Computation of Dynamic Loads in Wind Turbine Power Trains

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Abstract

In order to quantify backlash loads in the power train of wind turbines, a non-linear, three dimensional, transient dynamic model is developed. The numerical model includes all relevant mechanisms and structural components of the power train and in particular a detailed model of the planetary gearbox which accounts for all clearances of bearings and gaps in between contacting gear teeth. Experiences in the numerical modeling and analysis of dynamic backlash phenomena are commented and stipulations are done with respect to possible mechanisms which produce power train failure. Finally, the application example illustrates the power train dynamics in the case of an asynchronous generator which operates with nominal speeds of 1000 RPM and 1500 RPM respectively.

1. Introduction

Comparing the methodology for evaluating fatigue life in automotive and wind power industry, it is worthwhile to mention some evident differences. Before mounting a power train or suspension component in a prototype vehicle, there is performed an exhaustive fatigue testing of each component. The fatigue testing is done either until failure of the component, or until a number of load cycles which correspond to some multiples of the entire expected product life. Once the automotive components are optimised and approved by testing, they are mounted in a "miss use vehicle" in order to evaluate the failure modes of the assembly.

In the case of wind turbine components, the cost for fatigue testing until failure is extremely elevated due to much higher cycle numbers and due to much larger dimensions and loads. Performing on purpose "miss use manoeuvres" with wind power facilities in order to get more information on the "failure modes" can be excluded in most cases.

Taking into account the difficulties involved in the experimental measurement of detailed dynamic gearbox loads, advanced numerical simulation might be the most suited tool in order to obtain detailed knowledge of the load spectrum each power train component is subjected to.

It is stipulated that the principal cause for premature failure of wind turbine power trains is due to the dynamic impacts induced by periodic load inversions, i.e. backlash phenomena. These backlashes propagate through the entire power train and can be amplified due to the excitations introduced by rotor and generator torque variations. Taken into account that the induced peak loads are produced by oscillations which depend on the design of the entire wind turbine, the numerical model should include all relevant components including the dynamic properties of the rotor, the complete power train and finally the electro-mechanical properties of the generator. It is anticipated that a dynamic analysis can be done only successfully, if all the mentioned components and mechanisms, including the generator regulation, are taken into account.

2. Numerical Modelling in the Context of Dynamic Analysis

The dynamic amplification of impacts and backlashes depend on the damping and dissipation properties of the entire mechanical system, including the electro-mechanical dissipation properties of the generator. Accordingly the damping properties of all relevant elastic shafts or coupling elements and the dissipation induced by friction in the gearbox have to be included in the analysis. In that context it is crucial to account for all present clearances and gaps of the power train mechanics.

Additionally to the varying rotor torque, the generator has to be considered as an source of dynamic excitation of the power train and it is emphasized that the generator regulation in terms of slip behaviour has crucial impact on the global damping behaviour of the power train [1]. It is emphasized that the generator torque is an analysis result, but not a boundary condition. The generator torque is defined as a non-linear function of the slip with respect to the nominal speeds of 1000 Rpm and 1500 Rpm. These non-linear "torque versus slip functions" incorporate the generator characteristics. The generator slip is related directly to the generator velocity and presents an unknown degree of freedom of the numerical model. Accordingly, the generator torque is known, once the non-linear equations are solved for a given time integration step.

It is anticipated that an simplified analysis model of a wind turbine will not reproduce the peak loads responsible for premature power train failure. Further on it is emphasized that a numerical model with not properly tuned damping and dissipation behaviour will not even approximate the dynamic loads occurring in the power train. This is easily understandable due to the fact that the dynamic amplification depends essentially on the damping and dissipation properties of the system to analyse. If you consider from a theoretical point of view an elementary dynamic system subjected to a periodic excitation close to resonance, it is obvious that in absence of damping the response goes versus infinite due to dynamic amplification. As observed frequently in practice, the amount of dynamic loads due to amplification can be easily some multiples of the corresponding nominal loads. Taken into account that our investigations are centred in the dynamic amplification of backlashes, it is evident that damping or dissipation properties of the numerical model should be matched as good as possible to reality.

