WHITEPAPER

Measuring Torque Ripple and Its Effects on Electric Power and Noise & Vibration

Authors:

Mitch Marks
Business Development Manager – Electrification

Ed Green
Principal Staff Engineer –Sound and
Vibration Engineering Services

Brian Thom
Senior Project Engineer –Sound and
Vibration Engineering Services

INTRODUCTION

The electric motor has a very desirable torque speed curve because it can not only produce max torque at 0 speed, but across a wide range of speeds. While this ability creates new opportunities with the electric motor, it also creates some new challenges in comparison to internal combustion engines. One of these challenges is torque ripple, which has several implications including control, power output, noise, vibration, and durability. Torque ripple can be described as the variance of output torque as the motor rotates. This white paper will focus on the measurement of these signals and their implications for noise and vibration. The paper will also include examples from a couple of case studies which demonstrate the impact of torque ripple and its effects on NVH.

UNDERSTANDING TORQUE RIPPLE

Torque is often described as a DC quantity, but it does have a frequency component. Specifically, in electric motors torque will have a DC average, with a cyclical offset. This offset will have a frequency that is a function of rotational speed and an amplitude that is a percentage of the DC value. An example of torque ripple can be seen in figure 1, where the average torque is a DC, but the high bandwidth torque shows a roughly +-2Nm ripple. While this may not seem like a significant issue, the high frequencies of this ripple can lead to a variety of undesirable outcomes; including audible noise, structural vibrations, and gear fatigue. In order to mitigate the torque ripple, we need to understand its sources which include electrical excitation, machine construction, mechanical resonances, alignment, and loading.

SOURCES AND EFFECTS OF TORQUE RIPPLE

Electrical excitation of the machine contributes to the torque ripple because the torque of the machine will follow the current. The most extreme example of this is the single-phase machine where there will be cyclical torque at two-times the fundamental frequency, and a zero-torque element. By increasing the phases, you can eliminate the zero cross and amplitude of the ripple, but you will increase the frequency. The typical machine will have three phases, which is advantageous for torque ripple, but will not eliminate it.

Since the torque is created by the sinusoidal excitation, the torque ripple from excitation will be at the same frequency as the electrical signal, which means as speed increases, so will the torque ripple frequency. In addition, other elements of torque ripple will be present, because excitation is not a perfect sine wave. Inverters which operate at a high frequency are often employed, and the machine winding will affect the distribution of current. As a result, these issues will create additional torque ripple.

Construction is another example of a contributing factor which can impact torque ripple. In all machines torque ripple is driven by the machine winding function, and each machine type has a contribution of torque ripple form the rotor magnetics interacting with the stator iron. In induction machines, the torque ripple is smaller in amplitude and could be managed with the skew of the rotor bars. With an increase in the utilization of permanent magnet machines, you need to account for the effects of the magnets on the rotor, in addition to the winding function and skew. The magnets on the rotor will attract to the iron on the stator, and as the machine spins, the magnets will attract to each stator tooth. Since there are a fixed number of rotor magnets and stator slots, this element of torque ripple will also be proportional to speed. The high amplitude, and potentially high frequencies due to the speed of the machine make torque ripple from permanent magnets a difficult problem to characterize and reduce.

Given that excitation and the construction of the machine create torque ripple, you can also use these two features in combination to alleviate it. Different construction patterns combined with different types of machine control can be used to reduce torque ripple. Advances in feedback and inverter technology allow us to push the envelope of torque ripple mitigation. In order to validate that these methods of torque ripple mitigation work, engineers need to validate their designs with measurements.

TORQUE RIPPLE MEASUREMENT

Measuring torque ripple is not a simple task because of the accuracy and bandwidth requirements of both the sensors and instrumentation - the sensors need to be sufficiently accurate, so that you can trust small deviations in torque even on a large range torque sensor. The analogy of measuring the

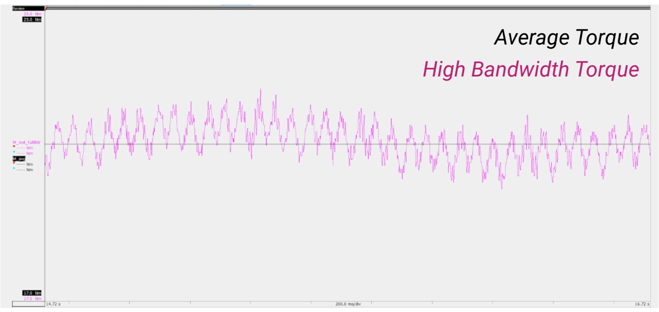

Figure 1: Torque ripple oscillating around an average with frequency and amplitude

feather on the back of an elephant is often used. For example, an HBM T12HP torque sensor seen in figure 2, is .02% accurate. If the sensor has a 1000Nm range, there will be an uncertainty of .2 Nm. Using a sensor this accurate, engineers can trust the amplitude of your torque ripple. If you want to trust the measurement down to a smaller value, engineers will need to use a lower range sensor. Calibration of a sensor can also reduce the measurement uncertainty of the torque amplitude measurement.

