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Frequency based Wind Turbine Gearbox Fault Detection applied to a 750 kW Wind Turbine

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Abstract— **Reliability and availability of modern wind turbines are of increasing importance, for two reasons. The first is due to the fact that power grids around in the world depends at a higher and higher degree on wind energy, and the second is the importance of lowering Cost of Energy of the wind turbines. One of the critical components in modern wind turbines is the gearbox. Failures in the gearbox are costly both due to the cost of the gearbox itself, but also due to lost power generation during repair of it. Wind turbine gearboxes are consequently monitored by condition monitoring systems operating in parallel with the control system, and also uses additional sensors measuring different accelerations and noises, etc. In this paper gearbox data from high fidelity gearbox model of a 750 kW wind turbine gearbox, simulated with and without faults are used to shown the potential of frequency based detection schemes applied on measurements normally available in a wind controller system. This paper shows that two given faults in the gearbox can be detected using a frequency based detection approach applied to sensor signals normally available in the wind turbine control system. This means that gearbox condition monitoring/ fault detection could be included in the standard control system, which potentially can remove the cost of the additional condition monitoring system and the additional sensors used in it.**

I. Introduction

One of the main objectives in wind turbine research and development is to lower cost of energy (COE) of wind turbines. COE is basically computed as the ratio between the total life time cost of the wind turbine and the total energy generated by the wind turbine during its lifetime. Consequently COE can be minimized by either lowering costs or increasing energy generation. Fault detection, isolation and accommodation is one of the areas to focus on to obtain this objective. Better fault detection, isolation and accommodation can lower the maintenance costs and as well the down time of turbines, thereby both lowering costs and the possible production of energy.

The predominant industrial approach for fault detection and accommodation in the wind turbine industry is to use simple fault detection methods applied to the available control system sensor signals, like thresholds on measurements, and as well condition monitoring systems used to monitor some of the expensive rotating parts like gearboxes and bearings. Normally these condition monitoring systems are systems with computers operating in parallel to the existing control system, and it is as well using additional often expensive sensors measuring accelerations, vibrations and/or sounds. In [1] and [2] more information on wind turbine condition monitoring can be found. It is consequently an expensive add-on to the control system. A number of reviews of wind turbine condition monitoring can be seen in [3], [4] and [5]. It would clearly be beneficial if one could use the measurements available in the control system to detect changes in the condition of e.g. the drive train in a wind turbine. In [6] some basic steps in using the existing control system was taken, as spectrum analysis on the generator current is used to detect a bearing fault in a 160 W direct drive turbine. To facilitative research in this problem a friction change in the drive train was included in the wind turbine fault detection, isolation and accommodation benchmark model proposed by the same authors in [7], in which the parameters in the 3 state gearbox model change slightly both in frequency and damping coefficient. A high number of contributions have been proposed to this model, but only a few deals with the gearbox fault in the benchmark model, some of the contributions to this benchmark model were evaluated in [8]. Solutions to this problem were presented in [9] and [10], in which two different time-frequency based approaches were used to detect faults in the gearbox, both showing a potential for wind turbine gearbox fault detection based on sensor signals available in the standard control system. The main idea of these approaches are that the frequency response of the gearbox changes with the occurrence of the fault.

The next step would be to apply these schemes to a high fidelity model of a wind turbine gearbox. In [11] a multibody model of the NREL GRC 750 kW gearbox is presented, with a number of faults in the gearbox. Frequency analysis are performed in this work to identify potential frequency ranges for fault detection in this gearbox, using both normal available speed measurements and as well additional speed measurements on additional stages in the gearbox. It is clearly less expensive to only use the existing speed sensors, and the potential gain of the gearbox fault detection is consequently higher if only existing sensor signals are used.

In this paper the frequency based detection scheme presented in [10] is applied to the data used in [11] and it is shown that faults can be detected using the rotor and generator speed measurements which are standard measurements available in wind turbine control systems.

