Observer structures in advanced power electronics for load analysis and power control

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Abstract

Observer structures are used to extract state information on the wind turbine usually not or only difficult to access, in any case, without installation of additional costly measuring devices. We focus on the torsional moment of the drive train. Depending on details of the observer model, it could be utilized to analyze loads in the different stages of the drive train. The same information could also be used for active drive train damping by feeding the observer signal into the generator torque demand. Proper software has been developed and a prototype of this observer has been implemented into the inverter controller of a turbine model. It has been tested in a small scale test stand of the ILAB at the Bremen University and also in an aeroelastic numerical simulation environment sufficient for load analysis of a generic 2 MW wind energy converter with a Kaimal wind field of different turbulence classes. We investigate different level of detailing, i.e. observer based on one-, two-, and three-body models. We find that already a one-body observer model gives plausible results. The one-body model is already capable for use as power/torque control with a desired feature of drive train damping. A modified two-body observer will be able to predict damage equivalent loads quantitatively. These load equivalents can be considered a quantity relevant for the life time of the component.

1. Introduction

Wind Energy Converters (WEC) are among those technical structures with highest number ($>10^9$) and at the same time high level of load cycles. Due to increasing power performance, in particular during recent years, wind energy converters (WEC) are reaching design data, in which mechanical stress within system components are no longer compatible with conventional stationary industrial plants. Typical challenges are frequent occurrence of high peak loading, influence of load-cycle changes in the drive train, high amount of partial loading, and aeroelastic oscillations of the rotor blades transmitted to the drive train. In particular the drive train suffers from high dynamical loads, since it comprises the direct connection between rotor (convertor of wind energy to rotational energy) and the generator including power electronics (convertor of rotational energy to electrical energy). As a

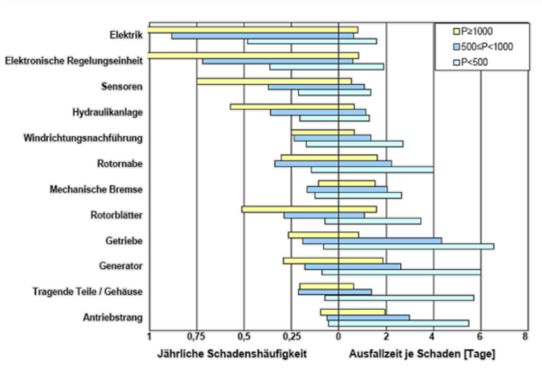

Figure 1: Downtimes and damage frequency for different components of a WTG from [2]

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consequence, e.g., the gear box suffers from high load and possible damage [1]. Failure leads to unwanted costs and downtimes [2], see Figure 1.

Monitoring of loads during operation that could give hints on the remaining fatigue life is not part of a standard operational or monitoring system. In addition, these dynamical loads are rather complex to be measured during normal operation routine. Alternatively an observer has been developed that allows one to detect these loads utilizing a simplified model of the real turbine and standard sensors available in the control system of the wind turbine and/or power electronics. To prevent drifting of the observer model a simple control feature has been added to reduce the error between reconstructed and measured input signal, in this case generator speed.

The observed torsional load has been analyzed by standard rain flow counting so that site specific fatigue damage can be accumulated. This fatigue analysis can be compared to the design loads. Another possibility is to use the observed torsional load as an active drive train damping. The observed torque is used as a control variable, i.e., the torque demand is corrected by the measured torque signal. The model has been demonstrated on the test stand of the IALB at the University of Bremen and in a standard WEC simulation environment at the Windrad Engineering GmbH.

2. Observer Structure

An observer structure is used, if the quantity of interest is not directly accessible or too expensive to be measured. We focus on the drive train of the WEC. The task to determine the torsional load in the drive train is utilizing an observer. The principle of an observer is shown in Figure 2.

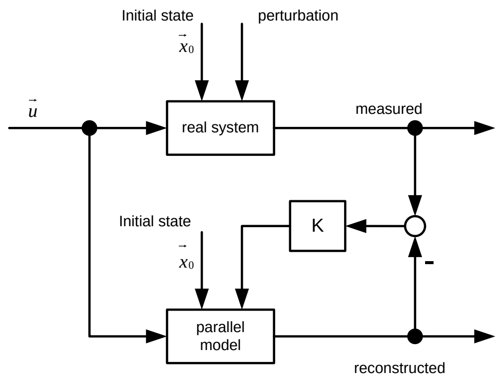

Figure 2: Principle of a simplified observer

A simplified observer structure consists of the following elements.

