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Dynamic Torque Measurements Reveal True Electric Machine Characteristics

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Mechanical power measurements of an electric machine are very important to help understand what the motor is doing at any given time and operating point. Mechanical measurements help characterize the motor, build up models for the machine, ensure confidence in controllers and understand the limits of the system. Torque accuracy and bandwidth are particularly important for designing a controller and implementing an electric motor solution.

In electric machines we often want to understand the efficiency and dynamics. Since torque is not a static value, it is preferred to have a highly accurate averaged measurement. This is comparable to using RMS values for electrical efficiency.

The torque accuracy is of high importance since electric machines can operate in the high 90s of efficiency percentage. If a machine has a 98% efficiency measurement, then a ±3% error implies the machine could have an efficiency of 101%, which of course is impossible. Therefore, a highly accurate measurement is required.

It's worth noting that this is a relatively new issue brought on by the development of highly efficient machines. For example, in the past we might have been dealing with an internal combustion engine, which has an efficiency of 38%. In that case the 3% error could lead to an efficiency measurement of 41%, which would be reasonable.

A high-bandwidth torque measurement is also needed to understand what happens instantaneously. This could be cogging torque for a steady-state operation, torque response during loading and even torque during control changes.

This article demonstrates the capabilities of using a highly accurate and high bandwidth torque sensor, such as the T12HP,[1] in combination with the eDrive power analyzer,[2] to make various types of high-bandwidth torque measurements. These measurements are made using high sample rates with real-time cycle count averaging to obtain faster torque measurements even during dynamic load changes.

Instantaneous And Average Torque

Fig. 1 shows torque during an efficiency measurement for a standard PWM inverter in a steady-state torque and speed scenario. The bottom section has a single voltage and current to show what is happening at the terminals of the motor. On top, a red waveform shows instantaneous torque which can be used to obtain a power value. However, typically what is desired from these efficiency cases is a good average torque that is on the same time basis as the average used for the electrical values, preferably on a per-cycle basis.

That means that every point measured from the torque sensor is summed and averaged over the time period of a fundamental frequency of current. This value is shown in the black waveform. This provides an accurate time aligned efficiency between electrical and mechanical values without inaccuracies being introduced from the natural fluctuations of the system or outside fluctuations from a dyno.

Sampling at a rate that encompasses the entire 6-kHz bandwidth of the sensor enables one to obtain accurate averages very quickly as opposed to other systems that sample slowly and need long averages to achieve a good average value. Slower sampling can require averaging on the order of minutes or at best tens of seconds to settle on a good value. Having a high-bandwidth sensor coupled with a high-sampling-rate DAQ with real-time cycle count averaging enables one to achieve both dynamic and averaged accurate torque measurements very quickly.