Figure 2: HBM T12HP torque sensor

The bandwidth requirement is also an important factor to understanding torque ripple, because the two main sources of torque ripple have their frequency increase with speed. Electric machines often operate at very high rotational speeds, which means they will have proportionately high frequency torque ripples. Inverter switching frequencies are also at higher frequencies and can also contribute to torque ripple. In order to understand the amplitude and frequency content of the torque ripple, a sensor needs to have enough bandwidth that you can trust these signals. Figure 3 shows an example of the same signal measured with three different filter rates - as the filter rates increase results in a loss in both amplitude and frequency.

The torque sensors from HBM utilize a digital frequency output type to minimize noise on the signal. In an environment that has a large amount of magnetic interference, such as an inverter driven machine, analog signals are susceptible to electrical noise. Using a digital output eliminates noise and ensures the quality of the signal for both accuracy and bandwidth. When measuring the digital output, you should ensure that the measurement equipment has high quality input channels to handle this high accuracy signal.

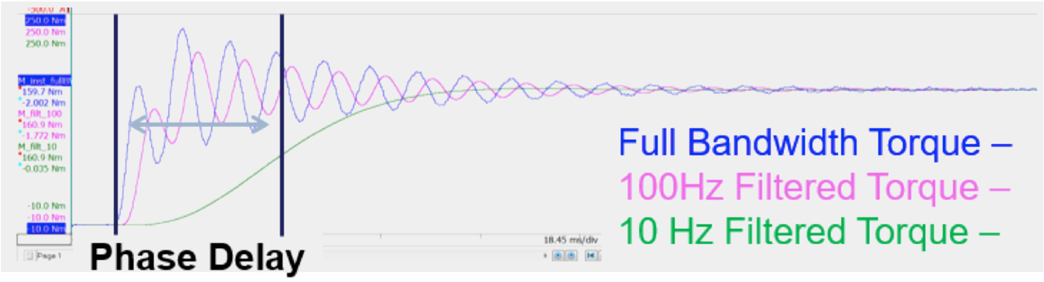

Figure 3: Load step on a machine at 7500 RPM showing high bandwidth torque at different filter rates.

The measurement of torque ripple is not only dependent on quality sensing equipment, it also requires facilities to execute a reliable test and measurement equipment to record the torque and other signals of interest. From the facilities side, a test requires a dynamometer that has a stiff speed control as well as a high disturbance rejection, so it can hold torque and speed for a test point. If the load machine is designed to have a low torque ripple itself, that will minimize external factors contributing to the torque ripple measurement. A couple of ways to improve the measurement quality of torque ripple include using a short and torsional stiff shaft which will minimize torsional vibrations as well as using a proper coupler with a dual flex plate in the driveline.

Torque sensors are the main element used in measuring torque ripple; however, measuring voltage, current, noise, and vibration will allow engineers to correlate their torque ripple to its source and characterize its effects. For this, the test will require other sensors with enough bandwidth and accuracy to meet the tests needs. These sensors will need to be measured with a system that can record data with enough bandwidth and accuracy for a wide variety of signals. An example of this type of measurement equipment is the HBM eDrive, figure 4, which can continuously record data for electric and mechanical signals. This variety of signals includes high accuracy timer counter channels for making the best possible measurements of a frequency output torque sensor. Time aligned signals for voltage, current, torque, sound, and vibration will allow engineers to identify problems, correlate data, and validate models.

Figure 4: HBM eDrive and measurement accessories

Once a test system is implemented it creates opportunities for engineers to do amplitude, control, or frequency analysis on their torque signals. Figure 5a shows an example of a speed ramp test torque ripple where the speed was ramped from 0 to max speed and the torque was held at a fixed value. It becomes very clear during a ramp test that there are resonant torque points at certain speeds. We can see this by the areas of increased amplitude in the torque and the increased percentage of torque ripple for specific speeds. These resonant torque points may come as a surprise to many engineers who are concerned with electrical and mechanical power output because they do not often see large fluctuations in power. This is because torque ripple is a function of rotational speed, and will average out to a static value over the rotation of the machine.

