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Using the Drive Train of an Gearless Wind-Energy-Converter for Active Damping of Oscillations in Rotor Blades

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Abstract— **By the increasing nominal power of wind energy converters, an optimized management, a higher level of efficiency and reduced costs are needed. In search of suitable generator systems and concepts for wind turbines in the MW class, among others, the permanent-magnet synchronous machine as a generator moves to the focus of current discussions. The Rotor and its blades are able to oscillate due to various dynamic loads a wind energy converter is exposed. In wind energy converters in the Multi MW-class the natural frequencies of the blades have the same range as the naturals of the drive train. Thus blades are no longer isolated from the generator and inverter system to consider in terms of their dynamics, but must be embedded in the overall structure of the energy conversion train. This paper deals with the different types of rotor blade oscillations and its influence to the drive train as well as the possibility to influence the oscillations develop and use a new control strategy for the drive train.**

I. INTRODUCTION

The acceptance of wind energy utilization has improved steadily over the past 30 years in relation to the technical, economic and social point of view. Last but not least the catastrophic events in the nuclear power plant in Fukushima, Japan, have led to a final rejection of nuclear energy and led to renewable energy sources like wind or solar energy sources. This trend is accompanied by a continuing high demand for locations for the use of wind energy. Meanwhile, all lucrative locations are occupied, so the yield will be considered by low wind sites, or a "repowering" of areas that were already used. Further potential lies in the use of off-shore locations because there is a direct attempt to install wind farms to several giga watts to decrease the specific costs to a minimum.

The expensive items are the anchorage of the plants in the ocean floor, and the connection to the grid. These are all reasons to install wind energy converter with an output of 5 MW or more. The increase in nominal power of wind turbines and wind farms, the interest in the management increases too. Criterias for the quality of the management are the load on the network by the wind energy converter itself and the power fluctuations caused by a change in wind speed. The last named effect has to be considered especially related to on shore applications. High availability and durability are key economic advantages, especially in case of offshore wind energy converters.

II. SYSTEM REQUIREMENTS AND CONCEPTION

A common requirement for wind energy converter, regardless of the performance category and site of operation is the possibility to achieve maximum power coefficient of the wind rotor to thereby maximize the energy yield. Another requirement is a minimal variation in the power that is released into the gird. A maximum possible energy yield requires an adjustment of the rotational velocity to the instantaneous wind speed. At the same time, a suitably designed power train can be used to smooth out power fluctuations and resulting flicker caused by short term changes in wind speed. A permanent magnet synchronous generator can be considered in spite of rising costs as a suitable basis for a variable-speed wind energy converter due to its low maintenance costs with no slip rings or brushes are available.

A generator system with gearless permanent excitation which is connected to the rotor forms the basis for the investigations.

III. OSCILLATIONS IN WIND ENERGY CONVERTERS

Wind energy converters are exposed to heavy duty dynamic loads. The reasons for this are the aerodynamic forces such as changes in wind speed per se, tower shadow effects, a erratic wind field or cross incoming wind and also unbalances in the power train.

The dynamic excitation can lead to oscillations in the wind energy converters. Other reasons are oscillations due to the control system itself. The reason can be for example poorly tuned time constants.

These oscillations are not wanted and lead to a more complex system caused by necessary installed damping systems and losses in the energy conversion process. They can also cause costly damages to mechanical or electrical components of the hole system.

Today's condition monitoring systems for wind energy converters are able to detect a variety of vibrations in

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wind energy converters and predict potential damages to such an early stage, thus reducing downtime. However, they cannot prevent any damage. These systems use a huge number of sensors installed in the wind energy converter.

So the

There are a huge number of vibration modes in wind energy converters. In addition to torsional vibrations in the drive system, the tower – machine housing system and the rotor blades into pan and lay direction are caused to vibrate. Leaves may be stimulated due pitch or stall regulation or generally interventions to control torsional vibrations.