In Section II the used gearbox model and the data generated by it are presented. The used frequency based detection scheme is described in Sec. III. The obtained fault detection results are presented in Section IV. A conclusion is drawn

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Type	3 blades,upwind
Power rating(kW)	750
Rotor dia.(m)	48.2
Rated rotor speed(rpm)	22/15
Power regulation	Stall
Nominal hub height(m)	55
Cut-in wind speed(m/s)	3
Rated wind speed(m/s)	16
Cut-out wind speed(m/s)	25
Design wind class	IEC Class II
Design life(year)	20

TABLE I
NREL GRC 750 KW WIND TURBINE DESCRIPTION.

Type	1P+2H
Gearbox ratio	1:81.482
1st stage ratio	1:5.714
2nd stage ratio	1:3.565
3rd stage ratio	1:4.000

TABLE II
NREL GRC 750 KW GEARBOX DESCRIPTION.(P: PLANETARY, H: PARALLEL HELICAL.)

in Section V.

II. WIND TURBINE GEARBOX MODEL AND DATA SETS

In this study, the 750 kW gearbox from the Gearbox Reliability Collaborative (GRC) project at National Renewable Energy Laboratory (NREL) is used [12], [13]. Tables I and II show the specification of this wind turbine and its gearbox. The gearbox is modeled in a multi-body simulation (MBS) software, SIMPACK, see Fig. 1.

The loads on gears and bearings are obtained from the decoupled analysis - more information about this approach can be found in Nejad et al. [14] and [15]. 60-second measurements of the global torques in a steady-state, non-transient condition under 100% torque representing the rated wind speed and 50% of rated wind speed are collected from the GRC dynamometer test bench. The input measurement is then applied on the MBS model - see Fig. 1- and a simulation with time step of 0.005 or 200 Hz is performed. The first 10

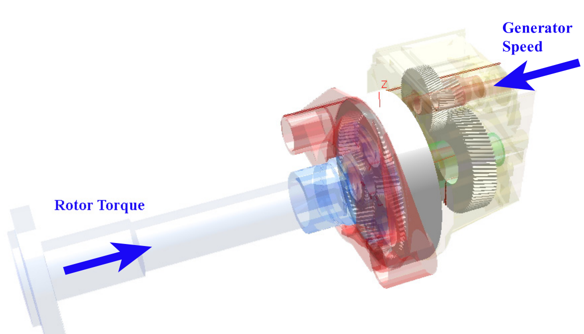

Fig. 1. 750 kW Gearbox MBS Model.

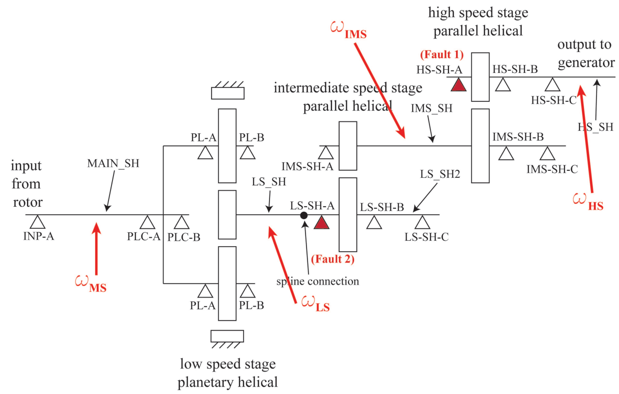

Fig. 2. Measuring sensors and fault cases.

seconds of data are removed to avoid numerical convergence uncertainties.

The bearing fault is modeled by changing the stiffness and clearance parameters of the bearing in MBS model. The non-faulty bearing is modeled by initial clearance and linear stiffness in multi body model. The damaged bearing follows a larger clearance and stiffness curve compared to the non-faulty bearing.

Two fault cases are considered, Fault 1 and Fault 2 in which one bearing in high speed stage and medium speed stage is defected. All load cases are simulated at the rated and 50% of the rated wind speed.

In a gear pair, the angular velocity error function, e is defined as [11]:

$$e[n] = \omega_{out}[n] - \alpha \cdot \omega_{in}[n]. \tag{1}$$

in which $\omega_{out}[n]$ and $\omega_{in}[n]$ are output and input angular velocity respectively. The α is the inverse gear ratio.