1. Real system
2. Parallel model
3. Measuring devices for feed back

The real system is the complete wind turbine with turbine control and all external (unknown) perturbations of the state of the WEC. In this study the real system was replaced either by a test stand or an aeroelastic simulation code. The parallel model is a model of the real system, in this case the drive train of a WEC, which is calculated in real time parallel to the drive train. This model consists of multi-body elements of the drive train that is solved in the rotational degree of freedom. The number of bodies depends on the desired degree of resolution. E.g., modelling of a gear box requires more information than modelling of a direct drive. This model is subject to the same input as the real system, so if the model is accurate, the initial states are the same and if no perturbation would be present, all the intrinsic states of the drive train could be calculated via the model. Unfortunately this is not the case, as unknown, uncontrolled influences exist. Also the initial conditions are not known to the required degree. This leads to an estimation error of the model, which means that the state of the parallel model might drift away from that of the real system. In order to remedy this, estimated values of those states that can be measured are subtracted from measured values and this estimation error is fed back via a correctional vector into the model. So drifting of the observer is prevented by feeding proper state signals of the real system such as, e.g., measured generator speed, to the observer. By selecting a suitable correctional vector the estimation error is minimized. This is illustrated in Figure 2.

A simple but already effective way to estimate the shaft torque is a reduced disturbance observer based on a one-body system. Such an observer is a regular state observer, but has only one state and is therefore easy to implement. First, a general one-body system is considered, where the input is the generator torque m_{Gen}. The resistance torque m_T is acting against the generator torque. Friction, stiffness, damping and backlash are neglected in this observer design. The torque m_T is subtracted from m_{Gen} and the difference is integrated and divided by the moment of inertia Θ. The result is the generator speed of the generator ω_{Gen}. The parallel model is a simple 1-dim equation

$$m_T - m_{\mathrm{Gen}} = \Theta\, \dot{\omega}_{\mathrm{Gen}} \tag{1}$$

The block structure is shown in Figure 3.

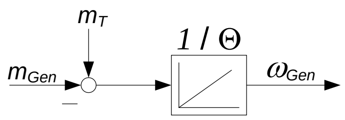

Figure 3: Structure of a one body system

Based on the dynamical equation of a one-body system (1), where the shaft torque is considered a disturbance, it is assumed, that the shaft torque is piecewise constant, i.e. $\dot{m}_T = 0$. So the state space equation of the one-body system with disturbance is:

$$\begin{bmatrix}\dot{\omega}\\ \dot{m}_T\end{bmatrix} = \begin{bmatrix}0 & \frac{-1}{\Theta}\\ 0 & 0\end{bmatrix}\begin{bmatrix}\omega\\ m_T\end{bmatrix} + \begin{bmatrix}\frac{1}{\Theta}\\ 0\end{bmatrix} m_{Gen} \tag{2}$$

For this system a reduced disturbance observer is designed (cf. [4]):

$$\frac{\Theta}{K}\dot{z} = m_{Gen} - \frac{K}{\Theta}\left(\frac{\Theta}{K}z - \Theta\omega\right) \tag{3}$$

$$\hat{m}_T = \frac{K}{\Theta}\left(\frac{\Theta}{K}z - \Theta\omega\right) \tag{4}$$

The block diagram of the corresponding observer is given in Figure 4.

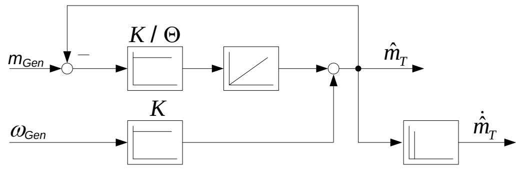

Figure 4: Observer of a one body system

This observer is quite simple, easy to implement, however, already powerful.

A simple two-body model is given in Figure 5.

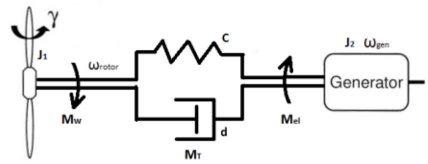

Figure 5: Two-body model of the WEC drive train. Only rotational DOFs are considered.