From a numerical point of view it is stated that the computation of dynamic transient loads in the power train of a wind turbine is particular difficult due to:

- The imposition to couple consistently different mechanisms and structural components in one analysis model [2, 3].
- The importance of damping and friction modelling in the context of dynamic amplification.
- The non-linear nature of frictional contact phenomena [4].
- The need to perform implicit unconditionally stable time integration in the presence of impacts and constraints [5, 6]. An explicit time integration is excluded for efficiency in particular due to the long time intervals to be analysed.
- The difficulties involved in the solution of highly non-linear equations in the presence of impacts [7].

A key feature of the numerical model is the consistent, implicit coupling of mechanism and structural analysis adopting an "Augmented Lagrangian Approach". Structural components are presented either in terms of fully non-linear Finite Element models, or in terms of "Super-Elements" [8, 9]. Readers interested in the mathematical background of the numerical model, should refer to the following references [9, 10, 11].

3. Conjectures About Power Train Failure Mechanisms

Numerical simulation has shown that the peak loads which might occur in the power train in the case of "extreme events" can be some hundred percent higher than the loads which correspond to the "nominal loads". There are events which produce loads much higher than nominal loads, having an deterministic character and which can be predicted like for example peak loads at generator connection or disconnection respectively. Unfortunately, there are as well "extreme loads" which are produced by aleatoric events which cannot be predicted a priori. Such kind of aleatoric events might be for example produced by important wind variations during a connection or disconnection of the generators. As follows some conjectures about possible failure mechanisms will be given. It is emphasized that the following remarks are not generally applicable, but only conjectures :

- Due to the variations of rotor and generator torques, the power train is excited dynamically producing a permanently varying pretension of the power train. The variation of the pretension of the power train can amplify dynamically such that there occur intermediate states, where the pretension of the power train is completely released or even inversed. The inversion of the pretension produces backlashes which can amplify due to the excitations introduced by the varying rotor and generator torque.
- It is stipulated that sudden energy release due to activation of over-load clutches can introduce very important dynamic loads due to the induced oscillations. In some cases it might be better to allow short instances of torques being much higher than the nominal torque instead of introducing oscillations by a sudden drop of the power train torque by means of an over-load clutch.
- Important peak loads can be produced by a sudden drop of the generator torque. Especially in the case of important clearances, a disconnection of the generator can produce violent backlashes.

- The generator regulation has a mayor impact on the power train torque and fatigue life. In that context it is stipulated that the main benefit of a soft generator regulation is not the reduction of the peak loads, but the reduction of fatigue relevant loads [1].
- Too low power train loads can produce as well a reduction of the fatigue life, since certain load variations produce a loss of pretension and backlashes might occur.
- There is a non-linear relation in between power train clearances and resulting backlash peak forces. If the clearances of the power train exceed a system dependant threshold, backlash loads can be amplified such that the power train is destroyed at short term. That non-linear relation in between clearances and resulting peak forces had been observed numerically in particular for the axial bearing clearances. In the case of excessive axial clearances, it is observed numerically that axial backlash forces augment to values which should destroy the bearings by impact.
- Under certain operation conditions it can happen that the generator is switching periodically in between motor and generator mode. If that phenomena occurs, loads can be amplified to levels which destroy the power train at short term.
- Most probably there is no way to eliminate completely backlashes.