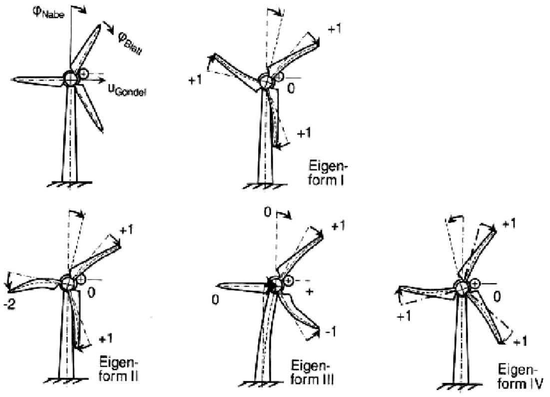

Fig. 1. Eigenmodes of the rotor blade vibrations in turn direction

In Fig.1, the eigenmodes of the blade vibrations are shown in the turn direction. The forces and moments are discharged into the hub. The eigenmodes I and IV have a resultant torque, which is discharged into the drivetrain. These vibrations can cause not only damage and excessive wear on the equipment like the blades, the hub or the gearbox, but also lead to loss of energy yield, caused by a not optimal power coefficient. It is therefore an objective to damp these vibrations actively.

Today's solutions against vibrations in wind turbines are usually based on external absorber systems, which transform the vibrations in thermal energy. So the losses increase and for example the cooling system is more expensive.

IV. STUDIES

The aim of the studies is to identify solutions to the problems that were outlined and to develop the basis for a cost-effective solution strategy. The focus of the studies is on the dynamic performance of the mechanical drive train parts including the damping capacity and the utilization factor and the coupling of the inverter.

A. Analytical Investigations

The models for the investigation of the blade vibrations are based on a power train model based on a multi-body system with axial rotational freedom degrees. As can be seen in the context of this manuscript, only the eigenmodes I and IV, in which the leaves are deflected each in the same direction relative to the blade axis, a three-mass system is used as a basis.

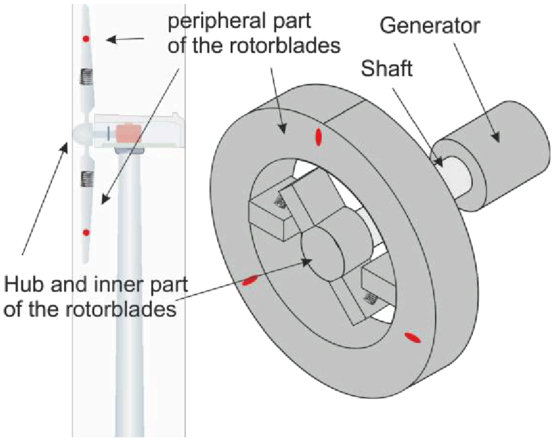

Fig 2. Representation of the model parts

One mass is represents the mechanical part of the generator, one the hub and the inner part of the rotor, and one mass represents the leaf tips.

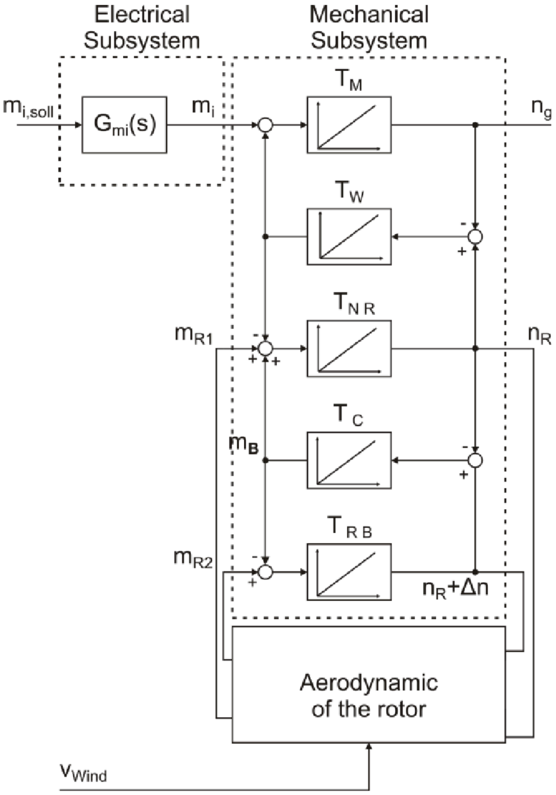

Fig. 3. Simplified, mathematical model of an mechanic-electrical drive train.

