Model train

Combining electromagnetic and mechanical simulations for better drivetrain designs

TIMO P. HOLOPAINEN, TOMMI RYYPPÖ, GUNNAR PORSBY – The power flowing to a typical rotating machine, such as a pump or compressor, passes through a complex mechanical and electrical transmission chain on its journey from the grid to the target device. This power must flow through all the components in the chain and each of these has to withstand the loading involved. This loading, including extreme forces brought on by resonance or failure modes, appear as torsion in the mechanical components. Mechanical modeling is able to simulate this behavior. However, electromagnetic effects, in the form of electromagnetic stiffness and damping, may also affect vibration behavior, but these effects have been difficult to incorporate into a holistic analysis of the drivetrain. Simulating the electromagnetic fields of an electrical machine is an activity in which ABB has long experience, and this experience is now being combined with mechanical simulation techniques to enhance drivetrain torsional analysis.

1 A typical drivetrain, consisting of a blower (left), a blower shaft (through the yellow cover), a gearbox (under the front yellow acoustic enclosure) and a motor with a cooler above (right).

A typical power transmission chain consists of a driven machine – such as compressor or pump – an optional gearbox, a motor, an optional frequency converter and the power grid. These individual components are mechanically and electrically coupled and the power needed to perform the final useful work, such as accelerating fluid in a pump, flows through each of them. All the components must endure this power flow, which appears in mechanical components as torque.

Nominal, or rated, torque is the basis of component dimensioning, but extreme loads can present themselves in resonance or failure conditions. Resonance vibrations occur when there is an excitation at one of the natural frequencies of the system – the lowest natural frequency of a large drivetrain is around 20 Hz, for example. Contributing harmonic excitations originate from all the main components: the driven machine, gearbox, motor, etc. [1] ➔ 1.

Title picture
Complementing mechanical models with electromagnetic simulation knowledge can improve the quality of rotating machinery design. How can these two disparate model worlds be combined?

Torsional analysis of drivetrains

The aim of a torsional analysis is to predict the vibration behavior of a drivetrain. This information is needed so that harmful vibrations do not appear under any operational conditions. At worst, shortcomings in this analysis may lead to an unpredicted interruption of operation or catastrophic failure.

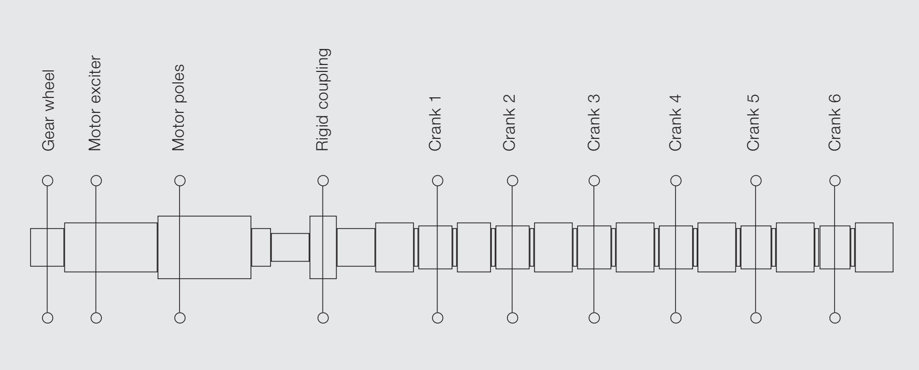
In most industrial cases, each drivetrain element is designed and produced by a different manufacturer, and often without due consideration of the other elements. This poses a challenge to the system integrator as a characteristic feature of drivetrain vibration is the interaction of these elements, which requires the system torsional vibrations to be analyzed as a whole. It is common practice for the system integrator to prepare a torsional model based on the data provided by the individual component manufacturers. Using this model, the system integrator, together with the manufacturers, tunes the drivetrain design to fulfill the torsional vibration requirements.

ABB has responded to drivetrain simulation challenges by developing simple, portable models that accurately describe electromagnetic interaction.

The torsional model applied is usually one-dimensional. This is practical because the full numerical model of each component would include information that is superfluous to the torsional analysis. In addition, the full model could unveil confidential product information. Therefore, the component models of torsional drivetrains are intended to be simple, portable and accurate enough for the job at hand but not overwrought ➔ 2.

Traditionally, an electrical machine in a drivetrain is modeled based on the stiffness and inertia characteristics of the rotor. This kind of rotor model is easily incorporated into the system model. The electromagnetic effects are usually neglected, even though they may affect the vibration behavior by introducing electromagnetic stiffness and damping. One of the reasons for neglecting these effects is the difficulty of incorporating the electromagnetic part of the motor model into the drivetrain model [2].

2 Schematic drawing of a torsional model for a motor-driven piston-compressor



The key is the calculation of electromagnetic spring (torsional stiffness) and damper coefficients.