The torque m_{wind} produced by the wind forces on the rotor acts against the torque m_T produced by the torsion of the shaft. The difference is divided by the moment of inertia Θ_1 of the rotor side and integrated, resulting in the speed ω_1 and, via second integration, the position ε_1 of the rotor side. By subtracting from the latter the position of the generator side ε_2 one gets the torsion angle of the shaft. Multiplication with the effective elasticity C_F of the (effective) shaft yields the shaft torsion torque m_T, which acts in part against the generator torque m_{gen}. The remaining part is divided by the moment of inertia Θ_2 of the generator rotor and integrated to yield the speed ω_2 and the position ε_2 of the generator. This is depicted in Figure 6.

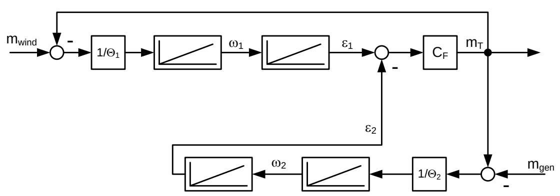

Figure 6: Two body model

The shaft torque and its first and second derivative can be written as:

$$
\begin{aligned}
m_T &= C_F \cdot (\varepsilon_1 - \varepsilon_2) \\
\dot{m}_T &= C_F \cdot (\dot{\varepsilon}_1 - \dot{\varepsilon}_2) \\
\dot{m}_T &= C_F \cdot (\omega_1 - \omega_2) \\
\ddot{m}_T &= C_F \cdot (\dot{\omega}_1 - \dot{\omega}_2)
\end{aligned} \tag{5}
$$

It is assumed, that the speed and position at the generator side can be measured.

The method presented in this paper therefore is, to estimate the position ε_1 and speed ω_1 of the rotor side, and calculate the torque via the equations given in (5). The observer is designed as a reduced observer for the system represented in Figure 3.

3. Implementation

Being a software module the observer can be embedded in the control system of the turbine. The software is fast enough to run in real time parallel to the real drive train of the turbine. It measures the torsional load on the drive train (or parts of it) depending on the specific wind conditions of the turbine site. In order to have the necessary accuracy this particular observer is embedded in the controller of the power electronics control that is operating in the kHz regime. This way, depending on the number of bodies to model the drive train, frequencies up to 1 kHz can be resolved if necessary. Presently, we investigate a one-body system several two-body systems and a three-body system.

4. IALB Test Facility

In the machine laboratory at IALB of the University of Bremen a test stand was set up in order to test new control concepts for wind energy converters. The test stand emulates the behavior of a WEC. An induction motor driven by a frequency converter provides the torque and simulates the wind driven rotor blades. The mechanical to electrical energy transformation is done by a doubly fed induction generator. Additionally the drive train comprises a single-stage spur gear box.

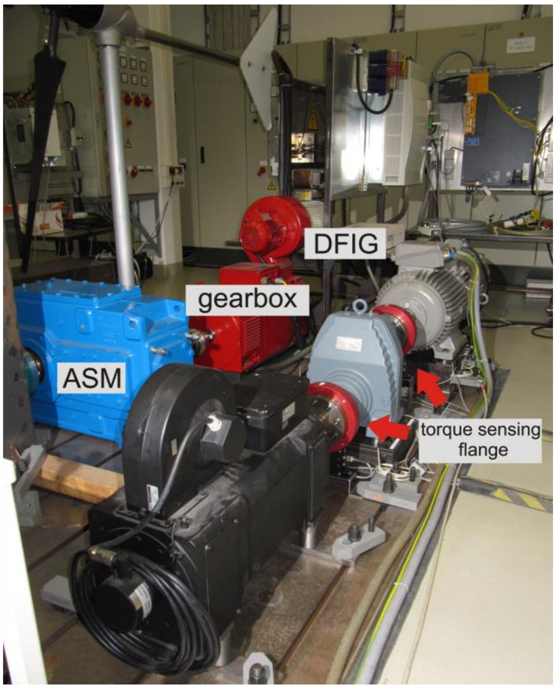

Figure 7: Test stand at IALB University of Bremen

Figure 7 shows the test stand and gives an overview on its components.

As a part of this project an energy recovery capable frequency converter was developed at IALB and set up at the test stand. The used power semiconductor modules are controlled by a Texas Instruments digital signal processor TMS320F28335. This DSP features free programmability and is an important prerequisite for the use of the frequency converter in implementing and testing new control concepts and even the observer structures at the test stand. In order to evaluate observer and control concepts the test stand is fitted with additional sensory equipment, so that dynamical loads can be measured under operating conditions. For example both sides of the gearbox are fitted with a torque sensing flange.

