WIND ENERGY CONVERTERS WITH ADVANCED POWER ELECTRONICS FOR LOAD ANALYSIS[1]

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Summary

This paper presents an observer structure which allows extraction of torsional loads on the drive train without additional measuring devices. This observer has been installed in the inverter controller of a turbine model. The software has been tested on a small scale test site at the University of Bremen. The response to wind fluctuations has been investigated by utilizing an aeroelastic numerical simulation of a typical 2 MW wind energy converter with a Kaimal wind field of different turbulence classes. This work was supported by BMBF.

1. Introduction

Loads on wind energy converters (WEC) not only consist of static but in particular of periodic and stochastic loads. Hence WECs belong to technical structures with highest number of load cycles and, also typically, frequent occurrence of high peak loading.

2. Drive train damage

As a consequence, e.g. the gear box, suffers from high load and possibly damage. Failure leads to unwanted costs and downtimes, classified e.g. in Ref. [1]. It has also been shown that the gear box contributes to about 5% of the total downtime [2]. Trivially, the reason for damage could be either due to wrong load assumptions or wrong design.

Unfortunately, monitoring of loads that could give hints on the remaining fatigue life is not part of a standard operational or monitoring system. They are usually part of a measurement campaign during the prototype phase.

3. Observer

In principle an observer 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 is fed with the same input as the real system, so if the model is accurate, the initial states are the same and if no perturbation is present, all the intrinsic states of the drive train can be calculated via the model. Unfortunately this is not the case, as unknown, uncontrolled influences, i.e. perturbations exist. Also the initial conditions are not known to the required degree.
This leads to an estimation error of the model. 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. By selecting a suitable correctional vector the estimation error is minimized. This is shown in Fig. 1.

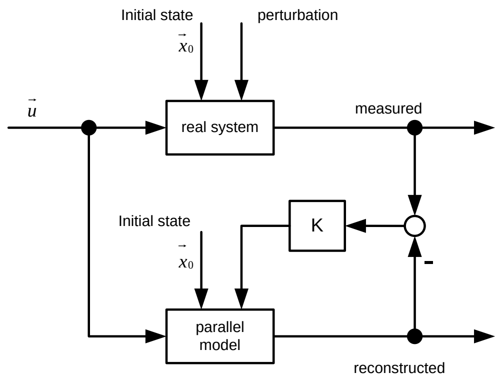

Fig. 1: Principle of an observer.

The observers of the drive train investigated in the aeroelastic numerical simulation of this paper are

- One mass system
- Variants of the two mass system
- Three mass system

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 elasticity C_F of the 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 Fig. 2.

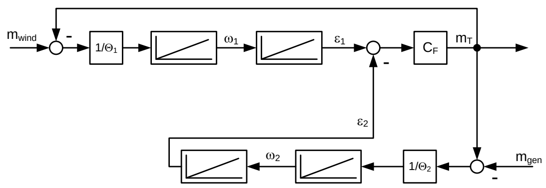

Fig. 2: Two-mass-model

[1] Based on talk presented at DEWEK 2012

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

$$
\begin{aligned}
m_T &= C_F \cdot (\varepsilon_1 - \varepsilon_2) \\
\dot{m}_T &= C_F \cdot (\dot{\varepsilon}_1 - \dot{\varepsilon}_2) \\
\dot{m}_T &= C_F \cdot (\omega_1 - \omega_2) \\
\ddot{m}_T &= C_F \cdot (\dot{\omega}_1 - \dot{\omega}_2)
\end{aligned}
\qquad (1)
$$

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 Eq. (1). The observer is designed as a reduced observer for the system represented in Fig 3.

An even simpler but still effective way to estimate the shaft torque is a reduced disturbance observer based on a one-mass-system. Such an observer is a regular state observer, but has only one state and is therefore very easy to implement.
First, a general one-mass-system is considered, where the input is the generator torque m_{Gen}. Acting against this is the resistance torque m_T. 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 devided by the moment of inertia Θ. The result is the speed of the generator ω_{Gen}. The structure is shown in Fig 3:

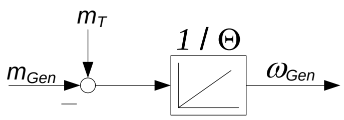

Fig 3: Structure of one-mass-system.

