TAMING THE POWER
ABB Review series
Part III

Twist off

Damping torsional oscillations at the intersection of variable-speed drives and elastic mechanical systems

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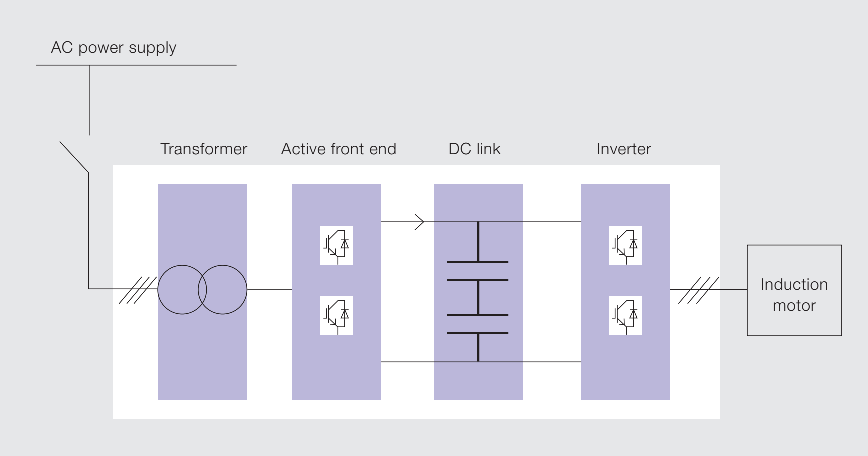
1 Example of an AC drive electrical system



Electrical drivetrains are all-pervasive in the modern world, converting electrical power to mechanical power in a plethora of industrial applications and performing the reverse conversion in power generators. However, all these rotating, variable-speed systems can experience torsional vibrations to some degree during startup, shutdown and operation. In problematic cases, excessive torsional vibrations can develop and these may lead to outcomes ranging from gear wear to broken shafts. Consequently, the torsional response characteristics of rotating equipment and the corresponding control loops have to be analyzed and evaluated to verify the stable operation of the system. This is especially important when the rated power is high because the shaft diameters, and thus the mechanical strength, cannot be increased proportionally with the power. The consequences of mechanical failure of a high-power drive are also more significant.

The severity of the torsional vibrations depends upon the magnitude of the torsional excitation and the difference between the excitation frequencies and natural frequencies associated with mode shapes of the shaft system and their damping. The desired situation is, naturally, one that avoids any coincidence of a torsional excitation frequency with a natural torsional frequency. Therefore, the natural torsional frequencies of the system should be calculated and the excitation forces that can be produced in the system, and the frequencies thereof, have to be defined. This is not a trivial task for complex systems with many elements in the drivetrain. In some cases even the finite stiffness of the motor bed and other flexible parts of the surrounding structures have to be taken into account.

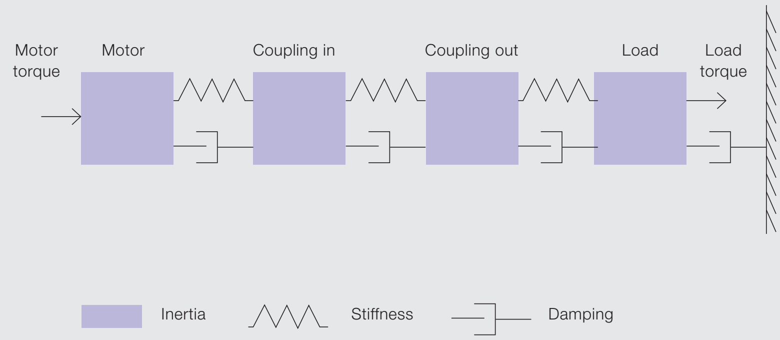
One specific challenge in the case of electromechanical systems is the fact that the electrical and mechanical parts are typically designed, analyzed and controlled separately, without considering their interaction with each other or with other components. Additionally, there can be cases where accurate information about the system is not known in advance. Reducing the degree of uncertainty by defining boundaries for the system parameters and taking care of the robustness margin for the whole range by proper control is the way forward in providing guaranteed stable operation across the entire drivetrain.

