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Controller Design for the Cancellation of the Tower Fore-aft Mode in a Wind Turbine

W.E. Leithead and Sergio Dominguez
EEE, University of Strathclyde
Glasgow, U.K.
`w.leithead@eee.strath.ac.uk`

Abstract— **With the increase in size of wind turbines, there is increasing interest in exploiting the pitch control capability of variable speed turbines to alleviate tower fatigue loads. The most direct method is to modify the blade pitch angle in response to a measurement of tower acceleration. It is shown that the flap mode has a central role in determining whether this approach is effective since there is a strong interaction between the blade flap-wise mode and the tower fore-aft mode. Several different approaches to the design of the controller for the tower speed feedback loop are investigated.**

I. INTRODUCTION

With the increase in size of wind turbines, as evident in the market penetration of multi-megawatt sized machines, there is increasing interest in exploiting the pitch control capability to alleviate fatigue loads. In particular, the alleviation of tower fatigue loads has received special attention due to the fact that, in off-shore wind turbines, the tower and foundations cost can account for roughly 40% of the total cost of the wind turbine. Since previous studies, see [1], have identified a potential for fatigue reduction via active control of the loads, the feasibility of so doing is worth investigating. Only cancellation of the fore-aft motion is examined, since this mode has been identified as the main fatigue driver.

The most direct option is to modify the blade pitch angle in response to a measurement of tower acceleration to cancel the tower fore-aft mode. The analysis and design of controllers of this type are analysed in this paper. The wind turbine investigated is a commercial, variable speed, three bladed multi-megawatt machine, with variable pitch capability for active control above rated.

II. MODELS AND DYNAMICS

The linear models for the wind turbine dynamics used in this paper are those reported in [2], [3]. These include all dynamic components significant for controller design and control performance assessment. In particular, it includes two modes for the tower, two modes for the blades and two modes for the drive-train. It also has models for the pitch and torque actuator and a model for the interaction of the rotor with the wind. The main differences to other linear models of wind turbines found in the control literature is the explicit inclusion of the tower and blade modes. The tower modes are of special importance in the design of controllers for wind turbines since they can introduce a pair of right half plane zeros which impose limitations on the generator speed loop [4], [5]. The blade modes are important since the flap mode interacts with the tower mode, as discussed in this paper, and the edge mode is strongly relevant in the determination of the first drive-train mode. An example of the wind turbine dynamics is shown in Fig. 1[1].

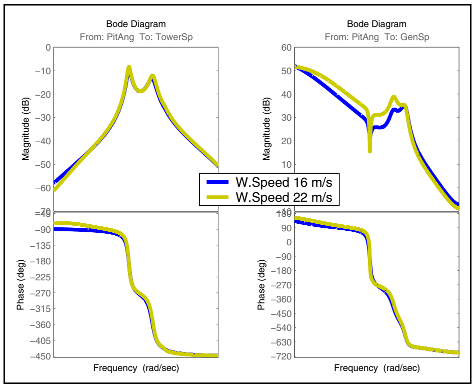

Fig. 1. Dynamics of a multi-megawatt scale wind turbine from pitch angle to tower speed and generator speed

The fore-aft mode and the side-to-side mode differ considerably on a wind turbine. The fore-aft mode is strongly damped, due to the aerodynamic damping of the wind turbine rotor in its fore-aft movement. The side-to-side mode is a lightly damped mode, since there is almost no aerodynamic damping in normal conditions. This influences the shape of the spectrum for both modes, see Fig. 2 which shows the Power Spectral Density (PSD) of the tower base moments, derived using FLEX, a wind turbine aero-elastic simulation package. FLEX uses a full two-dimensional wind field for the simulation to provide results representative of the full 20 years life-time of the wind turbine. In this figure the difference in shape of both modes is evident. The disturbance marked as $1P$ is due to rotor imbalance, which inevitably occurs in machines of this range. Due to its closeness to the tower mode it cannot be ignored in the controller design. The difference in spectral shape influences the range of

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[1] Unfortunately, no scales can be provided for the Bode plots due to restrictions related to commercial confidentiality.