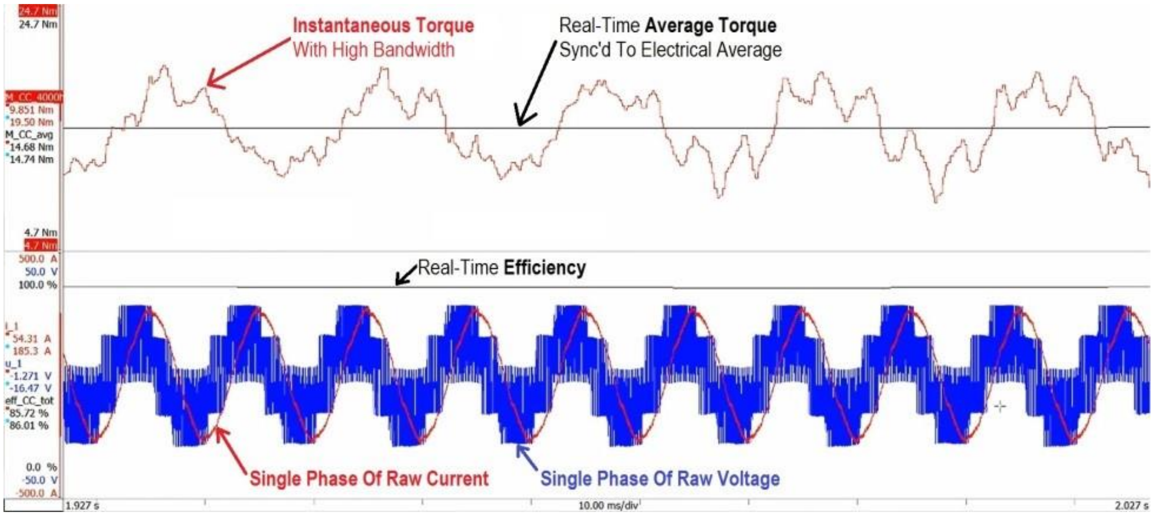

Fig. 1. Instantaneous and real-time average torque in an efficiency measurement taken with the eDrive power analyzer.

Dynamic Load Testing

Fig. 2 shows torque for a highly dynamic test of a motor at 5 kRPM, initially at 0 Nm followed by a load step to 70 Nm. The electrical characteristics respond very quickly. The red signal is a high-bandwidth torque, the blue signal is a 10-Hz filtered torque often encountered with typical torque cells and the black signal is a high-bandwidth real-time cycle averaged torque summed and averaged over the same time period as the fundamental frequency of current.

The dynamic torque in red clearly shows a dramatic peak up to 105 Nm followed by a valley down to 35 Nm. This is what is actually happening with the torque. The motor controller is reacting to the load step and has some mechanical damping and control settling time. In total, it takes about 1/10th of a second for the system to settle. More importantly, the torque is about 50% higher than the average.

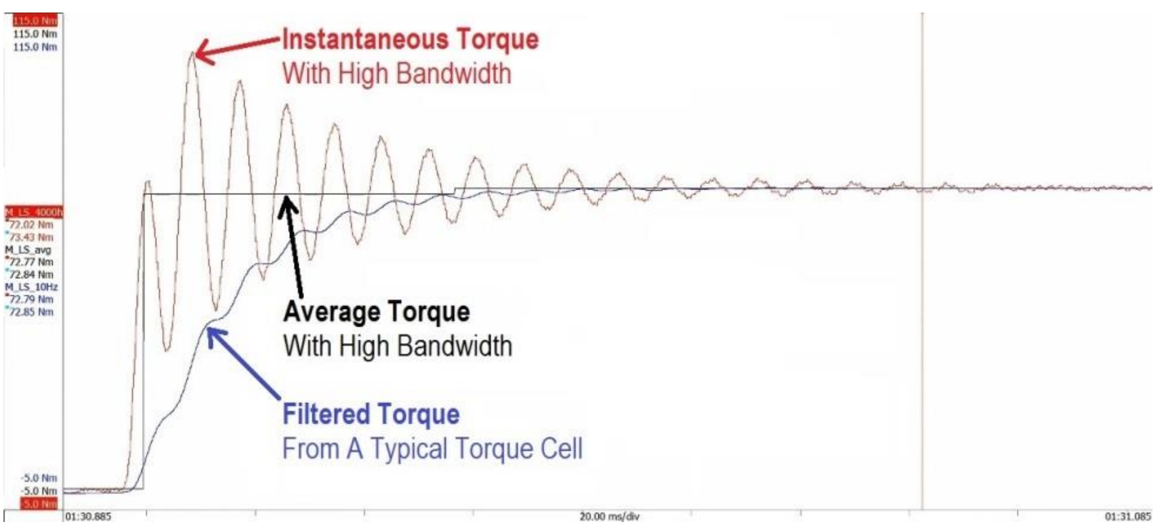

Fig. 2. Torque in a highy dynamic motor test from 0 Nm to a 70-Nm load step.