Drivetrains

Three key components can be identified in an electromechanical drivetrain: the power grid, plus possibly transformers and input/output filters; the power converter and motor or generator; and the load or turbine. Each of

Title picture
Potentially harmful oscillations can arise in electric motor drivetrains. What can be done to counter them?

2 Schematic of a motor, coupling and load system



Rotating, variable-speed systems can experience torsional oscillations to some degree during startup, shutdown and operation.

these can contribute to the torsional dynamics. Power grid variations can directly affect the torsional behavior of a direct online motor drivetrain. A power converter can largely isolate the torsional system from grid disturbances but, due to the semiconductors switching, a set of excitation frequencies that depend on the motor speed is produced. Most AC electric machines have very smooth torque when driven by sinusoidal voltage but special constructions such as some permanent magnet machines may have significant cogging torque. Finally, the mechanical load of a motor or turbine power of a generator may vary depending on the application and is in some cases difficult to predict.

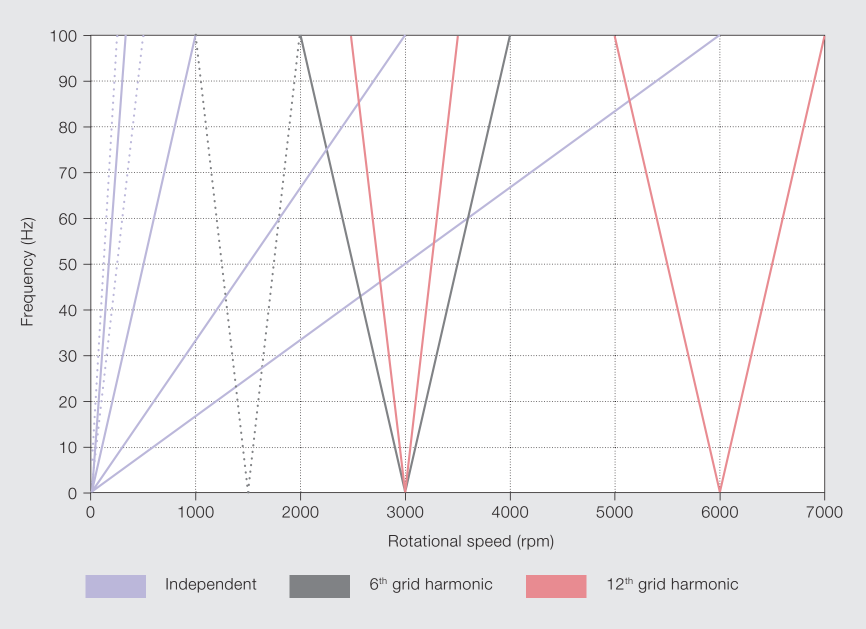
In problematic cases, excessive torsional oscillations can develop and these may lead to outcomes ranging from gear wear to broken shafts.

When studying possible torsional resonances in drivetrains, a so-called modal analysis is first performed and the natural frequencies found are compared with the possible excitation frequencies. For more detailed studies, the electrical system is modeled as discrete resistive, inductive and capacitive elements, while the mechanical driveline is modeled as discrete inertias connected with inertia-free elastic elements representing shafts and couplings → 1–2. Using the transfer functions or differential equations of the control system, the response for various excitations can be verified and optimized.

Ideally, if the model were to fully capture system behavior, appropriate control design could be carried out and performance could be guaranteed – but this is rarely the case as usually only the large concentrated inertias and the main elasticity are known with reasonable accuracy. For example, smaller and distributed inertias – such as those in a gearbox – are more difficult to estimate. The damping coefficients are another source of inaccuracy as it is usually difficult, if not impossible, to obtain these for many elements, so they are often neglected, even though damping can have a significant effect on the resonance frequency and – especially – the amplitude. On the other hand, the electrical characteristics of the motor and motor control certainly cannot be neglected in the drivetrain torsional model since these can significantly change the natural frequencies and the amplification of the excitations.

Because the drivetrain's electrical and mechanical parts are interconnected and oscillations might propagate be-

3 Example of a Campbell diagram for a two-pole motor, showing frequencies excited by an LCI at given rotational speeds



The natural torsional frequencies of the system should be calculated and the excitation forces that can be produced in the system have to be defined.

tween them, analysis cannot always be limited to one or the other, but must be extended to cover from the shaft end all the way back to the electric grid, including any optional frequency converter. Once this is done, solution strategies can then be formulated.