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frequencies over which the controller must act. Obviously to achieve a total reduction of the tower fore-aft mode the controller must be active over the range of frequencies over which the tower mode raises the PSD above the background level. However, the controller is constrained by the close proximity of the tower and blade modes, see Fig. 1 where the phase loss due to its presence between the tower peak and the blade peak is evident.

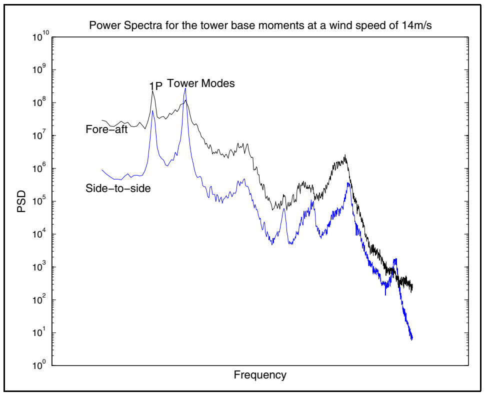


Fig. 2. Tower base loads power spectrum at 14 m/s

III. TOWER FEEDBACK LOOP FOR THE CANCELLATION OF THE TOWER FORE-AFT MODE

The cancellation of the tower feedback loop via control has received a good deal of attention over recent years, with several methods discussed in the literature [6], [7], [8], [9]. Essentially all methods involve a feed back of the tower speed, derived from a measurement of tower acceleration, thereby increasing the aerodynamic damping of the tower, as in the structure depicted in Fig. 3 where, $C(s)$ is the generator speed loop controller, WT represents the dynamics of the wind turbine from pitch angle to generator speed, $G_{act}(s)$ is the pitch actuator, $G_{tow}(s)$ is the tower feedback loop controller, ω_g represents the generator speed output, $\dot{\phi}_T$ is the tower speed output and ω_{SET} is the generator speed set point.

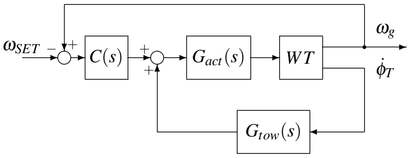


Fig. 3. Inner loop for the cancelling of the tower fore-aft mode

The procedure followed for the analysis and design of the tower feedback loop is described below. The tower feedback loop is designed as an addition, in the form of a fast inner loop, to an existing generator speed loop. However, it should not be necessary to redesign the speed controller in order to accommodate the control of the tower, since the range of frequency of the two does not overlap. During below rated operation the control objective for the speed loop is to track the required operating curve relating torque or power to rotor speed. During above rated wind speed, the objective is to maintain constant torque or power plus constant rotor speed; that is, to reject disturbances arising from wind speed fluctuations, see [10], [11]. Typically the bandwidth of the generator speed controller is chosen to be about 1 rad/s, well below the first tower mode. Consequently the generator speed control loop and the tower speed control loop should be active over different frequency ranges and not interact. In summary, the tower feedback loop controller should comply with the following requirements:

- Extract the tower fore-aft mode from the measured tower signal and, via the controller, feed it back as an additional pitch demand signal.
- Cause no reduction in the performance of the generator speed loop caused by the tower feedback loop.
- Ensure that by cancelling the tower mode no other modes are excited and the overall tower fatigue is reduced.

The more usual procedure would be to design the inner fast feedback loop first. In other words, the design and analysis of the tower feedback loop (TFL) would be carried out with respect to the open loop dynamics, *i.e.* $G_{tow}(s)G_{act}(s)WT(s)$. The open-loop dynamics must ensure effective control action at the tower frequency, together with closed loop stability. However, here, with an existing outer slow feedback loop already present, the tower feedback controller should be designed with the generator speed feedback loop already closed, see Fig. 4, where WT_{cl} represents the dynamics of the wind turbine with the generator speed loop closed.