This information is very valuable when determining what is actually happening in the motor. To relate this to electric cars, it is exactly what the passenger is feeling while driving. By knowing what the torque is actually doing, improvements can be made to control it much better. Also, later in time, there is actual ripple on the torque that has a cyclical nature. This is referred to as torque ripple and the presence of a high-bandwidth and high-accuracy sensor makes viewing this possible.

Seeing the dynamic torque provides the vital information on exactly when torque is applied. Systems that have filters have a phase delay. Notice the delay between the red full-bandwidth signal and the blue filtered signal. The rise time is also severely delayed with the low filter value and all the dynamics are lost. The eventual value is the same as the cycle-based average torque but one cannot see the torque ripple dynamics. This is a much slower signal and loses all the dynamics and makes testing require a much longer time period.

The cycle-averaged torque signal is almost instantaneously at the commanded value. This is due to taking an appropriate time average of all the points going equally higher and lower than the average, even during the settling time. This provides a reliable number for an efficiency reading but no sense of the dynamics. The cycle-based nature of the calculated average makes this a very accurate solution, even when doing dynamic testing. However, it also does not have the dynamics.

The combination of the averaged value and the instantaneous value make the high-bandwidth torque cell in combination with a real-time cycle-count-averaging DAQ a very powerful tool for understanding both the dynamics and averages of an electromechanical system especially during load steps.

Cogging Torque

Fig. 3 shows cogging torque caused by the permanent magnets of a machine. In this test, a motor was spun at a low speed and loaded at different levels. Observers of this particular test were very excited to see about a 2-Nm ripple from a machine while at a 100-Nm span. One can see a distinct pattern of peaks and low and high valleys.

When comparing the waveform to the geometry of the machine, one will notice that the pattern is actually the same as the shape of the magnets inside the machine. This can help determine how to operate the control or what operation regions to avoid based on the machine use case. This ripple will vary from load point to load point. In the case of electric vehicles, one may not want to operate in a high ripple region if the driver will feel it at the output.

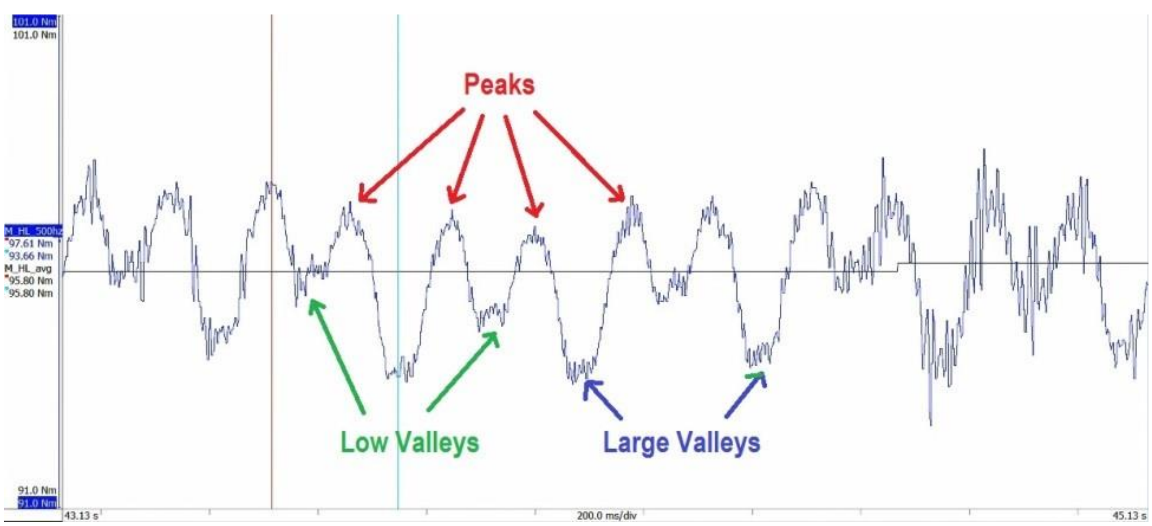

Fig. 3. Cogging torque waveform matches geometry of the machine magnets.