After successful simulations were made, the observer for a one-mass-system was implemented at the test stand in order to proof the functionality of the structure in a typical application. The estimated values are accessible through analog / digital converters controlled by the DSP and can be directly compared to the measured values provided by the torque sensing flange. Figure 8 illustrates the relative change of the observed (blue) and measured (green) shaft torque during an acceleration of the drive side from 200 rpm to about 450 rpm.

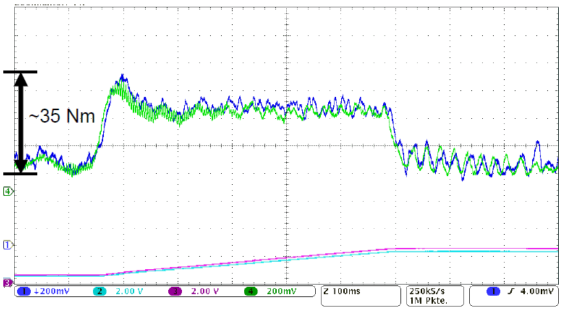

Figure 8: Measured (green) and estimated (blue) load side torque

A very good agreement between the measured and the estimated torque at the generator side of the gear has been fund. So the observer shows reasonable results with minimal implementation effort. The estimated torque is of such a quality, that it can be used for further load calculations concerning the drive train.

This simple one body observer is already capable of damping of the drive train. In this case the observed signal is used as torque demand for the generator invertor system. In order to compare both control concepts again the drive speed has been increased from about 100 rpm to 500 rpm within ½ s. The measured torque of the drive is shown in Figure 9.

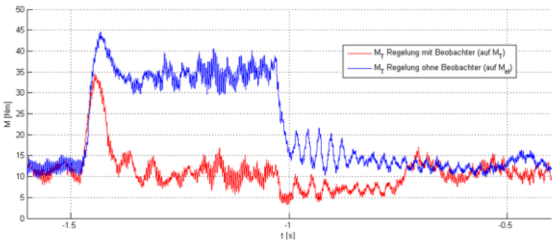

Figure 9: Torsional load on drive train (measured) using normal control (blue) and via observer (red).

It is clearly seen that the control strategy utilizing the observer signal is already reducing the peak loads.

5. Aeroelastic modelling

The aeroelastic simulation is done numerically by calculating the aerodynamic forces on the rotor and the remaining parts of the turbine, and from that deriving the response of the wind turbine structure in a consistent way. To this end a generic 2 MW turbine with a generic controller has been modelled. The numerical solution is based on modal analysis. Standard Kaimal turbulent wind fields common for certification have been used. Also, all turbulence classes and all standard wind speed classes have been investigated. The results of such an aeroelastic simulation are time dependent loads (time series) on the structure of the turbine at particular places usually denoted as sensors. One of these virtual sensors is the torsional load along the drive train, which we denote as MZR. For the time being we investigate regular power production only, since other load cases are rather turbine specific.