The objective for the tower controller to reduce the fatigue loads over the life-time of the machine, is indirectly and non-linearly related to the dynamics of the feedback loop. To estimate these loads requires extensive simulation studies over all possible operational conditions. Nevertheless, in addition to its other uses, the sensitivity of the tower feedback loop in Fig. 4 provides a simple way in which to asses the performance with respect to the tower loads. The PSD for the tower speed with the tower feedback loop closed is related to the PSD without the tower feedback loop by

$$\text{PSD with TFL} \equiv \text{PSD without TFL} \cdot |G_{eq}(j\omega)|^2 \qquad (1)$$

where $G_{eq}(s)$ is the sensitivity function in Fig. 4. Since the loads are directly related to the tower displacement, ϕ_T, it follows that a similar modification can be applied to the power spectrum of the tower loads, and, thereby, to the influence of the the inner feedback loop on fatigue. The ability to estimate the PSD of the tower loads with different controllers gives the possibility of rapidly estimating the effect that these controllers would have on fatigue, by using one of the frequency-domain methods for fatigue estimation [12] such as the Dirlik method [13]. Alternatively, it provides a direct guide to the modification of the tower loads, that is, it indicates which loads are increased and which decreased. A design criteria is that regions in which the load is enhanced should not coincide with structural frequencies that could be excited. At frequencies in the region of the tower mode, it should be noted that the tower feedback loop sensitivity function in Fig. 3 and Fig. 4 are similar. So equally well the sensitivity function for Fig. 3 maybe used in the above estimation procedure.

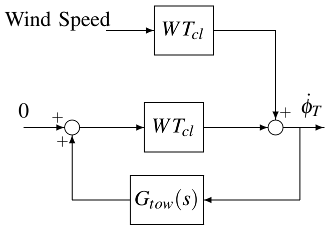


Fig. 4. Block diagram including disturbances

The impact of the inner loop on the outer loop must be checked. The dynamics of the outer generator speed feedback loop are modified by the presence of the inner tower speed feedback loop, as depicted in Fig. 5. The modification is again simply that the sensitivity function of the tower speed feedback loop, specifically, the open loop transmittance, is cascaded with G_{eq}. The resulting open loop dynamics can be analysed to asses any loss of performance in the control of the generator speed.

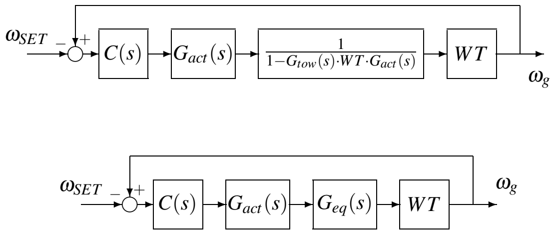


Fig. 5. Block diagram of controller, plant and TFL

IV. BASIC DESIGN APPROACH

A simple approach to cancelling a resonant mode via the control action is to directly feedback a measurement of the isolated resonance to suppress this resonance; that is, the plant is caused to act on itself. Its effectiveness is evident from the sensitivity function, which is the mirror image of the resonant mode but $0dB$ at other frequencies. The advantage of this approach is its robustness, with the filtering action automatically matching the dynamical characteristics of the resonance. For it to work effectively, the feedback must have sufficient gain that the resonant mode is shifted sufficiently above $0dB$.

Suppose the wind turbine dynamics consisted of only the tower mode, then the Bode plot of the transfer function would consist of a single isolated sharp resonance with roll-off at both low and high frequency. The controller for the tower feedback loop could then be chosen to be a simple gain; that is, corresponding to G_{tow} in Fig. 3 being a constant. This approach requires the following conditions to hold:

1) The tower mode must be the only mode strongly present in the tower acceleration signal, or the other modes must have much lower gain.
2) There must be no coupling between the tower feedback loop and the generator speed control loop.