In Fig. 3 the used mathematical model is presented.
From the simplified mathematical model of the transfer function can be derived. After a Laplace transformation and normalization can be derived following transfer function:

$$
\begin{aligned}
m_B(s) = &-\frac{\frac{1}{v_2+1}\cdot\frac{1}{s^2T_{ef1}^2+1}}{1+\frac{1}{v_2+1}\cdot\frac{v_1}{v_1+1}\cdot\frac{1}{s^2T_{ef2}^2+1}\cdot\frac{1}{s^2T_{ef1}^2+1}}\cdot m_i(s) \\
&+\frac{\frac{1}{v_2+1}\cdot\frac{1}{s^2T_{ef2}^2+1}-\frac{v_1}{v_1+1}\cdot\frac{1}{s^2T_{ef1}^2+1}}{1+\frac{1}{v_2+1}\cdot\frac{v_1}{v_1+1}\cdot\frac{1}{s^2T_{ef2}^2+1}\cdot\frac{1}{s^2T_{ef1}^2+1}}\cdot m_{R1}(s) \\
&+\frac{\frac{v_2}{v_2+1}\cdot\frac{1}{s^2T_{ef2}^2+1}}{1+\frac{1}{v_2+1}\cdot\frac{v_1}{v_1+1}\cdot\frac{1}{s^2T_{ef2}^2+1}\cdot\frac{1}{s^2T_{ef1}^2+1}}\cdot m_{R2}(s)
\end{aligned}
\qquad (1)
$$

with

$$T_{ef1}=\sqrt{\frac{T_W T_M}{1+v_1}},\quad v_1=\frac{J_M}{J_{NR}}=\frac{T_M}{T_{NR}} \qquad (2)$$

and

$$T_{ef2}=\sqrt{\frac{T_{NR} T_C}{1+v_2}},\quad v_1=\frac{J_{NR}}{J_{RB}}=\frac{T_{NR}}{T_{RB}} \qquad (3)$$

Input variables are m_i the air gap torque, load torque, the mechanical parameters (inertia, spring and damping constants) are taken into account by the time constants shown in Table I.

TABLE I. LIST OF ABBREVIATIONS

Symbol	Quantity
T_M	Time constant generator
T_W	Spring time constant generator – hub
T_{NR}	Time constant hub and inner part of the rotor
T_C	Spring time constant rotor blades
T_{RB}	Time constant external part of the rotor
v_1	Ratio of the mass inertia (generator, hub and inner part of the rotor)
v_2	Ratio of the mass inertia (hub and inner part of the rotor, external part of the rotor)

The transfer function (1) shows a direct correlation between the generator of the applied torque and the torque, which causes a bending of the blades in the turning direction. The preliminary factor of the generator air gap torque is enhanced by the mechanical parameters of the system. It shows the dependencies and restrictions of the generator torque and the blade vibrations. In function (4) is shown the relation between the blade bending and the generator torque after applying the central limiting value theorem.

$$
\begin{aligned}
&\lim_{s\to 0} s\cdot m_B(s) = \\
&-\lim_{s\to 0} s\frac{\frac{1}{v_2+1}\cdot\frac{1}{s^2T_{ef1}^2+1}}{1+\frac{1}{v_2+1}\cdot\frac{v_1}{v_1+1}\cdot\frac{1}{s^2T_{ef2}^2+1}\cdot\frac{1}{s^2T_{ef1}^2+1}}\cdot m_i(s) \\
&m_{B,end} = -\frac{\frac{1}{v_2+1}}{1+\frac{1}{v_2+1}\cdot\frac{v_1}{v_1+1}}\cdot m_{i,end} \\
&= -\frac{1}{v_2+1+\frac{v_1}{v_1+1}}\cdot m_{i,end}
\end{aligned}
\qquad (4)
$$

The function indicates the possible access to damp oscillations using the torque of the generator. If the ratio is inconvenient, it is needed to increase the nominal power of the inverter to procure the demanded torque.
By considering function (4), the main factor is v_2, the relation between the mass inertia of the inner part of the rotor in relation to the mass inertia of the external part of the rotor. So a guideline for a favorable mass allocation ist presented.

The success therefore has also a financial component. If there is a well constellation in the mechanical system and the oscillations are not too heavy, there is perhaps no need for a cost intensive upgrade of the inverter. On the other side there are the damages caused by the oscillations and the cost intensive downtime especially in case of off-shore systems. This is also a central aspect of the further studies of this work.