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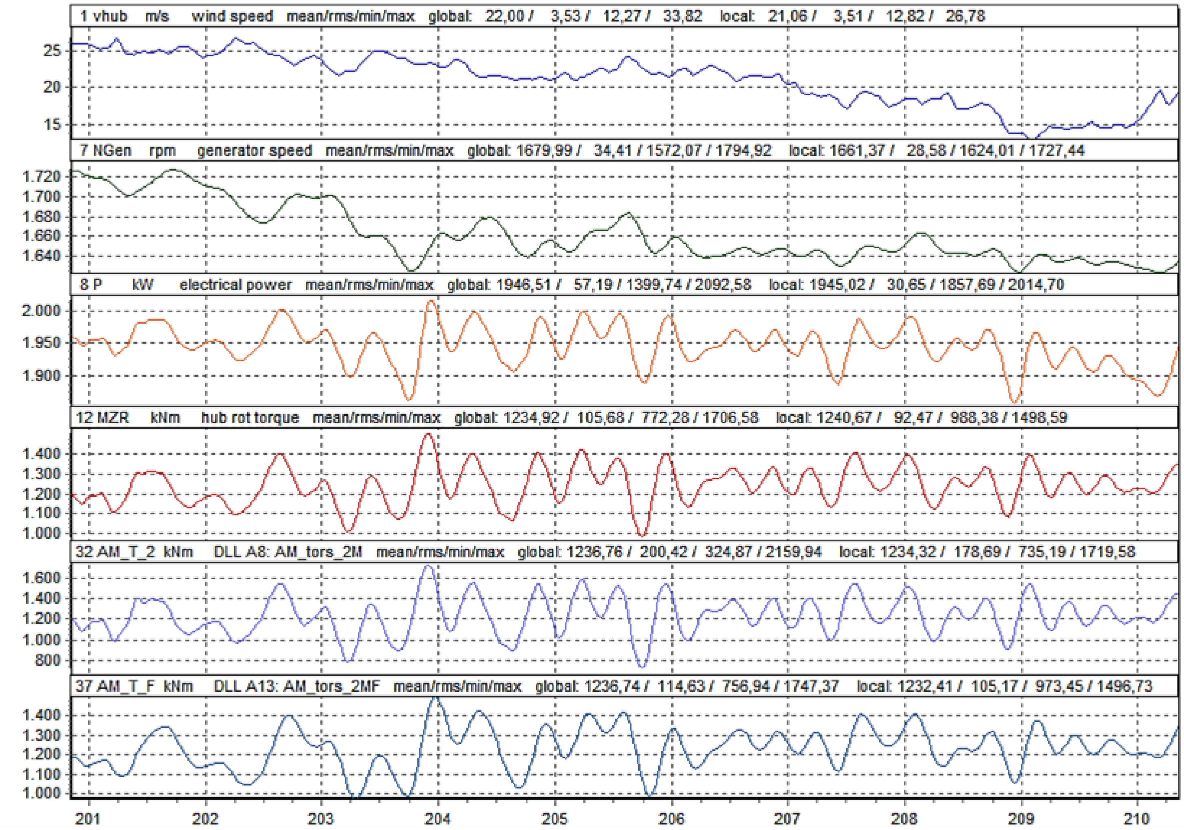

Figure 10: Detail of time series of the virtual turbine (abscissa time in s). Top to bottom: wind speed at hub height, generator speed, electrical power, torsional load, the next two panel are results of the observer giving the torque of the two body observer and the modified two body observer.

As an example Figure 10 shows a detail of a typical time series (time in s) for 22 m/s average wind speed (at hub height). The upper four panels reflect sensors of the full turbine model representing the “real turbine” in the sense of Figure 2. The lower two panels represent the results of the observer using the simplified parallel model. The respective torsional load is given in the lowest three panels. The full model result is denoted MZRef to be compared to the “naïve” two-body observer and the modified two-body observer (MZ2MF) of the lowest two panels, resp. On first sight they look rather similar. However, a closer look reveals that the “naïve” two body observer overestimates the load cycles. The reason are drive train oscillations that are feed into the observer via the controller term (K in Figure 2). This feed back enhances the oscillations of the two-body observer model via resonance effects and hence leads to larger load cycles. These effects could be cured by a slight time off-set or/and proper filter in the signal.

By means of statistical analyses one determines the fatigue loads emerging from the times series of the sensors. A standard procedure is rain flow counting (RFC). Assuming a mean yearly wind speed of 8 m/s (class II) the one-year load spectrum from production is shown in Figure 11. The blue and red line representing the full model and modified observer model coincide. The green line represents the naïve observer that does not match the full model result.

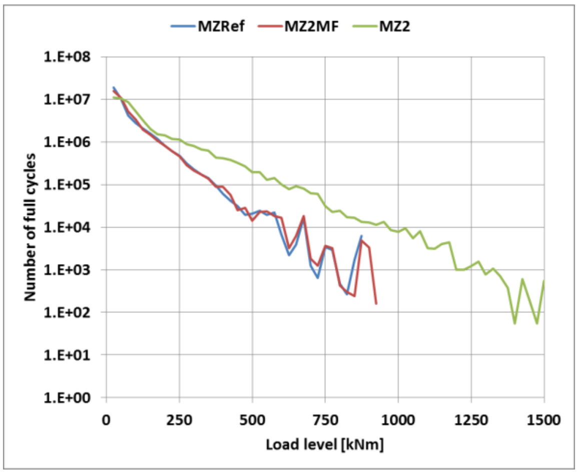

Figure 11: Load spectrum for full model (blue), naïve Observer (green), and modified observer (red) from RFC

Besides the load spectrum the damage equivalent loads (DEL) have been analyzed for each wind bin of 2 m/s width. The result is shown in Figure 12. Again the standard 2-body observer does not reproduce the full model, in particular for higher wind speeds. As already explained, the reason is a resonance feed back from the K-Term. This phenomenon is not seen at small wind speed.