However, the tower acceleration signal contains other modes close to the tower mode, such as the flap mode and, as is apparent from the following discussion, the consequence of the interaction of the flap mode with the tower fore-aft mode is that neither of these conditions are met. Nevertheless, this approach has been adopted on several occasions with some success. Their effectiveness is probably due to the fact that those controllers were designed for smaller wind turbines, where the effect of the interaction between the tower and the flap is less important. Unfortunately, using a constant gain for G_{tow} can render the wind turbine unstable and has been observed to do so on a multi-megawatt wind turbine, such as the one in this study, due to the interaction of the tower feedback loop with the generator speed loop.

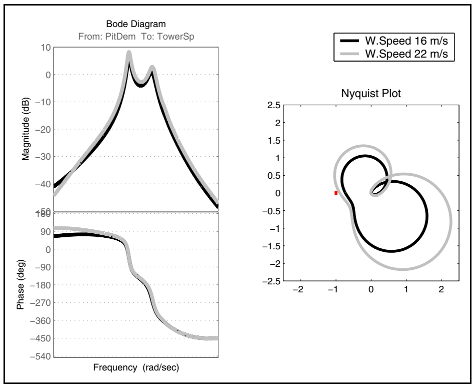


Fig. 6. Tower feedback loop open loop

In Fig. 6 the Bode and Nyquist plots for the transfer functions representing the dynamics from pitch demand to tower speed with a constant gain controller are shown. It can be seen that the dynamics are basically a rescaled version of those shown in Fig. 1. The peak in the Bode plot at low frequency is due to the tower mode and the peak at higher frequency is due to the blade flap mode. The prominence of the latter is dependent on some parameter values that are wind-speed dependent, see [3], and, therefore, may not always be as prominent. It should also be noted that the two modes are out of phase with a shift of 180^o between them. A similar pattern is observed in the dynamics relating wind-speed to tower-speed. Feeding back the tower speed signal with just a constant gain would imply that, since the tower mode has to be placed above $0dB$ for the control action to be effective, the rapid phase loss between the tower and the blade mode can very easily cause the Nyquist plot to approach -1, leading to much reduced stability margins or even instability, see [14]. It is stressed that this sensitivity stems from the phase loss rather than the blade peak itself. In essence, the need to raise the tower peak above $0dB$ is being compromised by the presence of the nearby right half plane zero.

A very prominent peak is apparent in the sensitivity function, see Fig. 7. Its frequency is very close to the frequency at which the open loop plot crosses -360^o (this is a positive feedback loop), between the tower mode and the flap mode. This peak is obviously also present in the closed loop dynamics, which are also shown in Fig. 7.

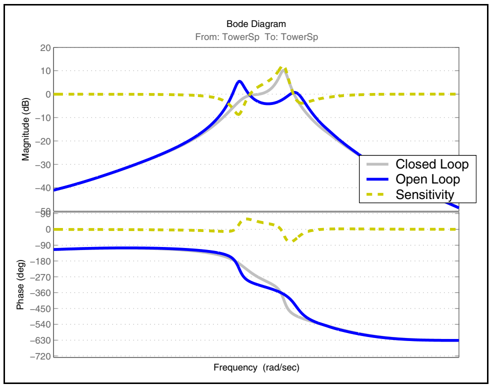


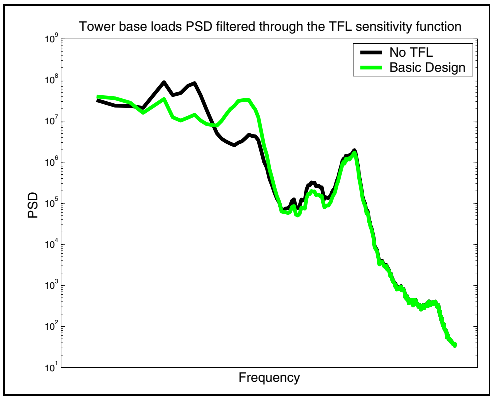
Fig. 7. Closed tower feedback loop and sensitivity function