The defect in the bearing changes the angular velocity error. The idea presented by Nejad et al. [11] is to capture the gear or bearing defects by signal processing of angular velocity error in the frequency domain, assuming the frequency content to change with time as a fault develops. The reference, non-faulty angular velocity error is obtained from the gearbox multi-body model (MBS). In practice, the reference values can be constructed by MBS model for whole range of operational wind speeds. Fig. 2 illustrates the fault cases and the location of the measuring sensors.

The simulation results show possibility of fault detection in Fault 1 and 2 cases, with bearing defect in high speed and intermediate speed shafts [11]. This two load cases are further investigated in this paper at 100% and 50% torque loads. Fig. 3 and 4 present the frequency spectra comparison between reference value and error function in Fault 1 at 50% and 100% input torque. The Fault 1 error function is calculated from ω_{HS} and ω_{IMS}. It appears that this fault can be detected in the frequency range 60-60.5Hz.

For Fault 2, the defect can be seen in the frequency range 25-27.5HZ as shown in Fig. 5 and 6. The Fault 2 error function is calculated from ω_{LS} and ω_{IMS}.

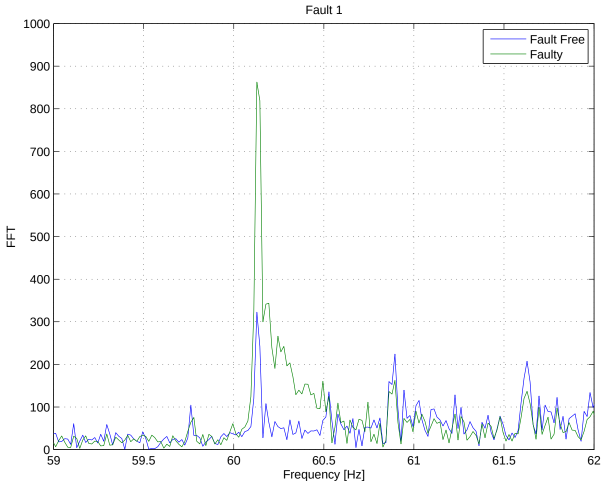

Fig. 3. Frequency spectra, Fault 1 and reference value at 50% input torque.

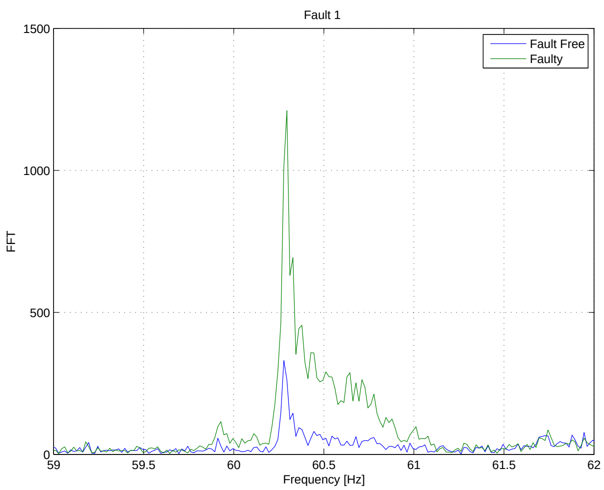

Fig. 4. Frequency spectra, Fault 1 and reference value at 100% input torque.

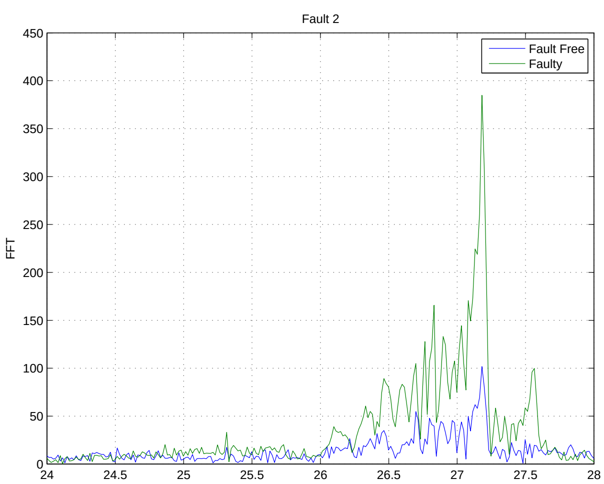

Fig. 5. Frequency spectra, Fault 2 and reference value at 50% input torque.