4. Application Example

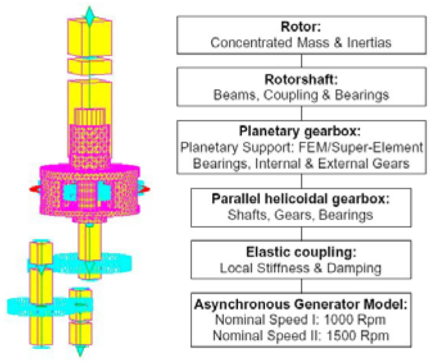

Fig. 1: Schematic presentation of the numerical model including structural FEM components and mechanism type elements

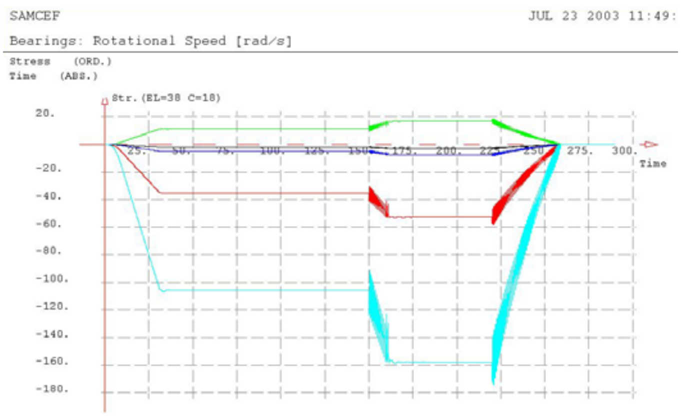

Fig. 2: Rotational speeds of all shafts [rad/s]:
a.) black: rotor shaft speed (hardly visible since less than 2.6 rad/s)
b.) dark blue: planetary gear I (relative rotational speed w.r.t. planet carrier)
c.) green: sun-shaft/output of planetary gear
d.) red: intermediate shaft in between planetary gear and generator shaft
e.) light blue: generator shaft

In order to illustrate the dynamics of backlash phenomena, a power train of the "Mega Watt Class" is analyzed numerically. As already mentioned, it is only possible to evaluate the dynamic loads, if the complete power train is included in the analysis model. Accordingly, the numerical model includes all components from the rotor to the generator, including all essential details of the planetary gear box. Figure 1 shows schematically the analysis model which is composed of structural elements and mechanism type elements. The "planet carrier" is included in terms of a condensed FEM-model, i.e. using the Super-Element technique. Beam elements are used to model the elastic and dynamic properties of all shafts, in particular the rotor main shaft and the gearbox shafts. The elastic and cinematic characteristics of the gears, as well as the electro-mechanical properties of the generator, are included in terms of mechanism type elements. Bearings are modeled by "generalized stiffness elements" which account for the clearances in axial and radial directions. These clearances are of outmost importance, because otherwise impacts or backlashes can not be reproduced properly. In order to present stick-slip effects, which might occur in between bearing and gearbox housing, Coulomb-type friction models are applied. Taking into account that the driving rotor torque presents a boundary condition, the dynamic properties of the rotor blades are reduced to a discrete inertia and mass which are connected to the beam presenting the rotor main shaft. Analogously, the dynamic properties of gears and the generator are introduced by further local masses and inertias. A disc brake is located in between the exit of the gearbox and the generator. That disc brake is included in the numerical model in terms of a velocity dependant friction law of Coulomb type.

It is emphasized that the generator load is not a boundary condition, but an analysis result. However, what can be considered as an boundary condition are the time instances where the generator model is activated, or disabled respectively.

As follows, the relevant boundary conditions are resumed:

- The driving aerodynamic rotor torque is approximated roughly by a load function which is applied to the degree of freedom which presents the rotor including the inertia of the blades. That rotor load function introduces within the time interval [0 <-> 220 seconds] a constant driving torque of 8E8 [Nmm] on the rotor. At time [220 seconds], the braking procedure is initiated. During the braking procedure, the aerodynamic rotor flap brake is idealized by a velocity dependant rotor torque which is inversed with respect to the initial driving torque. Further on, at the same time instance a disc brake, which is located at the exit of the gearbox, is activated.
- The generator torque is defined for two different nominal speeds as a function of the slip with respect to the grid frequency. If the rotational velocity is above nominal generator speed, the generator dissipates energy and if speed is below nominal speed, the generator acts as motor. At time [31 seconds], the lower "generator connection speed" is reached and the grid connection is simulated by the activation of the asynchronous generator model for 1000 Rpm. It is mentioned that the "generator connection speed" is slightly below the "nominal generator speed". In order to drive the wind turbine from 1000 Rpm to 1500 Rpm, the generator is disconnected within the time interval [150s -> 159s]. Slightly before reaching the higher nominal speed of 1500 Rpm (at the time instance [159.5]), the generator is reactivated, but using in that case the torque versus slip function for 1500 Rpm. At time [220 s] the generator is disconnected and the braking procedure is activated.