In Fig. 8(a), using the procedure described previously, the impact of the tower speed feedback on the tower fatigue is assessed. The power spectra with the feedback loop present is estimated by filtering the spectra from a simulation without the tower speed feedback. The peak in the sensitivity function manifests itself as a similar prominent peak in the spectra. In Fig. 8(b) the results of running the full non-linear simulation with the tower speed feedback loop are shown. The estimation using the sensitivity function gives a very good approximation of the spectral shape.

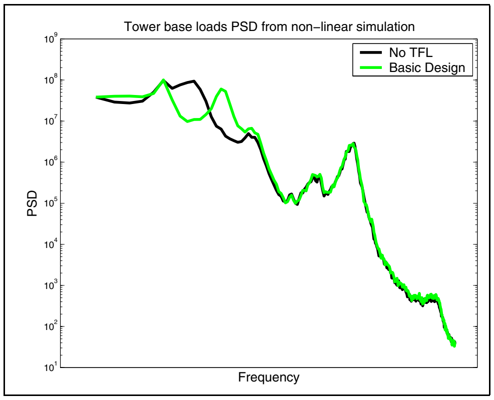
In order to compare the performance of this form of feedback with the benchmark set in [1], a full set of runs is done, with and without the presence of the tower feedback loop in the controller. The result is that the tower fatigue loads, understood as the constant amplitude cyclic loads that would produce the same fatigue damage as the full operational life of the wind turbine, are increased by 4%.

A further issue with this type of controller concerns the second condition stated at the beginning of this section. For the controller to be effective it must not affect the generator speed loop performance. In Fig. 9 the Bode plot and Nyquist plot of the transfer functions for the generator speed open loop dynamics are plotted with and without the modification caused by the tower feedback loop, namely G_{eq}.

The tower feedback loop induces an increase in the gain at the critical frequency, rendering the system unstable. It should be noted that the generator speed controller has additional filtering at intermediate frequencies to protect the actuator. This has been omitted to emphasise the impact of the tower feedback loop by rendering the closed-loop system unstable. With the additional filtering it remains stable but with very small stability margins.



(a) Estimated



(b) Simulation

Fig. 8. Estimated spectrum from filtering with the sensitivity function and spectrum of a simulation

V. ALTERNATIVE DESIGN OF THE TOWER FEEDBACK LOOP

As discussed above, the consequences of the coupling of the flap mode to the tower mode is that feeding back a signal proportional to the tower acceleration not only does not achieve a reduction on the tower fatigue loads, but it increases them.

In order to be able to feed back the signal coming from the tower accelerometer, it is necessary to isolate the tower mode. In order to achieve this, a filter of the form shown in Fig. 10 is chosen for G_{tow}, which is the tower feedback loop controller, see Fig. 3. The filter consists of a *bump* centred at tower frequency to enhance the part of the signal correspondent to the first tower mode, and a wash out filter that has two main objectives: filter out low frequency signals, to avoid sensor problems, such as drifts or offset in the measurement signal, and provide some phase advance at the region of the tower frequency. The peak at the left of the bump is placed at $1P$ frequency, to reduce locally the value of the sensitivity function. this is included in the TFL because the $1P$ disturbance has a significant impact on the fatigue