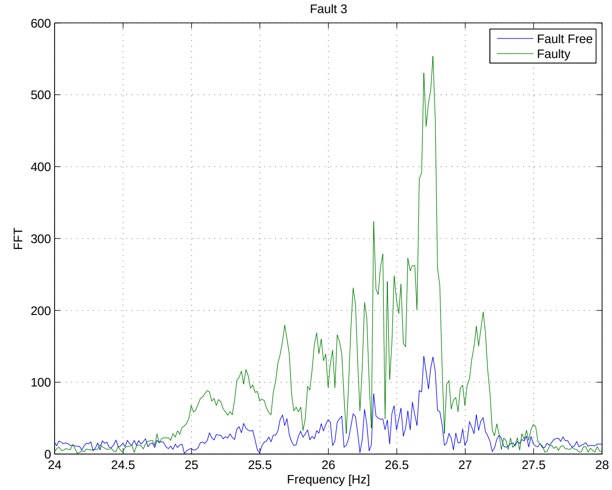

Fig. 6. Frequency spectra, Fault 2 and reference value at 100% input torque.

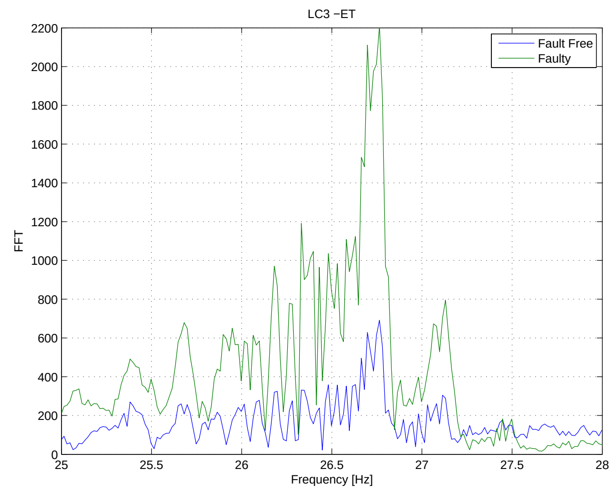

Fig. 7. Frequency spectra, Fault 2 and reference value measured from ω_{MS} and ω_{HS} error function .

The Fault 2 defect can be also detected from the gearbox input/output velocity sensors ω_{MS} and ω_{HS} as shown in Fig. 7. More information and discussion on the method and model can be found in Nejad et al. [11].

III. Frequency Based Detection Scheme

This problem of detecting changes in resonance frequency of a system, like the wind turbine gearbox, requires in principle a joint time-frequency based method, which provides support both in time and frequency, see [16], which covers a number of possible schemes from windowed FFT (Fast Fourier Transform) to Wavelet bases and other specific time frequency bases. The problem is a joint time and frequency problem since the frequency response changes with time as faults develops. This resonance frequency changing fault is illustrated in the frequency domain in Fig. 8, which shows an example of resonance frequency decreasing in value. In the following the approach proposed in [10] is presented and adjusted to the specified Gearbox model.

