.

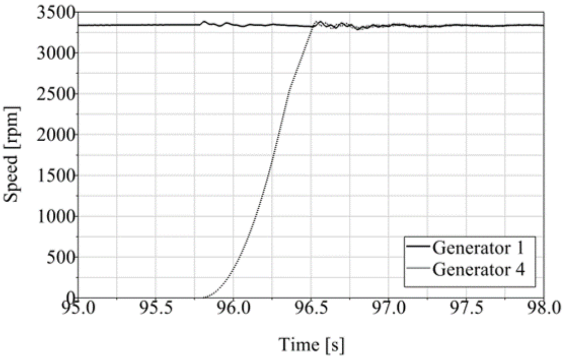


Figure 14. Generator Speed of Generator 1 and 4 during Coupling Procedure.

5. Discussion

Referring to Figure 10 it can be asserted that the Eigenfrequencies in the lower frequency area (up to 15 Hz) are, according to conventional WTG concepts, rotor dominated. The Eigenfrequencies that cause the vibration at n_gen = 4200 rpm (Figure 9) are mainly based on the torsional Eigenfrequencies of the entire gearbox that, through its power split in the first stage on six output shafts, differs structurally from conventional gearbox concepts with one single output shaft. To reduce the vibration observed in Figure 9 different strategies can be persecuted. One possibility is to change the ratio of stage 1 to change the exciting gear meshing frequency. Since this procedure can lead to new excitations and since the drive train is by now modeled quite stiffly using rigid gear wheels with one degree of freedom, another approach will be chosen. Through using elastic bodies the Eigenfrequencies of the model shall be shifted in an operational area where the loads are lower. In a first step the rigid planet carrier will be substituted by elastic bodies, followed by the gearbox housing and the base frame.

Regarding Figures 11-14 it can be seen that the vibration at n_gen = 2125 rpm is not visible when the model is operated with operation strategy and loads calculated from a wind file. This compared to the synthetic load case improved behavior is probably based on the aerodynamic damping and the rotor blades structure damping. According to this is has to be evaluated if it is necessary to reduce the vibration visible in Figure 9 for the analysis of the operational behavior of the entire wind turbine model (including operational strategy and aerodynamic wind loads).

The couplings have been implemented successfully. In Figure 14 it is visible that there are some vibrations in connection to the coupling procedure visible but they equalize rapid. By now it takes about 0.75 s until the synchronous speed is reached. This time needs to be shortened and the influence of this reduction on the vibrational behavior of the drive train has to be investigated.

6. Conclusion

Within the RapidWind project a novel drive train concept with 6 MW rated power with power split on six generators with 5000 rmp rated speed has been developed. The efficiency of the system " gearbox and generator" combined with the developed operation strategy has a better efficiency than conventional DFIG concepts. Switchable couplings enable to switch of inactive partial drive trains to reduce losses. To evaluate the operational behavior of the WTG concept a MBS model has been built up and combined with the developed operational strategy. The inactive drive train is ramped to synchronous speed y the motor driven generator before the coupling is activated. It can be stated that switchable couplings can be basically used in the RapidWind concept without causing extensive vibrations.

7. References

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