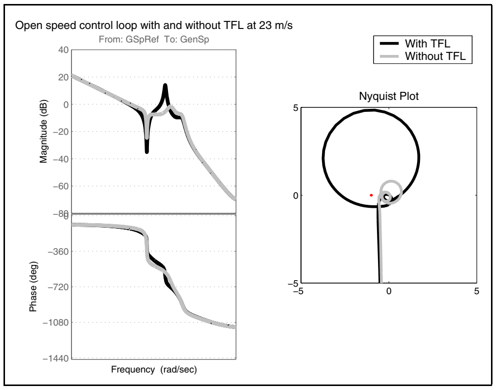


Fig. 9. Generator speed loop

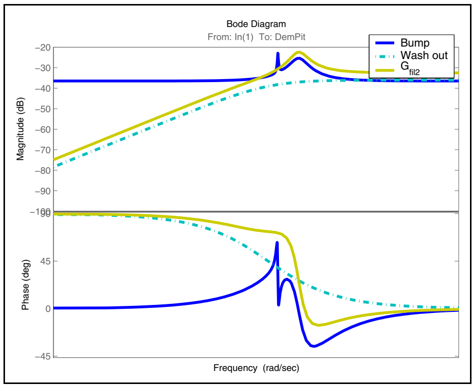


Fig. 10. Alternative design of the tower filter

loads on the tower. The disturbance differs from one wind turbine to another, since it is mostly due to tolerances in the manufacturing and imbalances during the mounting of the blades.

In Fig. 11 the open loop dynamics linking pitch angle to tower speed with this implementation of G_{tow} are shown. It can be seen how the filter succeeds in placing the tower mode above $0dB$ without exciting the flap mode.

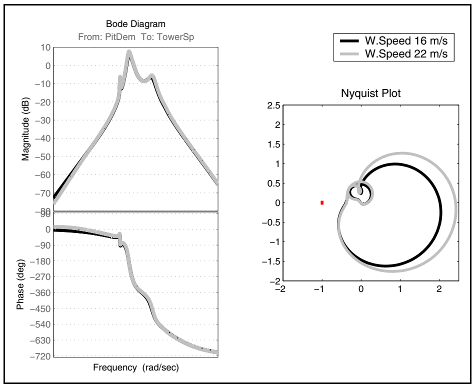
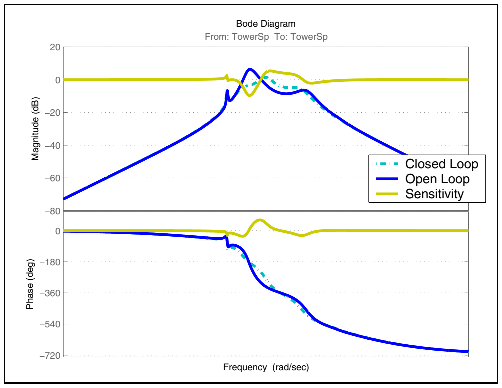
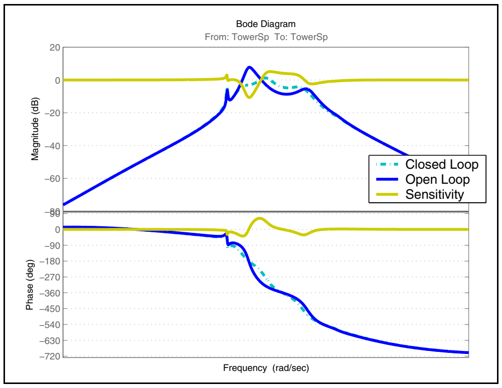


Fig. 11. Tower feedback loop open loop with the alternative implementation of the filter

The closed loop dynamics and sensitivity function for this alternate approach are shown in Fig. 12. The peak in the sensitivity function and the closed loop dynamics is still present. This peak is, nevertheless, much smaller in this implementation than in the case where the tower mode is fed back with a constant gain, see [14]. This is due to the fact that the flap mode has a very low gain in this implementation and to the phase advance given by the wash out filter, which causes the positive part of the sensitivity function to be shifted to the right.