As follows an extract of the numerical results will presented and commented. It is anticipated that the exposed results do not present any extreme loads, but correspond to typical connections and disconnections of the generator. The maximum dynamic amplification of gear or bearing forces is about 100%, thus presenting rather successful maneuvers under constant wind conditions.

The rotational velocities of all relevant shafts are depicted in figure 2. During the generator connection at the time 31[s] with a nominal speed of 105 [rad/s]= 1000 Rpm, as well as during the connection at the instance 160 [s] with an nominal speed of 157 [rad/s]=1500 Rpm, the velocity oscillation are quite small compared to the oscillations during the disconnections. It can be seen clearly that the important velocity oscillations occur during the disconnection of the generator, i.e. during the time interval from 150 [s] to 159 [s] and during the interval from 220 [s] to 265 [s] respectively.

The torque in the rotor main shaft is depicted in figure 3. The peak rotor shaft torques occur shortly after the generator connections, i.e. about the instances 33 [s] and 164 [s]. Backlashes occur during both generator disconnections and are identified by the sign change of the rotor shaft torque. It is interesting to notice that the backlashes which occur at the final disconnection of the generator, i.e. during the time interval [220s -> 265 s], produce rotor shaft torques nearly 100 % higher than the nominal rotor shaft torque.

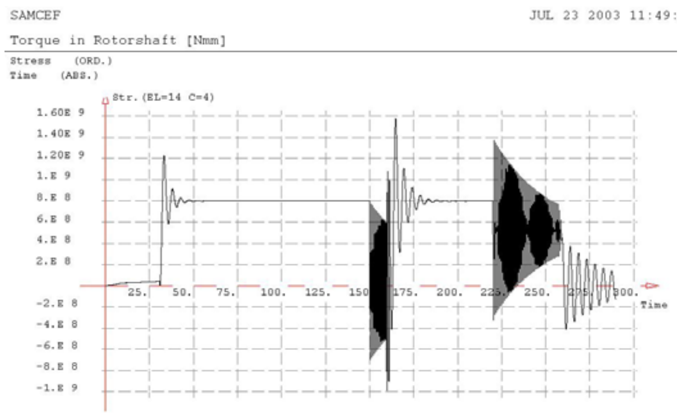

Fig. 3: Torque in rotor shaft [Nmm]

The computed generator torque is depicted in figure 4. It is mentioned that the generator is activated slightly below nominal speed and as a consequence the generator acts for a short instance as motor. Referring to figure 4, this is reflected by the negative sign of the generator torque at time instances 31 [s] and 160 [s] respectively. As can be deduced from figure 4, the connection at the lower nominal speed produces less oscillations compared to the oscillations occurring at the connection at 1500 Rpm. At time 220 [s] the generator is disconnected and the torque drops to zero. It

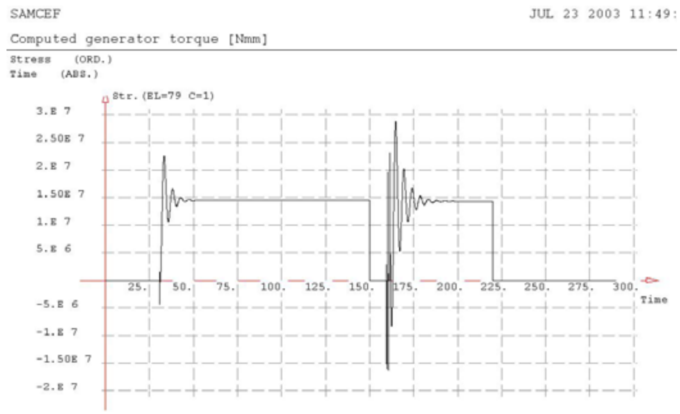

Fig. 4: Generator torque [Nmm] (being an analysis result, but not a boundary condition).

is well known that it is crucial to connect the generator at the right instance. However, the velocity slot where a generator connection can be performed properly is very small and numerical simulation is a perfect tool in order to optimize the generator connection.

