2024 European Control Conference (ECC)
June 25-28, 2024. Stockholm, Sweden

Second Harmonic Torque Suppression in Electric Propulsion Systems

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A propulsion system for a single phase ac fed electric train is shown in Fig. 1. To absorb the inevitable so called second harmonic input power component of such systems, large and bulky hardware filters are traditionally added, cf. the red components in the figure. These dedicated hardware filters keep the intermediate so called dc-link voltage smooth, but add cost, weight and space to the system. Removing the filters instead leads to large second harmonic dc-link voltage oscillations, which may propagate to the motor torque. The oscillating dc-link voltage component is sinusoidal, where the frequency is twice the supply frequency and the amplitude is proportional to the system power. Even with traditional broadband suppression of dc-link voltage variations, the remaining second harmonic torque ripple may still be large enough to damage mechanical components of the system, and to cause annoying noise in the car body. To enable practical operation without second harmonic hardware filters, improved disturbance suppression is therefore required, which is investigated in this presentation.

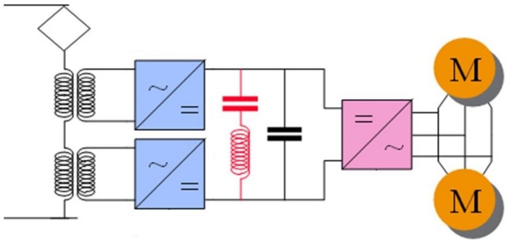

Fig. 1. Ac propulsions system

To specifically suppress second harmonic torque oscillations, an adaptive feedforward scheme as depicted in Fig. 2 is applied. The effect of the disturbance on the output is counteracted through a feedforward controller. The control signal is generated by amplifying and phase shifting the narrow-band disturbance component, which is extracted from a disturbance measurement. To optimize steady-state suppression, the controller parameters are further online adapted, based on the measured (or estimated) system output.

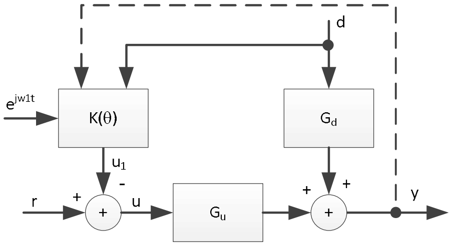

Fig. 2. Adaptive feedforward cancellation (AFC), where a (broadband) disturbance *d(t)* affects the output *y(t)* of a dynamical system.

Although general disturbance suppression over a large frequency range is a challenging task in itself, it is shown that also interaction with additional system dynamics may have to be considered. With the industrial application studied in this contribution, efficient disturbance suppression may in fact cause unfortunate interaction with the dc-link voltage control, cf. the block diagram of the system in Fig. 3.

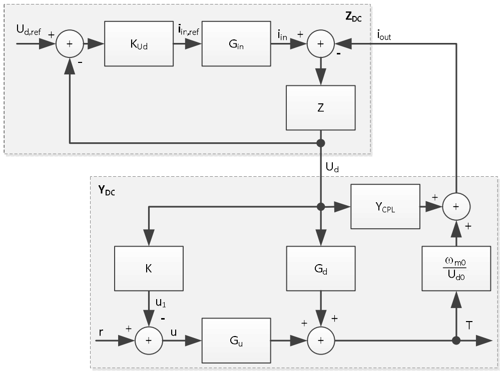

Fig. 3. Propulsion system dynamics.

Perfect suppression of dc-link voltage oscillations implies an internal so called constant power load (CPL) behavior, which is known to cause stability problems in dc fed propulsion systems (with poorly damped input LC filters). Suppression of dc-link voltage variations must then be designed under the constraint of also keeping the overall system stable. For a structured trade-off between suppression bandwidth and overall system damping, the dynamical properties of disturbance suppression need to be understood and analyzed. Although the applied feedforward

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suppression controller is not described by ordinary differential equations, but also involves demodulation and remodulation, its Laplace transform can still be derived (with fixed controller parameters). This work exploits this to allow analytical analysis of the overall system properties.

The performance of the designed adaptive feedfoward cancellation is verified both through hardware in the loop (HIL) simulations, but also through real train experiments. One example is shown in Fig. 4, where the amplitudes of the second harmonic torque and dc-link voltage components (in this case 33.3 Hz) are shown as functions of motor speed with and without additional disturbance suppression. This train actually contains a second harmonic filter, but the resulting dc-link voltage oscillations are still large enough to cause undesirable torque ripple. It is verified that additional disturbance suppression significantly decreases the torque oscillations.

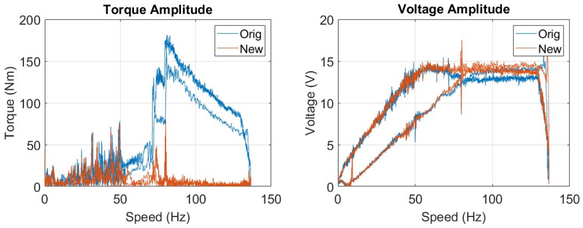

Fig. 4. Torque ripple from train tests during entire load cycles. Here the second harmonic frequency is 33.3 Hz and the specific train runs with a second harmonic filter. The low remaining dc-link voltage ripple still results in rather large torque ripple. The torque ripple would be even larger with more unfortunate filter components (manufacturing tolerances or aging effects). Results are shown both without (blue) and with (red) additional suppression.