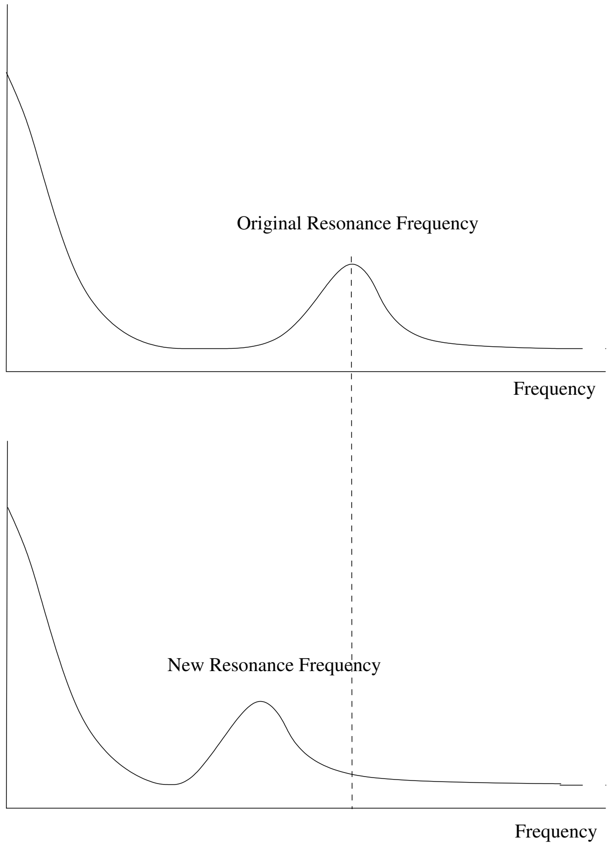

Fig. 8. Illustration of a changed resonance frequency plotted in the frequency domain.

In questions of finding a suited base for detecting certain phenomenons in time, frequency or time/ frequency domains, it is important to find a base which supports the phenomenon which one wants to detect. In this case the problem is to detect a changing resonance frequency, it would be relevant to consider a windowed FFT or cosine base, which basically shows the frequency domain for given time intervals/ windows. The window length should be selected such that short time variations in the operation is leveled out, while short enough to detect changes in frequency content of the measurements, like changes in different resonance frequencies. The frequency responses obtained by the windowed FFT algorithm would subsequently be compared to determine if the response is as expected. The problem with such a scheme is that it is relatively computationally demanding. The development of faults in the gearbox can be considered having very slow time constants, and is significant slower than the dynamics of the gearbox itself.

Instead an approach is proposed in which it is assumed that a certain energy level will be present at a given frequency, e.g. due to resonance frequency, f. Define the signal on which the frequency detection should be applied, $y[n]$.

The first step is to extract the energy in the signal at the requested frequency, by a band pass filter, $H_f[z]$. This filter is subsequently applied to the signal $y[n]$ to obtain $y_{Hf}[n]$.

The next step is to compute the energy in the signals for a given window length, L. The energies, $E_{Hf}[n]$, for the energy in the band pass filtered signal, and $E[n]$ the energy in the normal signal, are computed as:

$$E_{Hf}[n] = \mathbf{y}_{Hf}[n] \cdot \mathbf{y}_{Hf}[n]^T, \quad (2)$$

$$E[n] = \mathbf{y}[n] \cdot \mathbf{y}[n]^T, \quad (3)$$

in which,

$$\mathbf{y}_{Hf}[n] = \begin{bmatrix} y_{Hf}[n-(L-1)] & \cdots & y_{Hf}[n] \end{bmatrix}, \quad (4)$$

$$\mathbf{y}[n] = \begin{bmatrix} y[n-(L-1)] & \cdots & y[n] \end{bmatrix}. \quad (5)$$

Subsequently a ratio, $\gamma[n]$, between these two energies can be computed, which can be used to detect if the energy level at this frequency drops, which could indicate the frequency spectrum of the system changes.

$$\gamma[n] = \frac{E_{Hf}[n]}{E[n]}. \quad (6)$$

This ratio $\gamma[n]$ would subsequently be compared with a thresh hold κ.

In cases where the resonance frequency is depending on operational conditions, the center frequency of the H_f filter can depend on this, and a number of filters might have to be computed in advance.