Simulation of electromagnetic fields

To accommodate the typical behavior of rotor and stator electromagnetic fields, two-dimensional numerical models are often used to describe an electrical machine's electromagnetic behavior ➔ 3. The figure shows a snapshot of typical magnetic fields and currents in an electric motor during operation. Magnetic flux density and flux lines are shown in the upper left part of the figure. The magnetic field lines flow in the plane of the figure; the electric currents in the rotor and stator windings flow in the perpendicular direction. The electromagnetic field rotates around the shaft center. The rotor accompanies the rotating field either synchronously or slightly lagging. Typically, electromagnetic fields, even in steady-state operation, must be simulated in the time domain. The maximum length of the simulation time step is determined by the accuracy required but is usually some tens or hundreds of microseconds.

Simulation is made difficult by the variation in the rotor/stator air gap geometry caused by the machine rotation (the nonlinearities introduced by the magnetic saturation of the constituent steel also complicate matters). The main task of electrical machines – converting electrical energy to mechanical power – is carried out in the air gap, so a diligent mathematical analysis of electromagnetic field behavior in the gap is essential for accurate calculation of the mechanical torque.

Coupled analysis of electromagnetics and drivetrain mechanics

One way to simulate a torsional system is to make the mechanical drivetrain model part of the electrical motor model. In this case, the electrical motor model will use a varying rotor rotational speed – one that is determined by the motor torque, load torque and the equations of motion. Such a simulation is relatively straightforward as long as the mechanical rotor model of the drivetrain is simple and uses well-known elements. This kind of model enables simulation of various operational conditions – for example, the mechanical response to torsional excitations originating from the driven machine, gearbox, electrical motor or supply system. In addition, transient events, such as short circuits or system startup, can be analyzed.

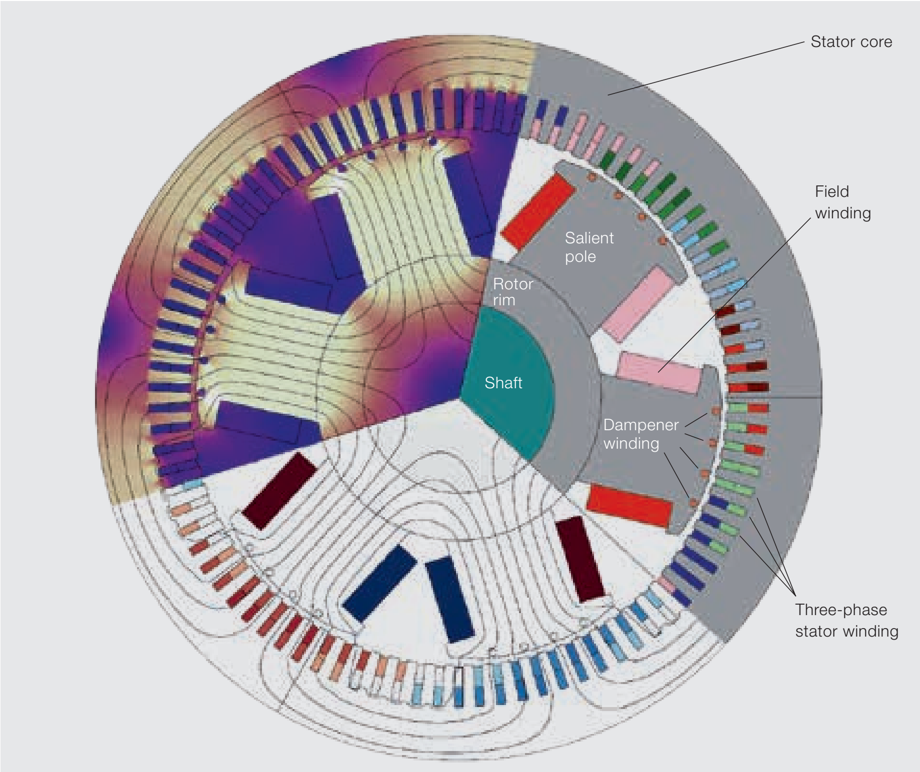
This approach is an excellent way to evaluate electromechanical effects on torsional dynamics and has been used successfully by ABB in some special cases. However, this type of simulation and analysis is computationally too laborious to be used in standard torsional drivetrain design. Further, the system integrators or their consultants do not usually have access to appropriate simulation tools.

Electromagnetic stiffness and damping models

ABB has responded to drivetrain simulation challenges by developing simple, portable models that accurately describe electromagnetic interaction [3]. The key to these models is the calculation of electromagnetic spring (torsional stiffness) and damper coefficients ➔ 4. Both of these coefficients are frequency dependent and can be determined without a mechanical drivetrain model by simulating the motor in the steady-state operation condition. The torsional stiffness is the ratio between the oscillating torque and angular displacement amplitudes, and the damping is the ratio between the torque and velocity amplitudes.

A consensus of common and simple models that accurately describe electromagnetic effects in drivetrains is emerging, though the exact form of these models is still open.