Solution strategies

Depending on the nature of the vibrations, different strategies can be employed to reduce, restrict or prevent them. These strategies generally fall into one of three categories: system design, system operation and active damping.

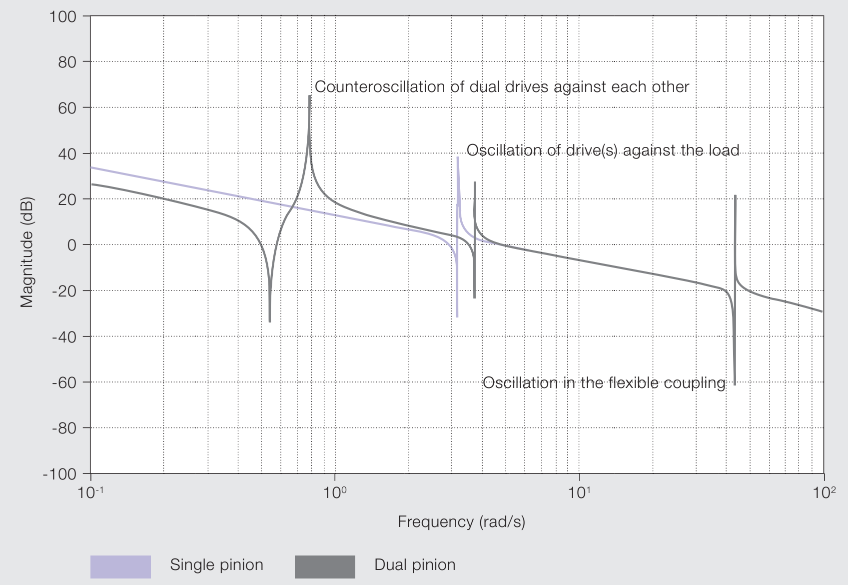
The system design strategy takes preventive action against vibrations by introducing dissipative components such as elastomer or hydrodynamic damped couplings that decrease the vibration amplitude by converting the energy from excitations into heat, or by shaping the spectrum of the excitations with hardware-based sine filters at the converter output. Such methods are also referred to as passive damping methods. Although practical in some applications, they have the drawback that the energy dissipated constitutes wasted energy and the mechanical or electrical filtering slows the system dynamics. These measures are often costly and elastomer couplings suffer from aging.

The second approach uses the modal analysis to determine resonance-free speed ranges in which continuous operation is possible. As the number of motor poles affects these speed ranges, the optimum pole number is selected to give the best fit for the process needs. The method is practical and simple to implement. However, it is not always possible to find wide enough speed ranges, and the rapid accelerations and decelerations required to cross the forbidden resonance speed ranges are not always acceptable.

The third class of strategies is based on the emulation of the physical behavior of dampers. Virtual-resistor and model-based active damping methods are examples of such software-based active solutions. State-space methods are particularly advantageous for high-order systems – they allow the full system, including the interconnections, to be modeled and controlled, and nonlinearities such as friction and backlash to be considered. On the other hand, frequency-based methods are best suited to identifying the critical modes.

Hybrid methods are also often employed by combining two or more of the strategies described above. For example, stiffness of the shafts or the

4 Frequency responses of dual- and single-pinion setups



A modal analysis is performed to determine the natural frequencies in the drives and compare them with the possible excitation frequencies.

couplings can be lowered in order to move the resonance of the system into a bandwidth where an active damping method can then be used to counteract the oscillations. Another example is the use of frequency analysis to provide the system spectrum and the desired target spectrum – afterwards, time-based energy shaping methods can be employed to shape the system spectrum. This example of a hybrid of time and frequency methods gets the best of both worlds: capturing the frequency behaviors and employing state-space techniques.

The torsional response desired is generally one that avoids any coincidence of an operating speed or torsional excitation harmonic with a natural torsional frequency.