Based on the dynamical equation of a one-mass–system, $m_{Gen} = m_T + \Theta\dot{\omega}$, where the shaft torque is considered a disturbance, it is assumed, that the shaft torque is piecewise constant ($\dot{m}_T = 0$). So the state space equation of the one-mass-system with disturbance is:

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

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

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

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

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

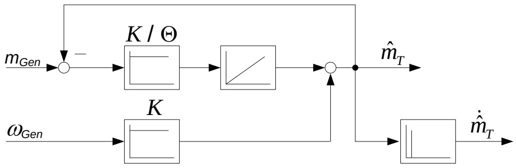

Fig. 4: Observer of one-mass-system.

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

4. Test stand

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. Fig. 5 shows the test stand and gives an overview over 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 proposed 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

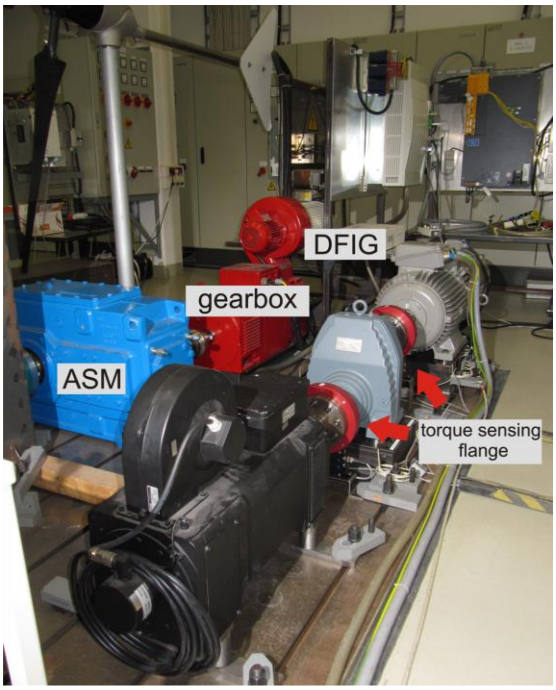

Fig. 5 Setup of the wind energy test stand.

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. Fig. 6 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 (red). There is a very good agreement

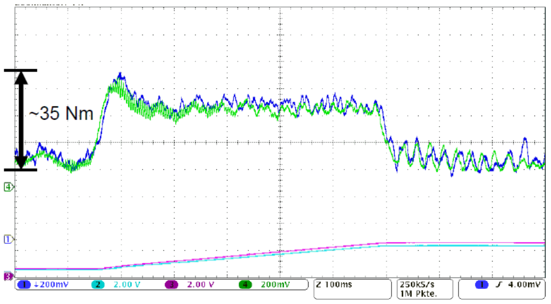

Fig. 6 Measured and estimated load side torque.

between the measured and the estimated torque at the generator side of the gear. 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.

5. Aeroelastic simulation

The aeroelastic simulation is done with a code that simulates the aerodynamic forces on the rotor and the remaining parts of the turbine, and from that derives the response of the wind turbine structure in a self-consistent way. To this end a typical 2 MW turbine has been implemented. The solution is based on modal analysis. For the simulation 26 degrees of freedom have been enabled. Standard Kaimal turbulent wind fields common for certification have been utilized. Also, all turbulence classes and all standard wind speed classes have been investigated.
Besides the observer that has been installed on the test stand of the IALB mentioned in the previous sections, further observers have been investigated in the aeroelastic simulation. Based on the two mass system these models have implemented effects of the aerodynamic damping and filters in the measurement signal. In addition, a three mass observer has been developed with the rotor consisting of two masses to account for additional dynamical effects related to drive train frequency shift.