B. Simulation studies

For the simulation experiments, the parameters of a 5 MW wind energy converter have been used. The simulation studies were carried out with different control strategies differently parameterized and different levels of nominal current.
The parameterization of the system was changed to examine which system parameters abet or interfere an active damping. The goal is to achieve within realistic system parameters and with limited actuating variable and sensor useage a significant improvement in the damping characteristics of the powertrain.

To excite vibrations in the drive system, the wind turbine was for example stimulated using a slack (10 m/s - 8 m/s - 10 m/s within a 20 s interval) (Fig. 3, upper panel).

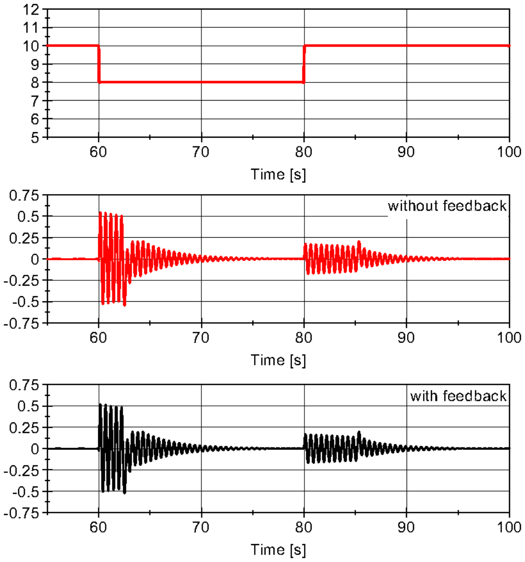

Fig. 3. Extract of the studies

Figure 3 shows an extract of the simulation studies.

In the upper diagram, the excitation (slack) is shown, including a profile of the oscillation of the rotor blades tips of the axis in the turn direction. In the lower diagram a control method was used, which contains a feedback of the instantaneous rotational speed difference between blade tip speed and hub speed and the speed control is superimposed.

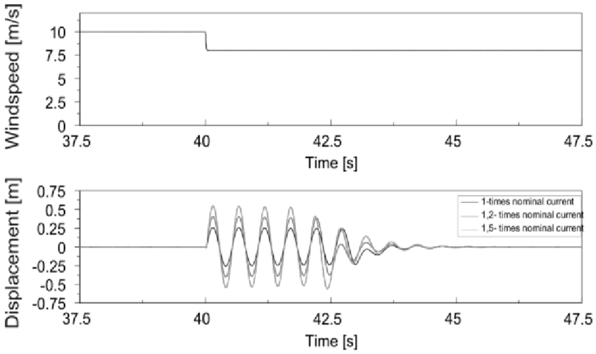

Fig. 4 Amplitude of the oscillation in dependency on the nominal current

Using the feedback causes a significant improvement in the damping behavior. The actuating variable reserve was not increased, to show only the effect of the control method.

In Fig. 4 the dependency of the oscillations amplitude is shown in dependency on the nominal current of the inverter. As shown, increasing the nominal current in combination to a useful control method is an effective way to damp rotor blade oscillations in wind energy converters.

TABLE II. LIST OF ABBREVIATIONS

	Maximum Displacement [m]	Regulation time [s] (Displacement < 0,01 m)
nominal current	0.55	44.9
1.2 nominal current	0.40	44.7
1.5 nominal current	0.26	44.7

The modeling of the rotor blade is kept relatively simple. By using a more accurate model, it is assumed to use an observer-based control strategy. Table II shows the results of increasing the manipulated variable reserve. The improvement is significant but only within the maximum displacement and not the regulation time.

V. CONCLUSIONS

The investigations show that the active damping of blade vibrations by using the drive train is possible. The analytical considerations indicate some requirements on the drive train configuration, to realize an active damping of rotor blade oscillations It also be improved by increasing the reserve of the actuating variable.

The adjustment of the controller and the arrangement of the inertia in the drive system are essential. An increase of the actuating variable also leads to a more effective active damping of drive system oscillations.

Further investigations in the abilities of observer based control strategies make sense because of cost reduction by reducing sensors. An decoupling of the blades with each other will be part of the improvement of the model.

Also an integration of a cost model is useful to find the most cost effective combination of the mechanical and the electrical system.

The future investigations will include more control methods for active damping, a financial model and the grid connection or a possible DC coupling to a whole wind park to check the interactions of several wind energy converters.

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