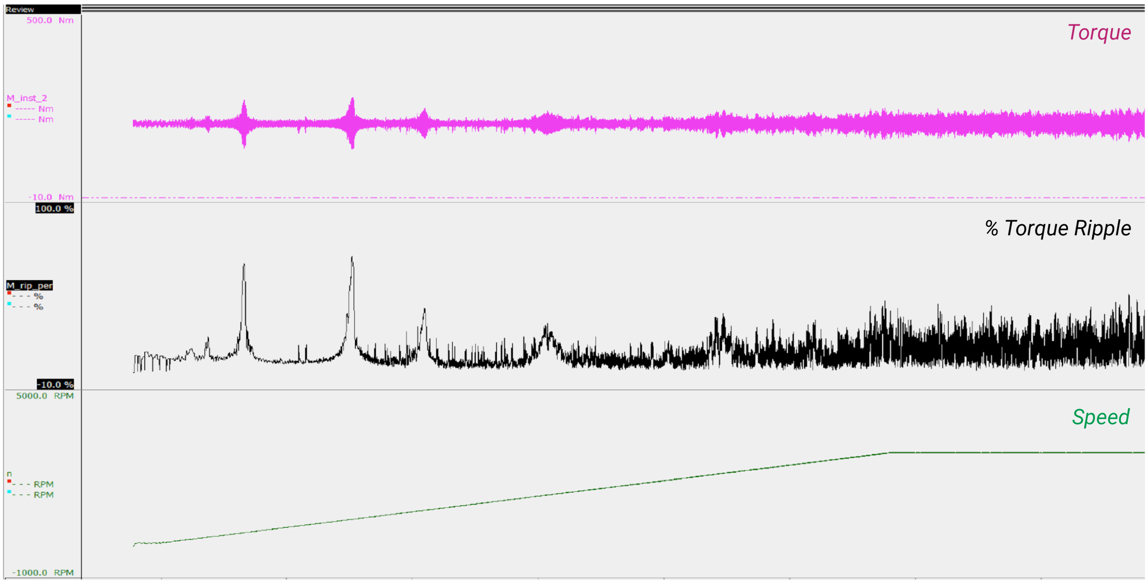

Figure 5a: (Top) Torque ripple and torque ripple percentage for a ramp from 0 to nominal speed

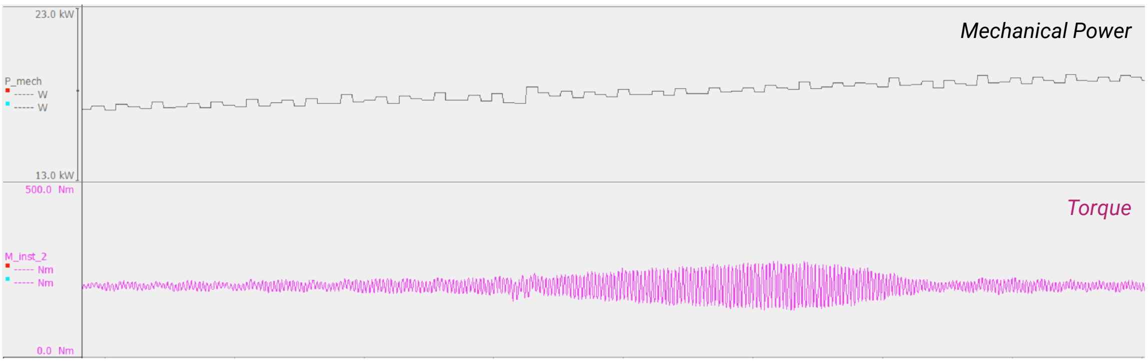

Figure 5b: (Bottom) Zoomed in segment of resonant torque ripple and power

This averaged power during a torque resonance can be seen in figure 5b, which is a zoomed section of torque and power for the first resonant point. Power is averaged per rotation so the fluctuation remains very low, despite their being nearly 60% torque ripple. Torque ripple, not having a large effect on average power, but having a large frequency content, creates a need to do frequency analysis on the signals for negative effects like noise and vibration.