3 Cross-section of a six-pole synchronous high-power motor



In principle, these stiffness and damping ratios can be calculated for one frequency by forcing the rotor to oscillate at that frequency and calculating the oscillation of torque at the same frequency. In practice, this becomes complicated because the rotor and stator slotting generates torque harmonics that may coincide with the frequency under investigation. This interference can be eliminated by calculating a reference analysis with exactly the same parameters but without the rotor oscillation and "subtracting" it. The only drawback of this approach is the large amount of computation needed: Two time-domain simulations with post-processing are required to yield the coefficients for just one frequency at one specified operation condition.

A more effective solution is to apply a spectral method that is based on the impulse excitation. In this approach, the rotor is excited by a forced rotational pulse and the torque response is simulated. After calculating the difference between the results of this simulation and the reference solution, the electromagnetic stiffness and damping coefficients can be determined for a frequency range. This range is dependent on the pulse parameters but it easily covers the frequency range of interest to drivetrain torsional design. Surprisingly, this kind of impulse method can be used for a nonlinear and time-harmonic system – numerous simulations show that the system seems to be linear with respect to the excitation amplitude and, thus, the calculated stiffness and damping coefficients describe behavior during arbitrary torsional oscillation.

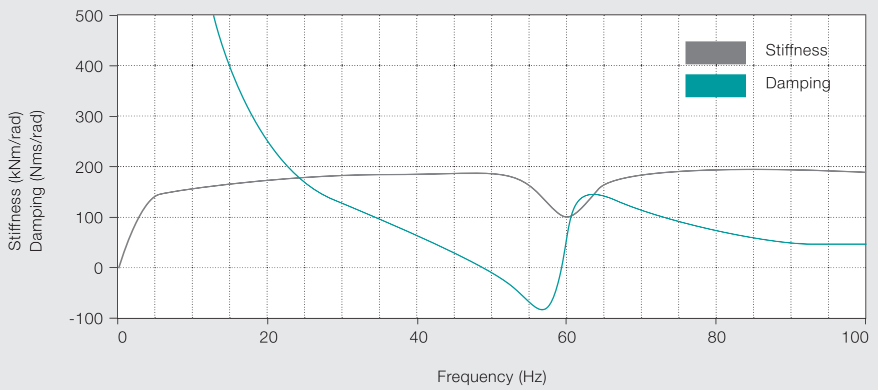
In this way, the large number of simulations previously needed to determine the stiffness and damping coefficients can be replaced by just two.

The electromagnetic stiffness and damping coefficients thus extracted can then be included in the drivetrain torsional analysis. The frequency dependency of these parameters may complicate their inclusion slightly but, in principle, all analysis programs can handle this kind of dependency. Of more concern is the fact that the coefficients are calculated for only one operational condition.

Equivalent circuit model

A more flexible, but slightly less accurate, solution is to apply an equivalent circuit model that handles the electromagnetic effects. At ABB, this approach has been used in drivetrain analysis and design for more than 20 years: A sophisticated in-house software – Simulation of Machine

4 Electromagnetic torsional stiffness and damping – clearly dependent on the vibration frequency – of a 60 Hz / 932 kW induction motor [3]. Note negative damping between 49.7 and 59.4 Hz.



Transients (SMT) – was developed in the early '90s and this has had great success, especially for systems featuring large synchronous motors.

An equivalent circuit model is an analytical motor model described by a limited number of parameters (about 10, in the simplest models). Such models describe the behavior of an electrical machine from the supply voltage entry point all the way through to the resultant shaft torque and speed. They were developed for electrical analysis and design before the advent of computers but are still useful as part of a drivetrain torsional model. The challenges of using them here are related to the coupling of the equivalent circuit model to the mechanical drivetrain model. The former is not a standard component of a typical torsional model and, therefore, its inclusion without source code access or in-depth understanding is challenging. However, it is eminently feasible and this kind of a motor model is often used as a part of a frequency converter control system.

Accuracy is another challenge inherent in equivalent circuit models as they were developed during the pioneering years of electrical machines when model parameters were based on the actual dimensions of critical parts and experimental results. Today, simulation models can be applied to determine model parameters. This approach combines the accuracy of simulation and the simplicity and portability of the equivalent circuit models.

Model role

Today's electromagnetic field simulation models produce accurate information with little effort, but electromagnetic effects are only occasionally included into the torsional design of drivetrain systems. The main reason is, probably, the difficulty of including the effects in a standard calculation program that can be made available to system integrators.

There are various ways to combine the mechanical and electrical parts of the drivetrain torsional models, but a consensus of common and simple models that accurately describe electromagnetic effects in drivetrains is emerging, though the exact form of these models is still open. ABB continues to work in close cooperation with customers and the rotating machines community to refine these models. This development work will make it easier for electromagnetic effects to be included in drivetrain analysis as a matter of course and lead to new, improved drivetrain products.

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[3] T. P. Holopainen, et al., "Electromechanical interaction in torsional vibrations of drive train systems including an electrical machine," in Proceedings of the 8th International Conference on Rotor Dynamics. Seoul, Korea, September 12–15, 2010.