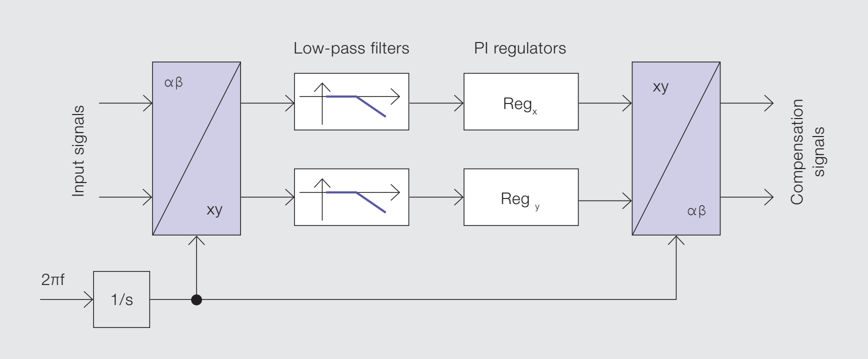
Some practical examples serve to illustrate the different approaches.

Electrically driven compressor stations

Variable-speed drives (VSDs) are commonly employed in natural gas compressor stations. The power range of such stations is typically between 10 and 70 MW, and the rotor rotates with a speed of a few thousand rpm. A step-up gear and relatively long and thin driveshaft links the VSD with a number of compressor stages, forming a rather flexible structure with high load inertia and distinct torsional natural frequencies. A continuous excitation of these frequencies, stemming from one of the compressor stages or from the VSD, can lead to high torsional oscillation amplitudes, which the driveshaft may not be able to endure. The consequences vary from increased wear and reduced lifetime of the gear to catastrophic failure of the couplings or the shafts.

Due to its proven reliability and efficiency, a classic configuration of the VSD system comprises a synchronous machine fed by a load-commutated inverter (LCI), such as ABB's Megadrive-LCI. However, the LCI can generate harmonics in the drive torque, the frequencies of which depend on the drive's pulse number and which

5 Typical compensation algorithm



There are many active control strategies to dampen torsional oscillations and a specific formulation for dual-pinion drives has been patented by ABB.

vary with rotor speed ➔ 3. For certain speeds, these frequencies match the natural frequencies of the driveshaft. A straightforward measure to reduce torsional oscillations is to avoid certain speed ranges, when feasible. Any remaining torsional oscillations excited by, for example, crossing natural frequencies, are either dampened actively or are just left to fade away by themselves.

Variable-speed mill drives

Though a relatively rare event in grinding mills, the undamped effects of torque pulses resonating with one of the drivetrain eigenfrequencies could be serious.

Dual-pinion ring-geared mill drive solutions, for example, are very attractive for medium-sized grinding applications, but they also present a challenge due to their torsional resonance profile and preventive action may need to be taken. In the simplest view, the dual-drive system can be considered to be a collection of flexibly coupled elements formed by the two motors and the mill, which leads to two natural modes of torsional oscillation ➔ 4:

– One in which the motors oscillate in phase against the mill – this frequency is often about 0.5 to 0.6 Hz.
– One in which the motors oscillate against each other – the speed of one increases, while the other's decreases, then this situation reverses itself, ad infinitum. The motors thus alternate at driving the mill, which maintains a constant speed. With relatively long driveshafts and soft couplings, the natural frequency of this mode is around 0.1 to 0.2 Hz.

