A novel method of drive train damping for large wind turbines

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Abstract. Based on actual damage to shaft couplings and elastic supporting caused by drive train vibration which occurred in a low wind speed mountainous wind farm in China, this paper proposes a novel drive train damping method. Instead of a common lead compensator, a delay compensator is used for phase correction. Features of both methods are analysed and compared. Compared to common dampers, the proposed one is only effective at centre frequency of damping, and will not magnify responses at other frequencies, especially high frequencies. Simulations with different configurations were implemented to verify effects of the proposed method. A field test has been implemented on Shanghai Electric 2MW wind turbine. The test result shows that the proposed method is effective to solve drive train vibration, and can be extended to large-rotor turbines located in slow-speed and mountainous areas in China.

1. Introduction

Rapid development of wind energy pushes the industry to improve control algorithms with which wind turbines can operate efficiently and safely [1-4]. With increasing of rotor diameter, drive train coupled frequency and in-plane coupled frequency are reducing to multiple rotating frequencies such as 6P and 9P, which will trigger drive train vibration easily [5-7]. Therefore, necessary damping is needed to suppress drive train vibration, so as to avoid damage of elastic supporting of gearbox and shaft coupling. Two key features of drive train dampers are: (a) to extract vibration signals at specific vibration frequencies with filters such as low-pass filter (LPF), band-pass filter (BPF), and notch filter [5, 7, 8], and (b) to reduce vibration torque by torque compensation. However, the extracted vibration signals cannot be used to compensate torque directly because of phase misalignment, which is caused by time delay in converter execution, signal detection and transmission, etc. Without regard to time delay, compensated torque may be inefficient, or even bring adverse results.

Phase correction is an effective way to solve this problem [9]. It can improve control system by adjusting phase. Lead compensator is a common method of phase correction in wind turbine control, which is able to ensure optimal damping [5, 7]. But it may cause adverse impacts in gain margin sometimes, especially at high frequencies. This paper proposes a novel phase correction method through a delay compensator. Structure and principles of the compensator are demonstrated and analyzed in this paper. Simulations were implemented on GH Bladed and a field test was implemented on a Shanghai-Electric 2MW wind turbine. Results of the simulations and the field test verified that the proposed method is effective to correct phase at specified frequencies and further dampers drive train vibration.

2. Methodology

2.1. Common method of drive train damping
A reverse generator torque is commonly used to reduce divergence of generator speed and torque caused by drive train vibration (shown in figure 1). There are three factors for damping: a gain, a band-pass filter, and a phase correction [10, 11].

A second-order Butterworth filter [8, 12] is used in this paper, as follows,

$$BP(s) = \frac{s(\omega_H - \omega_L)}{s^2 + \omega_0^2 + s(\omega_H - \omega_L)} = \frac{\omega_0 s}{Q s^2 + \omega_0 s + \omega_0^2 Q} \quad (2)$$

where, \(\omega_0\), \(\omega_H\) and \(\omega_L\) are the center, cut-out and cut-in frequency of the band-pass filter, respectively; \(Q = \omega_0/(\omega_H - \omega_L)\) is quality factor.

Generally, transfer function of lead component can be expressed as follows [9]:

$$Lead(s) = \frac{1 + \tau_a s}{1 + \tau_b s} \quad (3)$$

In practice, shift of phase angles of signals due to transmission delay can be observed, which requires the proposed damper to create a phase correction to offset phase lag. Phase correction of a lead component at some damped frequency can be implemented by adjusting \(\tau_a\) and \(\tau_b\), while the magnitude is also changed as an undesired by-product. Over-damping caused by high magnitude in torque response could be seen in following simulations.

In general, the designed gain and center frequency of the filter are close to the results from field validation, but converter signal delay, as well as estimated rotor inertia, which also affects delay, could have unexpectedly large errors. Thus, field validation is a must for phase correction.

2.2. Proposed method of drive train damping

A novel drive train damper is proposed as follows:

$$D_{\text{delay}}(s) = K \ast BP(s) \ast Delay(s) \quad (4)$$

where \(K\) is a constant gain; \(BP(s)\) is the transfer function of the band-pass filter the same as that in equation (2), and \(Delay(s)\) is a delay component used to correct phase [9],

\[ \text{Figure 1. Principle diagram of drive train damping.} \]
where \( \tau \) is a characteristic constant.

Note that adding a delay will not have any influence on the magnitude of the original transfer function but correct the phase by adjusting \( \tau \) because of its frequency-domain characteristics

\[
\text{Delay}(j\omega) = \exp(-j\tau \omega) = 1 \angle -\tau \omega
\] (6)

The proposed transfer function equation (4) is discretized by using Tustin Approximation, and then the novel damper program can be compiled. The lagging time step is rounded, which leads to a small error in phase shift (can be seen in figure 2). But in practice this error makes little difference as long as it is within \( \pm 10^\circ \). The simulation results are shown in the following section.

2.3. Comparison between the two methods

The goal is to design a transfer function that only corrects phase but has no magnitude amplification over all frequencies. In our project, the major peak of the response of generator speed locates at 1.51 Hz, so we are more concerned about damper performance at this frequency. Moreover, avoiding undesired high-frequency response is also taken into account. Through rigorous design, the lead-approach can indeed introduce a desired phase compensation at a certain frequency, but it inevitably results in magnitude amplification at high frequencies because of its essential property. The proposed pure time delay component, however, only affects the phase of the system without altering magnitude, which is the reason why it is preferred compared to the lead component.