MOTOR CONSTRUCTION – SOURCES OF TORQUE RIPPLE

As discussed above, several characteristics of the electric motor system influences torque ripple including the number of phases of the motor, excitation frequency of the motor, and architecture of the motor windings. These characteristics can incur forces that are tangential, which causes torque ripple, and radial force, which causes stator noise.

There are several definitions of the fundamental excitation frequency of the motor (including torque and radial forces). The following equation is common:

$$Fex(Hz) = pN/60$$

Where p is the number of pole pairs and N is the rpm. In an alternate definition p is the number of poles rather than the number of pole pairs.

An example of torque ripple in a system as seen in figure 6, consists of a simple synchronous motor system with ten pole pairs. In this system the rotor is a powerful magnet, the motor stator is iron, and they are separated by a small air gap. The radial forces and the lesser tangential forces produce stator vibration and motor torque ripple, which increase as load increases. The fundamental frequency in this example is the strongest forcing function that is observed in the data, but several other orders are also observed. These orders are present due to geometry and mechanical, magnetic, and current imperfections in the system.

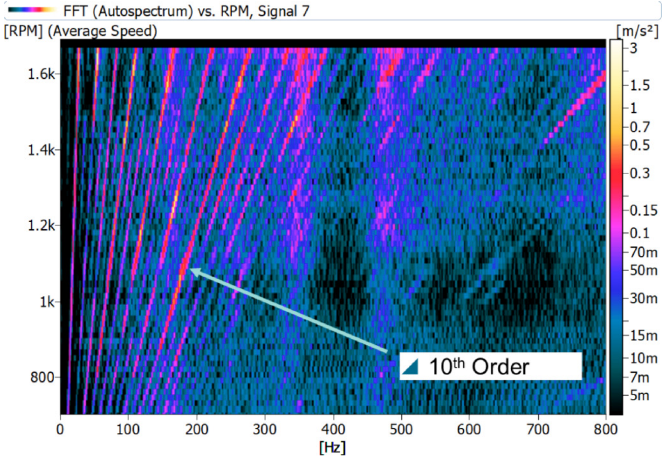

Figure 6: Example FFT colormap of synchronous motor run up

IMPACT OF TORQUE RIPPLE IN AUTOMOTIVE APPLICATIONS

Torque ripple has an impact on what the driver hears and feels inside the vehicle. As such, torque ripple generated in the motor is transmitted into the body through the powertrain mounts and suspension. These dynamic force inputs into the body can cause noise, vibration, and shudder (low frequency vibration), that can be observed by the occupants in the vehicle. In order to isolate the vehicle from torque ripple, the effect of the ripple should be minimized by motor design and considered when designing motor mounting strategies and bushing rates. The degree to which the dynamic forces become NVH issues depends on the structure borne and airborne sensitivity of the body – the P/F and P/Q transfer functions, respectively.

NVH CASE STUDY 1: SIMULATION OF DIFFERENT MOTORS INTO A CAR

Advanced simulation tools can be used to quantify the impact of the torque ripple at a receiver position given a similar body structure. Simulations of noise characteristics caused by torque ripple can be created from a hybrid CAE-test model. This hybrid model consists of mount forces and source strengths calculated in CAE combined with measured test data to create drivable NVH models in the VI-Grade NVH driving simulator.

As shown in figure 7, by calculating switched reluctance motor and an induction motor forcing functions (acoustic source strength, Q, and vibration force, F), and combining them with the measured vehicle body sensitivities (P/Fs and P/Qs), the amount of noise generated from the electric motor can be modelled in the occupant positions in the vehicle. The forcing functions were calculated by Romax Technology (mount forces, F), and the acoustic source strengths (Q) were calculated by Actran. This allows the NVH attributes of the proposed electric powertrain to be evaluated without building prototype vehicles.

This case study can provide insight into radial forces vs. torque ripple. In some scenarios torque ripple can produce a similar noise to radial forces. The tones from the switch reluctance motor have a higher loudness level than the induction motor which can be seen in figure 8. The torque ripple for the switch reluctance motor has a high contribution around 300 rpm exceeding the gear noise at that motor speed. This example illustrates the importance of torque ripple, how in some cases the torque ripple can be similar or greater than radial forces, and how it can be observed by an occupant of a vehicle.