A. Specific Design

In this considered case the sample frequency is at 200 Hz. In the specific application it is necessary to filter out the DC energy content in the signal $y[n]$ before the proposed scheme is applied to $y[n]$, a cut off frequency at 0.5 Hz is selected for this low pass filter. Consequently a low pass filter with a cut off frequency at 0.5 Hz is applied to $y[n]$ before $E[n]$ is computed. The used low pass filter , $L[z]$, can be seen in (7).

$$L[z] = \frac{(6.0086 + 18.02z^{-1} + 18.02z^{-2} + 6.0086z^{-3}) \cdot 10^{-8}}{1.0000 - 2.9843z^{-1} + 2.9687z^{-2} - 0.9844z^{-3}}. \quad (7)$$

In [11] and Sec. II it was found that the faults were detected in the frequency ranges 60-60.5Hz and 25-27.5HZ for Fault 1 and Fault 2 respectively, see also Section II. $H_f[z]$ was designed using the Matlab function *butter*, which designs Butterwoth filters, a filter of order 3 with a center frequency at 60.25 Hz and 26.25 Hz were respectively designed. The filter with a center frequency at 60.25Hz relates to fault 1, and is subsequently denoted H_{f1} and the other filter relates to fault 2, and is subsequently denoted H_{f2}. The filters can respectively be seen in (8) and (12). The amplitudes of these filters can be seen in Figs. 9 and 10.

$$H_{f1}[z] = \frac{\mathbf{B}_2 \cdot \mathbf{Z}_6}{\mathbf{A}_2 \cdot \mathbf{Z}_6} \quad (8)$$

in which

$$\mathbf{B}_2 = \begin{bmatrix} 4.7695 \cdot 10^{-7} \\ 0 \\ -1.4309 \cdot 10^{-6} \\ 0 \\ 1.4309 \cdot 10^{-6} \\ 0 \\ -4.7695 \cdot 10^{-7} \end{bmatrix}^T \quad (9)$$

$$\mathbf{A}_2 = \begin{bmatrix} 1 \\ 1.8890 \\ 4.1580 \\ 3.9881 \\ 4.1147 \\ 1.8498 \\ 0.9691 \end{bmatrix}^T \quad (10)$$

$$\mathbf{Z}_6 = \begin{bmatrix} 1 \\ z^{-1} \\ z^{-2} \\ z^{-3} \\ z^{-4} \\ z^{-5} \\ z^{-6} \end{bmatrix}. \quad (11)$$

$$H_{f2}[z] = \frac{\mathbf{B}_3 \cdot \mathbf{Z}_6}{\mathbf{A}_3 \cdot \mathbf{Z}_6} \quad (12)$$

in which

$$\mathbf{B}_3 = \begin{bmatrix} 5.6070 \cdot 10^{-5} \\ 0 \\ -1.6821 \cdot 10^{-4} \\ 0 \\ 1.6821 \cdot 10^{-4} \\ 0 \\ -5.6070 \cdot 10^{-5} \end{bmatrix}^T \quad (13)$$

$$\mathbf{A}_3 = \begin{bmatrix} 1 \\ -3.9693 \\ 8.0964 \\ -9.8467 \\ 7.6833 \\ -3.5745 \\ 0.8546 \end{bmatrix}^T \quad (14)$$

The window length L and the threshold values κ_1 and κ_2 which are the threshold values for the two respective faults are found based on trial and error on the data obtained from the model presented in Sec. II, these parameters are found in Section IV in which the proposed scheme is simulated and evaluated.

IV. Simulations and Results

A part of this design is based on trial and error on the simulated data, meaning that certain parameters are found based on simulations with the model. It is at present not possible to introduce the faults in the gearbox within a simulation, so the method is applied to data sets with and without faults in the entire range of these data sets. The

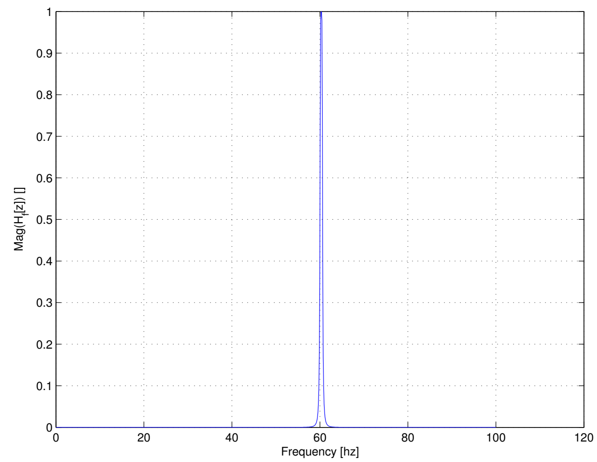

Fig. 9. The amplitude of the $H_{f1}[z]$ plotted as a function of frequencies.