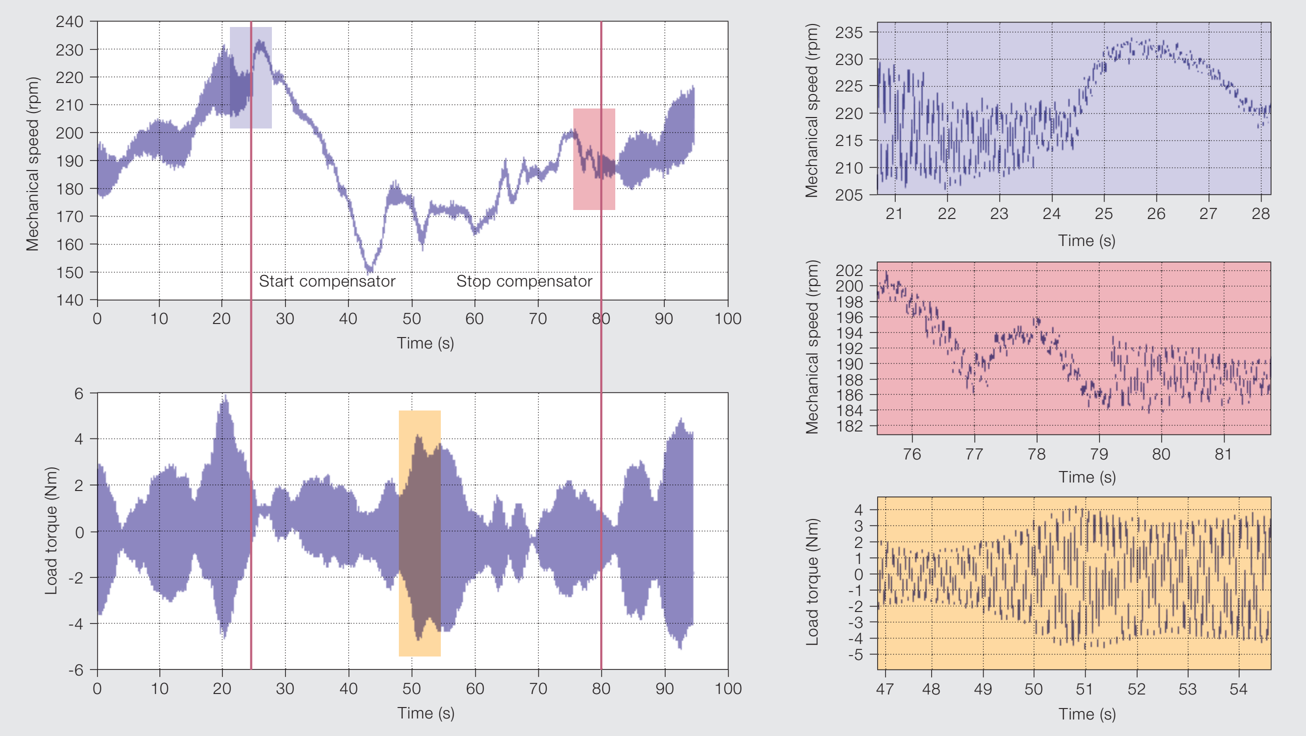
Special attention needs to be paid to the second mode since issues such as worn-out gearing can lead to excitations in the relevant range. There are many active control strategies to dampen torsional oscillations and a specific formulation for dual-pinion drives has been patented by ABB (WO/2012/020031).

In that particular approach, measurements from both drives are used to compute distinct feed-forward control actions to dampen both natural modes, whereas the mill speed is regulated in a traditional master-follower configuration.

Wind

Describing the interactions between systems in a wind turbine is not always straightforward. The aerodynamic interaction between the wind and the blades leads to effects like wind shear and tower shadow, which could be visible as torque harmonics in the rotating shaft. The latter, moreover, is a multi-mass system with natural resonances that cannot be neglected. Even the natural resonances of the tower could contribute to torque oscillations during transients. At the other end of the shaft, the generator torque might also not be ripple-free. Depending on the generator type and structure, different sources of ripples may exist – for example, cogging torque in permanent-magnet synchronous generators, or grid voltage asymmetry in doubly-fed induction generators.

6 Laboratory example of third-harmonic compensation



For all the torque harmonics appearing in the main rotating shaft, there is the opportunity to perform a real-time signal frequency analysis, and classification and compensation of the ripple.

Achieving torsional oscillation damping in these systems cannot always rely on a priori knowledge of the harmonics so real-time analysis of measured or estimated signals (currents, speed) is sometimes used. However, the analysis must always be followed by an automatic classification (eg, “Where does the harmonic come from?”) and, of course, a compensating action performed by the drive control. A typical algorithm for compensating a single frequency is shown in ➔ 5. A laboratory emulation of the third-harmonic compensation in a small-scale wind turbine test bench is shown in ➔ 6, where the emulated turbulence of the wind moves the average value of the speed while generating torque loads with varying magnitude.

The sheer number of applications that use electromechanical drivetrains and the potential for damage resulting from unchecked torsional oscillations in them means that it is essential that close attention is paid to eliminating these harmful effects. Rigorous design and analysis techniques have been shown to be effective at accomplishing this.

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