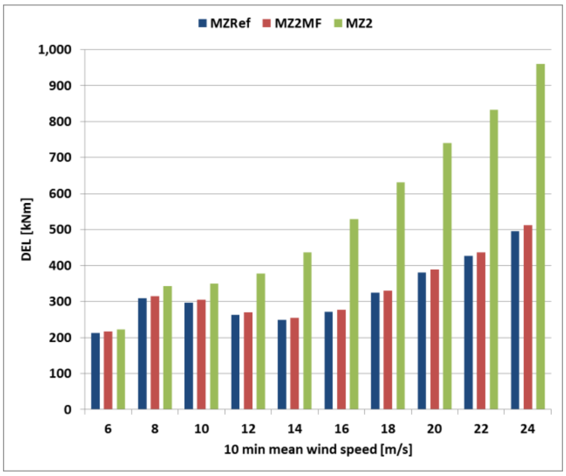

Figure 12: Damage equivalent loads: full model (blue), naïve 2-body observer (green), modified 2-body observer (red) for 10 min time. Fixed S/N slope (Wühler slope) m=5.

However, the modified 2-body observer reproduces the bin-wise damages sufficiently well. Note that this analysis is bin wise for the wind speeds and does not include any effects of wind speed distributions, e.g., Weibull distribution. The load duration distribution (LDD) widely used, e.g., in the context of gear box design for one year and mean yearly wind speed of 8 m/s is shown in Figure 13.

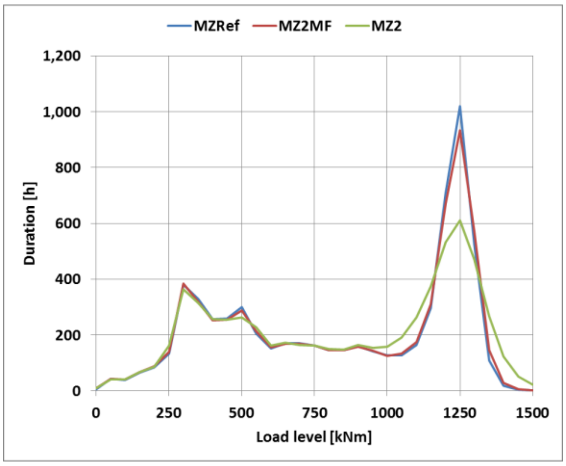

Figure 13: Load duration distribution for one year and average wind speed of 8 m/s.

Also this quantity shows quite a good agreement between the full model and the modified observer. The standard observer shows a mismatch. In particular around rated torque (maximum) the deviation is quite large, whereas partial loads are reproduced quite nicely. Finally, we present the damage equivalent loads accumulated for on year for the various S/N slopes (Wöhler coefficients) m.

Table 1: Damage equivalent loads for torsional load on drive train for various models. M denoted Wöhler slope, number of load cycles normalized to 1Hz, extrapolation to one year.

m	Full Model	Modified Observer	Standard Observer
	kNm	kNm	kNm
3	180	183	316
4	229	234	370
5	283	290	426
6	338	345	481
7	388	397	536
8	434	443	589
9	476	485	642
10	513	523	693
11	547	558	744
12	577	589	794
Mean	854	855	855

The modified two-body observer represents the full model results. However, the standard observer overestimates damage.

6. Summary and Conclusion

We have shown that a rather simplified model of the drive train of the wind energy converter implemented in the power electronics control opens the possibility to extract various loads relevant for fatigue damage of the components of the drive train. The statistical evaluation (i.e. rain flow counts) and analysis could be done on a regular basis in order to provide an early detection, e.g., of unwanted damage by comparing the actual fatigue damage evaluated by the observer system on site with the design damage accumulated up to the present turbine age. We have shown that a suitably modified observer structure is capable to serve this task. We have implemented it on a small scale test stand (demonstrator). In addition, the special stochastic challenges of the wind have been tested with a proper numerical simulation of a complete generic turbine model of the 2 MW class.

Besides using the observer model for condition monitoring it is also possible to utilize the observer data for active drive train damping. This has been tested on the test stand and in a simpler variant is used in turbine control. More sophisticated damping algorithms based on multi-body observers could be developed. A custom tailored commercial version of the observer could be developed by Windrad Engineering GmbH.

7. Acknowledgements

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