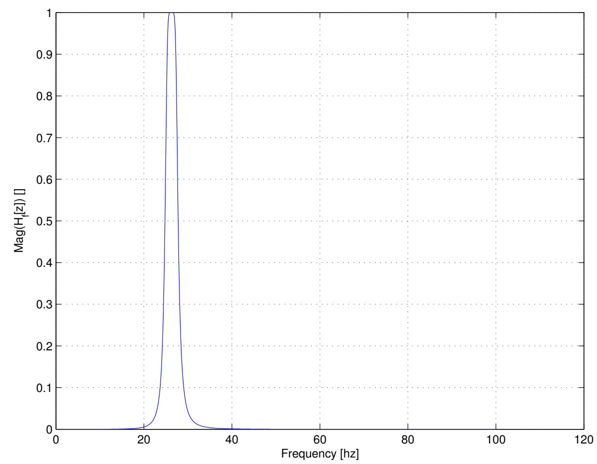

Fig. 10. The amplitude of the $H_{f2}[z]$ plotted as a function of frequencies.

computed values of γ_1 and γ_2 are subsequently average over the entire data sets, this means that $L = 12001$.

Wind turbines operates normally in a number of modes. The two main modes are partial load in which the rotor speed is variable and this is used to extract the maximum energy from the wind, and full load in which the rated power is generated by the turbine, in this mode a constant rotor speed are kept. The data is generated in case of partial load (50%) power operation and full load power operation of the wind turbine of the wind turbine, details on wind turbine operation can be seen in [17]. The results can be seen in Tables III -IV.

In both load cases it is clear that both Fault 1 and Fault 2 can be detected, and thresh holds κ_1 and κ_2 can in both cases

Fault No.	γ_1	γ_2
Fault Free	0.089	0.046
Fault 1	0.341	0.054
Fault 2	0.113	0.487

TABLE III

Partial load results, γ_1 and γ_2 are given for the fault free and faulty cases.

Fault No.	γ_1	γ_2
Fault Free	0.050	0.085
Fault 1	0.361	0.063
Fault 2	0.051	0.610

TABLE IV

FULL LOAD RESULTS, γ_1 AND γ_2 ARE GIVEN FOR THE FAULT FREE AND FAULTY CASES.

be set at 0.22, which ensures that the faults are detected and as well significant higher than the largest value of γ_1 and γ_2 in the fault free cases, such that false positive detections can be avoided.

This study has shown that the proposed filter based approach for time-frequency based fault detection of wind turbine gears using generator and rotor speed measurements shows a potential on data obtained from a high fidelity wind turbine gearbox model. The next steps would be to apply the scheme for detection of other kinds of gear box faults like spalls and cracks, and as well to test it on a model of a larger offshore turbine, since potential for such a fault detection scheme are higher in large offshore turbines than in smaller onshore turbines. A second task would be to apply it on more data to give a better statistical basis on which to draw conclusions.

V. CONCLUSION

In this paper a time-frequency based detection scheme implemented using filters, which output are averaged over a certain window length is applied to simulation from a high fidelity wind turbine model of a 750kW wind turbine gearbox. The proposed scheme shows it potential in detecting two potential faults in the gearbox, which normally would be detected using a condition monitoring systems which runs in parallel with the wind turbine control system, using its own computer and expensive additional sensors. The potential of the proposed scheme is to include fault detection of the wind turbine gearbox in the existing wind turbine controller using the sensor signals normally available for the wind turbine controller. This do present a potential cost reduction in the wind turbines, and thereby lowering the cost of energy.

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