(a) Wind speed 16 m/s

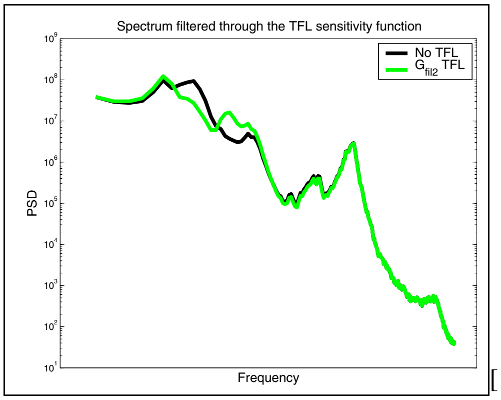


(b) Wind speed 22 m/s

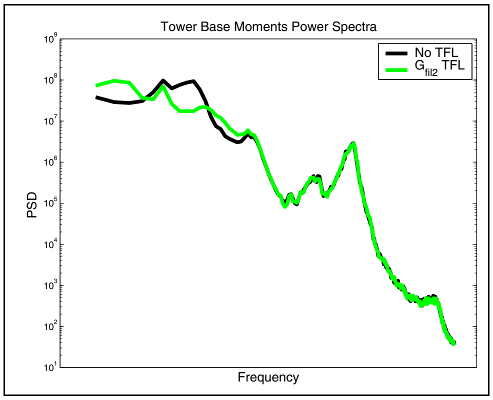
Fig. 12. Closed tower feedback loop and sensitivity function

In Fig. 13(a), using the procedure described previously, the impact of the tower speed feedback on the tower fatigue is estimated. The power spectra with the feedback loop present is estimated by filtering the spectra from a simulation without the tower speed feedback. The peak in the sensitivity function manifests itself as a similar prominent peak in the spectra. The results of the simulation with the TFL present are depicted in Fig. 13(b). The estimation using the sensitivity function gives again a very good approximation of the spectral shape.

The result given by the full non-linear simulations with this form of controller, is that the tower fatigue loads are reduced by 8%. The coupling with the generator speed loop induced by this tower feedback loop is shown in Fig. 14 it can be seen that there is almost no coupling and little



(a) Estimated



(b) Simulation

Fig. 13. Estimated spectrum from filtering with the sensitivity function and spectrum of a simulation

reduction in performance.

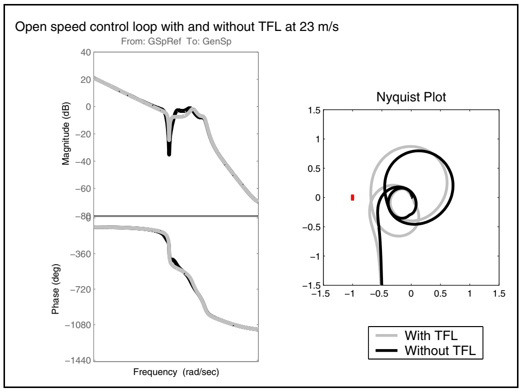


Fig. 14. Generator speed loop

VI. DISCUSSION AND CONCLUSIONS

The most direct method of exploiting the pitch control capability to alleviate tower fatigue loads is to modify the blade angle in response to a measurement of tower acceleration. This approach is analysed using a simple linear dynamic model of the wind turbine. It is shown that the flap mode has a central role in determining whether the tower feedback loop is stable or unstable. However, the importance of this role is not usually recognised in the literature, probably because the situation described here does not necessarily arise in smaller wind turbines. Its importance is due to a phase difference of 180^o between the flap mode and the tower mode. The associated change in sign of the feedback loop results in instability when the gain of the feedback loop exceeds $0dB$ at the flap frequency. The analysis and the linear models are validated using non-linear simulation and measured data from a multi Megawatt machine. An approach to the cancellation of the tower fore-aft mode is discussed. A filter is included in the feedback loop and the tuning procedure described.

- The cancellation of the tower mode by a signal proportional to the tower speed leads to an increase in fatigue loads
- A G_{tow} designed to make the tower mode more prominent and isolate it from other modes is effective, achieving a fatigue reduction over the life-time of the wind turbine of the 8%.

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