Control Change

In Fig. 4, the system switches from a PWM to a six-step modulation, which can be easily seen in the bottom section. The blue PWM voltage has a smooth sinusoidal current and then a control change happens and the current becomes more jagged. Looking at the top section one can see the instantaneous torque in red, the 10 Hz filtered in blue and the cycle-based average in black.

Before the control change, the instantaneous torque in red has significant cyclical torque ripple on the order of 9 Nm peak-to-peak. One can also see that the torque is in phase with the current, however, the filtered blue torque has both an amplitude reduction and a phase shift of about 90 degrees. The amplitude difference is down to a 1-Nm ripple peak-to-peak. This is obviously incorrect from what is actually happening in the machine.

Once the change happens the instantaneous torque has a 50-Nm ripple for 20 ms. Looking at the blue filtered or even black cycle-based average, both of these values look fairly static during the change. However, instantly there are reverse torques and potential load swings. This is a very traumatic event. Once the torque settles into a cyclical range there is still a cyclical ripple on the order of 25 Nm peak while the average is somewhere around 11 Nm.

Looking at the cycle-based average torque, it is actually very fast responding. Cycle-averaged torque is much faster than the filtered value. Unlike the filtered value, it does not have a cyclical nature so it does not need time to be averaged, just a number of cycles.

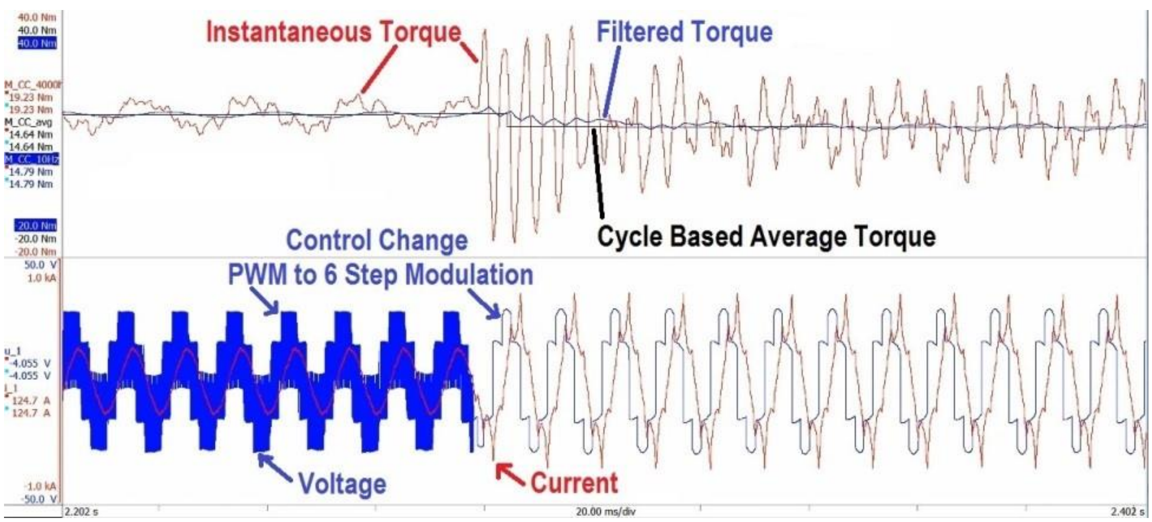

Fig. 4. Torque during a control change from PWM to six-step modulation.

References

1. "T12HP Torque Transducer" HBM web page.
2. "HBM edrive" web page.

About The Author

Mitch Marks is the motor testing specialist for HBM Test and Measurement where he serves as a business developer and application expert for electric motor testing. This role continuously brings him to many labs in many different industries across the country offering him a unique perspective on some of the best practices for designing a motor test cell. In previous roles, he ran a power research lab, focusing on *distributed grids and traction motor testing. Mitch received bachelors and masters degrees from the University of Wisconsin-Madison WEMPEC program for electric motors and drives. He can be reached at Mitchell.Marks@hbm.com.*

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