Different characteristics of the two methods can be easily seen from the comparison of the Bode diagrams in figure 2. Choosing the comparison between the phase lead of 60° and lag of 300° is to keep consistent with the parameters that was used and validated in the field test, which yielded representative damping effects. The phase difference between the two settings is exactly one period, so both methods have the same effect on periodic phase compensation.

As shown in figure 2(a), adding a lead component, at the center frequency of damping, obtains a phase lead of 62.7 degrees. On the other hand, magnitudes at that frequency and higher frequencies are increased, which means the lead compensator arouses high-frequency response of torque command. A common practice is to increase the center frequency of damping and decrease the gain to reduce high-frequency influence caused by drive train damper.
However, in figure 2(b), the delay compensator shifts the phase downwards by approximately 300° at the center frequency (1.51 Hz), but it does not respond to high-frequency responses, nor increase the gain. Figure 1 shows that as drive train damper is paralleled to torque-speed loop, and only the generator speed at center frequency is used. Thus, phase lag at other frequencies will not influence overall torque-speed loop.

3. Simulation Analysis

By altering $\tau$, we can obtain different phase lags. Figure 3 shows responses of a damper with delays of $\Phi = 0^\circ$, 90$^\circ$ and 180$^\circ$ in frequency domain. In figure 4, two signals (both at 1.51 Hz) with 180$^\circ$ and 0$^\circ$ phase lag clearly show a time delay of approximately 0.33 seconds, i.e. half a period. Due to large inertia of drive train of wind turbines, in most vibration cases generator speed gradually diverges, rather than in a fast manner. Thus, the designed delay time is sufficient to tackle transient problems in general situations.

Simulations with different configurations were implemented on Bladed, which are listed in table 1. A Shanghai Electric 2MW wind turbine model was used in the above simulations. The mean wind velocity was 10m/s and the turbulence intensity was set as Class B in IEC 3rd Edition.

Time domain signals of generator speed are compared in figure 5, where simA owns large fluctuations but both simB and simC are relatively stable. Effects of different configurations on torque are shown in figure 6. Torques of simB and simC are in general consistent with that of simA, which means drive train vibration can be restrained at the cost of a slight effort on torque.

![Figure 3](image3.png)  
**Figure 3** Bode diagram when lag phase angle $\Phi = 0^\circ$ (solid), 90$^\circ$ (dash) and 180$^\circ$ (dot).

![Figure 4](image4.png)  
**Figure 4** Measured generator speed (upper) and band-pass filtered signals (BP) with phase lag (lower) of $\Phi = 0^\circ$ (dot) and 180$^\circ$ (solid).

| Symbol | Definition                                      |
|--------|------------------------------------------------|
| simA   | Simulation without drive train damper (DTD)    |
| simB   | Simulation with lead                           |
| simC   | Simulation with delay                          |
| simD   | Simulation with filter only and without delay  |
Figure 5. Generator speed, time domain. (blue: simA; black: simB; red: simC).

Figure 6. Generator torque, time domain. (blue: simA; black: simB; red: simC).

Figure 7. Generator speed, frequency domain. (blue: simA; black: simB; red: simC).

Figure 8. Generator torque, frequency domain. (blue: simA; black: simB; red: simC).

Figure 9. Comparison between effects with and without delay in generator speed (a) and generator torque (b). (blue: simC; black: simD).
In addition, from figure 7, amplitudes of generator speed of simB and simC at frequency of 1.51 Hz are lower than that of simA, which means both ways of lead and delay can improve the performance of the original system.

From the viewpoint of generator torque (shown in figure 8), higher amplitudes at higher frequencies (3 Hz – 8 Hz) of simB are revealed than simA and simC, which is caused by natural property of lead method as mentioned above, while the performance of simC is still satisfactory.

With regard to simD, as there is no delay time correction, extra ‘damping’ torque is added at the wrong moment so that the drive train vibration is aggravated, leading to divergence of generator speed (shown in figure 9) and eventually over-speed shut-down. It is proved that inappropriate delay time correction (relevant to the phase correction) may cause adverse impact on drive train.

4. Field Test
A field test on the proposed method was implemented on Shanghai Electric 2MW wind turbine, and test results are shown as figure 10. When the generator speed is in a certain range, the drive train begins to vibrate, and the generator speed starts diverging. Once the proposed damper is turned on, the speed stabilizes in a few periods and the generator keeps operating smoothly. When the damper is turned off, the generator speed diverges rapidly. A constraint from the converter is acting on the changing rate of the generator torque. When the drive train begins to oscillate, the converter limits the changing rate of the torque. Thus, the torque signal is ramping up and down instead of remaining a sinusoidal shape. Once the generator speed converges, this constraint is deactivated and the torque signal recovers to be sinusoidal.

Particularly, if zooming in the signals when enabling the damper (as shown in figure 10, circled by the ellipse), a clear phase shift in the generator torque command could be observed (as shown in figure 11, circled by the ellipse), resulting in the compensation for time delay caused by signal transmission in line and rotor inertia.

5. Conclusion
From the simulations and field tests, conclusions can be drawn:
1) Due to time delay in sensors and actuators, phase correction plays a critical role in a drive train damping, without which the compensation torque could have adverse impacts, such as aggravating vibration.
2) A lag compensator is effective to compensate the phase shift due to system delay.
3) Compared to a lead compensator, a lag compensator can correct the phase without magnifying compensation torque at high frequencies.

4) The novel method of drive train damping in this paper is validated to be effective and can significantly reduce drive train vibration.

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