5. Results

The mean values of different observers ($MZ_{\#M}$, i.e 1-mass, 2-, and 3-masses) compared to the reference value (MZ_{Ref}) is shown in Fig. 7. It is obvious that the observers are reproducing the mean values of

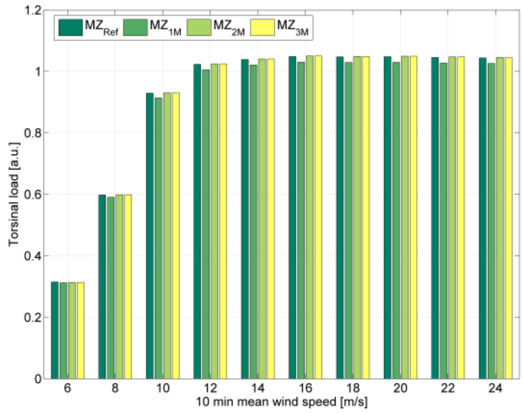

Fig. 7: 10 min mean values of estimated torque.

torsional loads quite well. A slight underestimation of the 1-mass observer is also seen.
A closer look can be achieved by following the time series and here strong differences are seen in the region above rated wind. The load cycle widths are larger for the "naïve" observer as compared to a modified observer. The origin of this is related to the drive train oscillations that influence the estimation error and excite the observer via the control element

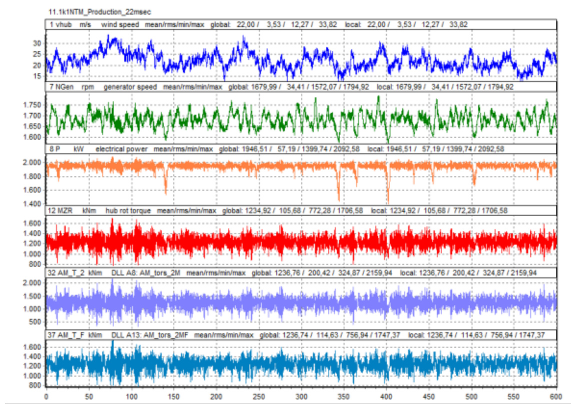

Fig. 8: Time series of wind speed, generator speed, power, MZ_{Ref}, and MZ_{2M}, MZ_{2MF} (top to bottom).

K of Fig. 2. This can be cured by introducing a filter. A typical result is given in Fig. 8 and a close up in Fig. 9, where the torque of the naïve two mass

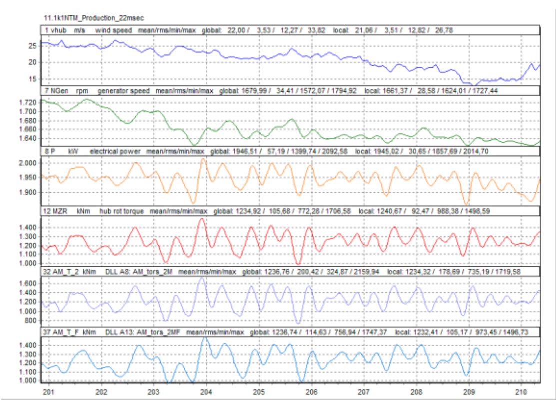

Fig. 9: Zoom of time series of Fig. 8.

observer (MZ_{2B}) and the modified two mass observer (MZ_{2BF}) is compared to the reference torsional load of the full model along with some external variables used in the simulation. Although a point to point time correlation between the reference load and the observed load cannot be achieved due to the excitations mentioned before the time series of the observers still allow one to utilize statistical analyses of the loads with a rather small time delay.

In the present simulation model the analysis has been done off-line, i.e. after performance of the simulation. The statistical analysis utilized here is the rain flow count. This is a standard procedure to determine load spectra and damage equivalent loads, also in the context of certification. To be specific the damage equivalent loads shown in the following have been calculated for turbulence class A and two different mean wind speeds used in a Rayleigh wind speed distribution.