Figure 5 shows the gear normal contact force in between the teeth of planet I and the internal gear. As already commented in the former figures, no relevant backlashes occur at the first generator connection, but important backlashes occur during both, generator disconnection and during the second generator connection at 1500 Rpm. The peak "gear tooth contact force" occurs at time instance 164 [s], i.e. during the generator connection and is about 100 % higher than nominal gear contact force. It is emphasized that these peak forces present no extreme event.

Figure 6 illustrates the dynamics of the axial bearing forces of the "planet carrier". The planet carrier is supported by two bearings which work both in radial direction, but each of them incorporates axial stiffness in only one axial direction each. Accordingly the axial load is overtaken always by only one of these two bearings. The red plot of figure 6 shows the axial bearing force in the case of normal operation and the black plot of figure 6 shows the axial bearing force of the opposite bearing which is working in case of load inversion. That load inversion occurs typically during the braking maneuvers, or in case of backlashes.

Figure 7 shows the displacement plots of the "sun gear center" in the plane perpendicular to the rotor shaft, i.e. the X-Y plane. It is mentioned that gravity forces are taken into account and are applied in -Y direction, thus producing initially an offset of the "sun gear center" in -Y direction (see red plot until time=31[s]). Once the power train is under tension, the gear contact forces in between the wheel gear of the sun-shaft and the pinion of the intermediate parallel shaft push the "sun shaft" against gravity in +Y (red curve). The largest offset of the "sun gear center" occurs during the backlashes at time 155 [s] accounting 0.15 [mm] in -Y direction.

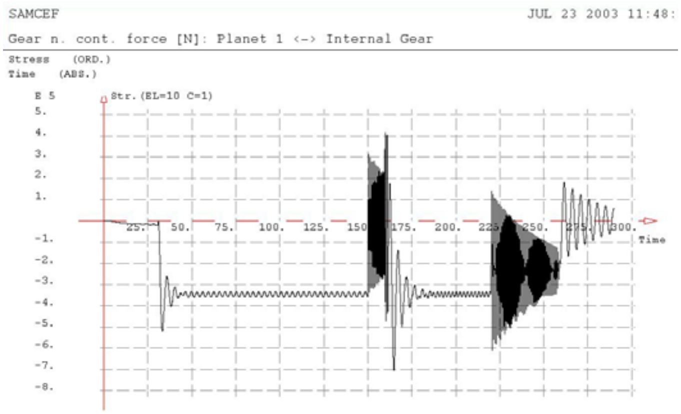

Fig. 5: Gear normal contact forces [N]: Planet I <-> Internal gear

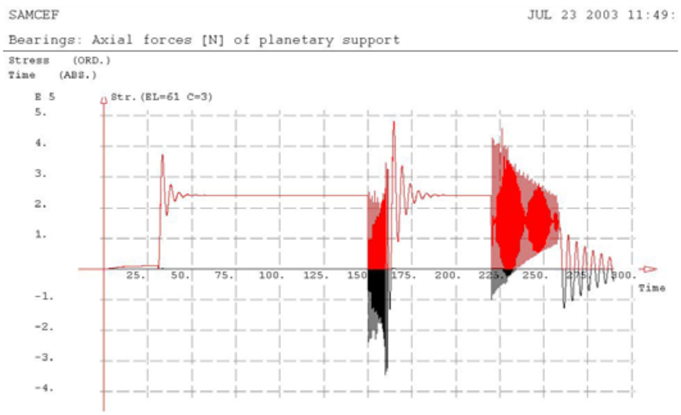

Fig. 6: Axial forces [N] of the two opposite bearings of the "planet carrier".