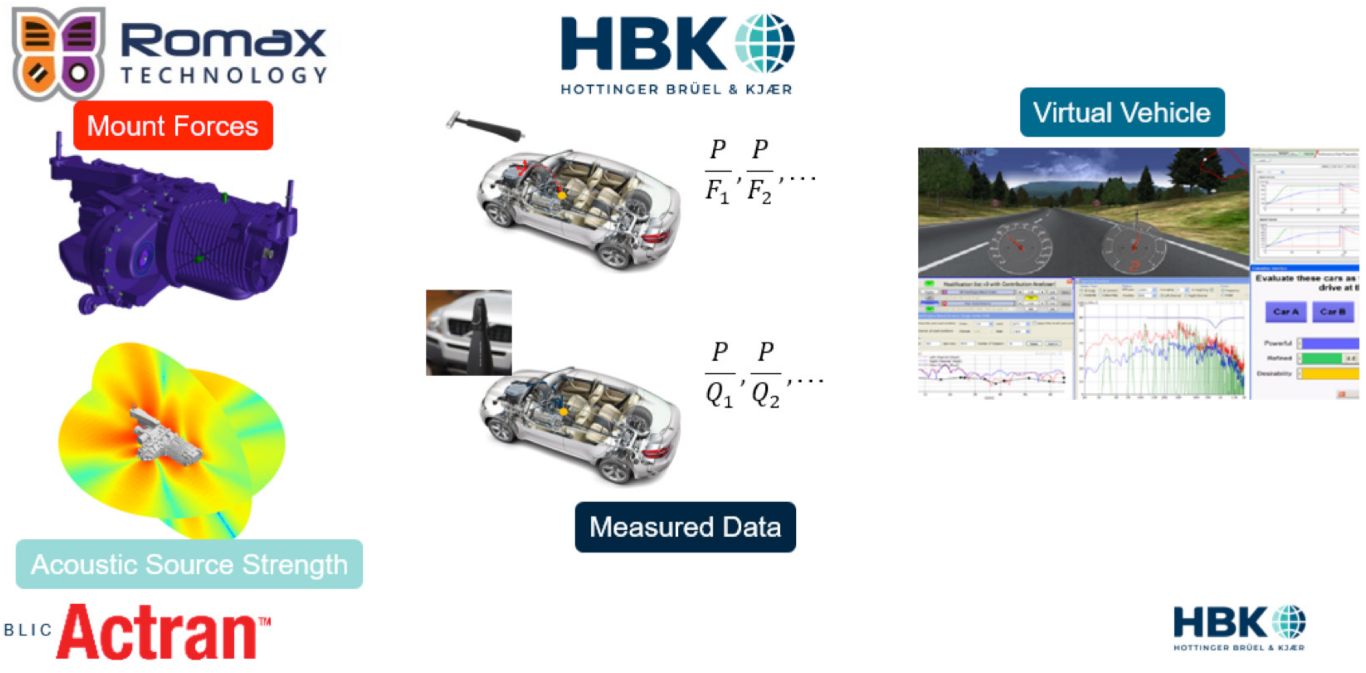

Figure 7: Calculated acoustic source strengths combined with measured body sensitivities to create an NVH simulation model

NVH CASE STUDY 2: PERMANENT MAGNET TRACTION MOTOR

An automotive traction motor at Millbrook Revolutionary Engineering was suspected to have unacceptable torque ripple. The Genesis HighSpeed transient recorder and data acquisition system along with the Perception software from HBM were used to acquire a combination of electrical and NVH data including high voltage, motor current, torque output, microphone signals, and accelerometer signals. Brüel & Kjær's BKConnect software was used to process the signals after down-sampling and re-sampling the signals to a sample frequency of 65,536 samples/second.

Next, a sweep measurement was conducted at 200 Nm to understand the performance of an electric motor with four pole pairs. An investigation of the current and voltage colormaps as seen in figure 10) show strong fourth order content as expected due to the four pole pairs motor construction. However, the fourth order content had very little effect on torque ripple, the torque signal can be seen as a resonance that is present at 340 Hz that elevates the levels of several orders.

The origins of the order content observed in the torque plot are not due to the four-pole pair construction of the motor but other physical components in the motor (i.e. shaft resonance).