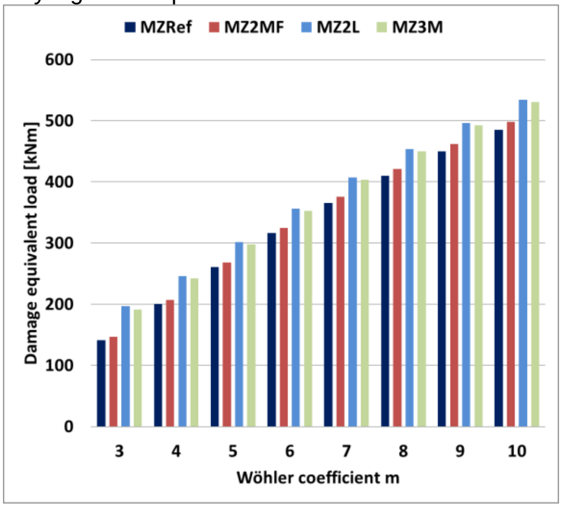

Fig. 10: Damage equivalent loads <v>=5 m/s accumulated for one year.

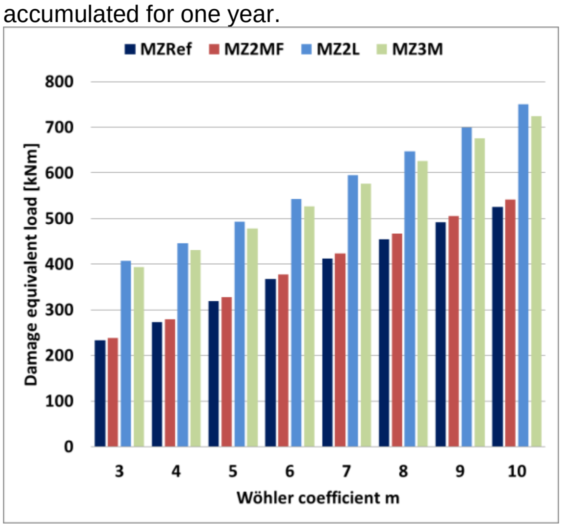

Fig. 11: Damage equivalent loads <v>=8 m/s accumulated for one year.

Figs. 10 and 11 show damage equivalent loads from the full simulation (MZ_{Ref}), which would be a basis of design loads to the ones that can be extracted by the "naïve" observers: MZ_{2L} with effects of aerodynamic damping, MZ_{3M} a three mass realisation, and the modified observer MZ_{2MF} with a filter for the drive train oscillations. All DELs are given for different Wöhler coefficients representing different materials.

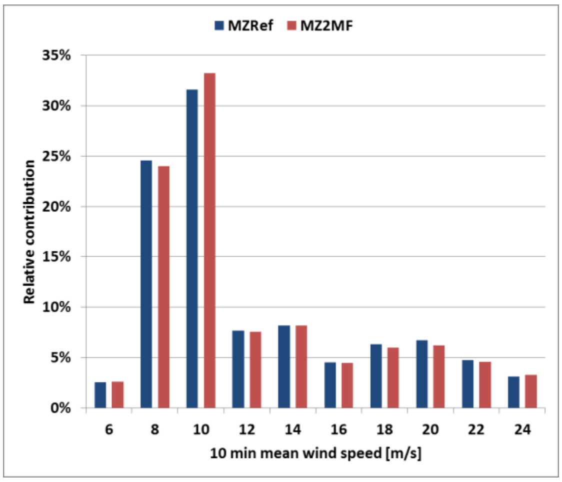

Fig. 12: Relative contribution to damage equivalent loads for Wöhler coefficient m=4.

From comparison it is seen that the modified observer is able to predict the damage equivalent loads for the torsional loads. Even for the relative contributions given for different wind bins a reasonable agreement can be achieved, see Fig. 12. In turn, it would be possible to derive quantities such as life time consumption and in addition through on-line evaluation open the possibly to determine early detection of damage.

6. Acknowledgement

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7. References

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