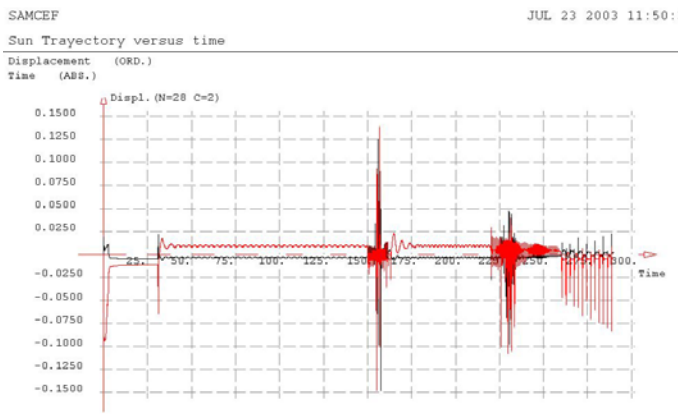

Fig. 7: "Sun Gear" displacements [mm] versus time [s]: X (black curve),Y (red curve)

In order to conclude, it is emphasized that due to dynamic amplification, the presented power train loads can augment to several multiples of the exposed results. The amount of dynamic amplification depends on the choice of crucial design parameters like for example clearances and generator regulation.

5. Future Developments and Investigations

Future investigations will be centred in the experimental validation of the numerical power train models, in the acquisition of better insight with respect to fatigue and extreme loads and finally in the optimisation of design parameters of power trains.

The "Deutsches Windenergie-Institut/DEWI" is working presently on the monitoring of wind parks in order to acquire detailed information about transient loads, especially in the case of "extreme events". A crucial boundary condition of the numerical model presents the "aerodynamic rotor torque". It is reminded that the "aerodynamic rotor torque" does not present "rotor shaft torque". The "rotor shaft torque" depends on the entire power train dynamics and is an analysis result. The "aerodynamic rotor torque" is proportional to the introduced wind power and presents a boundary condition of the numerical simulation. The availability of experimentally measured "aerodynamic rotor torques" and "rotor shaft torques" constitute a very promising data base for advanced numerical power train analysis. In that case experimental data is applied as boundary condition to the numerical model in terms of introduced "aerodynamic rotor torque" and simultaneously experimental data is used for the validation of the numerical model by comparison of numerical and experimental "rotor shaft torques". Reminding that the generator load presents an analysis result, a further validation of the numerical model could be obtained by comparing additionally the numerical and experimental transient load curves of the generator. Concerning the validation process of the numerical models, it is commented that this process had been accomplished successfully for a wind turbine power train using parallel helical gears. In that particular case, the axial oscillations of the gearbox shafts had been measured during backlashes and numerical and experimental results matched very good. In the case of power trains using planetary gears that validation process has not yet been accomplished. However, a very first comparison of experimentally measured data from DEWI to the corresponding numerically computed data, shows encouraging qualitative agreement. Combining the experimental results extracted from the monitoring of wind parks with advanced numerical simulation could provide the insight in order to understand better the failure mechanisms and fatigue behaviour of wind turbine power trains. Anticipating that many power train failures occur after some years of successful operation, the importance of more precise fatigue considerations is obvious. Presently mayor effort is put in the parameterisation of power train models in order to be able to perform sensitivity analysis and in order to optimise the design parameters of mayor importance. Concerning the sensitivity analysis, purpose is to identify the mechanical design parameters, which especially affect the dynamic behaviour. These design parameters might be for example stiffness and damping behaviour of elastic couplings, bearing and gear clearances, or the slip regulation of the generator. To conclude it is anticipated that advanced numerical simulation might become in the imminent future a substantial tool in order to optimise wind turbine power trains.

6. References

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