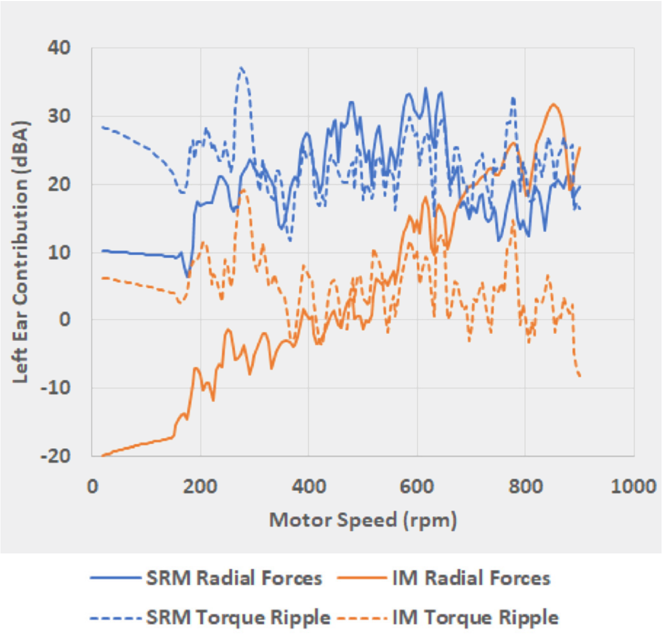

Figure 8: Radial and force torque comparison for SRM and IM motors

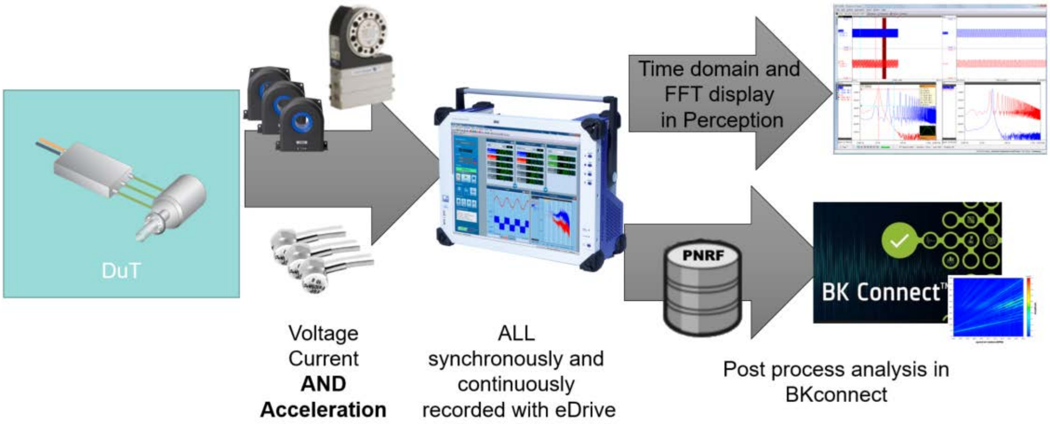

Figure 9: Hardware and software setup

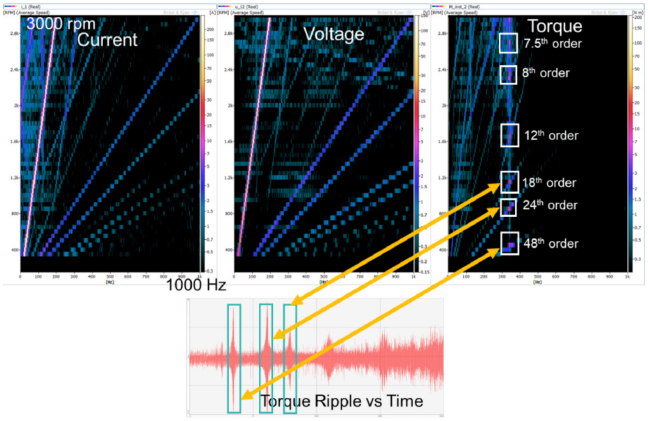

Figure 10: Current voltage and torque colormaps for a 200Nm sweep

Using an approach of combined NVH and power electronics measurement techniques helps to shed light on the NVH performance of electric motors. This combination highlights the resonant frequency causing the torque ripple. The next step in troubleshooting the issue is to apply a combination of conventional NVH testing, knowledge of the motor construction and operation to determine the source of the resonance in order to look for a solution to reduce the torque ripple.

There are many contributing factors to torque ripple and even more complexity in how it gets transmitted to noise and vibration. Acquiring these quantities in a single measurement platform, and having transparency to all steps of the transition from electrical, to rotational, to noise and vibration, will allow engineers to solve problems more quickly. HBK offers a variety of products and services for achieving these goals.

HBK – Hottinger Brüel & Kjær
www.hbkworld.com
info@hbkworld.com

www.hbkworld.com