Measurement of Instantaneous Torque Ripple, Transient Torque, and 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. Measuring torque with high accuracy, bandwidth, and resolution is 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 90's of efficiency percentage. If a machine has a 98% efficient measurement with a ±3% error, this means it could have an efficiency of 101%, which is impossible. Therefore, a highly accurate torque measurement is required. This is a relatively new issue since internal combustion engine efficiency is much lower.

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
- Torque during control changes

1. Instantaneous and Average Torque

Figure 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, meaning that every point measured from the torque transducer 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.

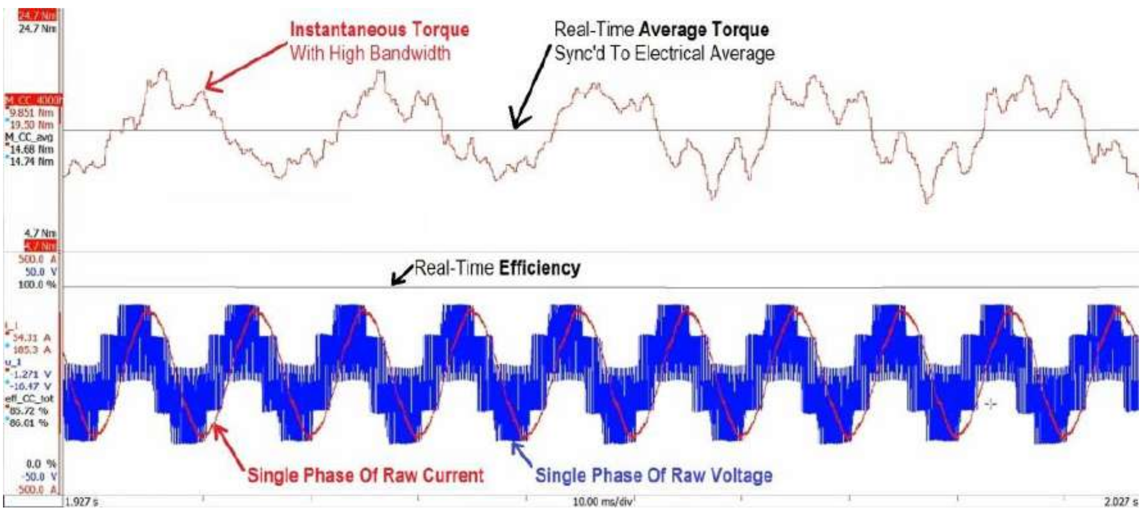

Fig. 1 – Instantaneous and real-time average torque in an efficiency measurement

Using a data acquisition system that records data at a sufficient rate to view the full 6 kHz bandwidth of the torque sensor enables one to obtain accurate averages very quickly. Data acquisition systems that sample at a slower rate will require long averages to achieve the same result, often on the order of minutes Having a high-bandwidth and accurate torque transducer 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.

2. Dynamic Load Testing

Figure 2 shows torque for a highly dynamic test of a motor at 5000 rpm, 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 transducer 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. For choosing the correct nominal range of the torque transducer dynamic torque has to be considered. Depending on the characteristic of the electric machine, peak torque can be estimated by 2-3 times of the torque at nominal speed of such machines. 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. 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 torque transducer with a high bandwidth and high accuracy makes viewing this possible.

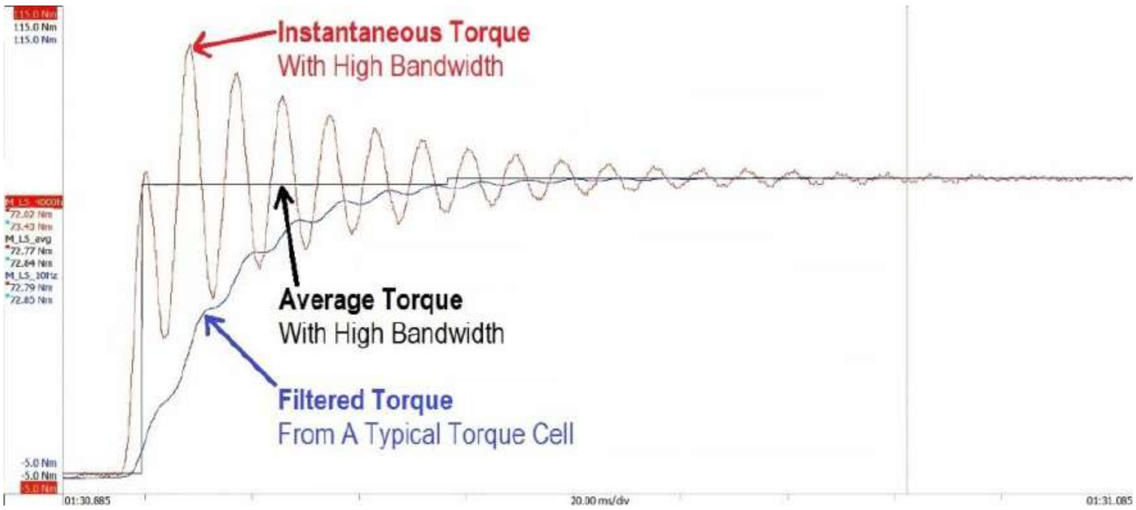

Fig. 2 - Torque in a highly dynamic motor test from 0 Nm to a 70 Nm load step

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 transducer 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.

3. Torque Ripple

Torque ripple occurs in permanent magnet synchronous motors due to non-sinusoidal flux density distribution around the air gap and variable magnet reluctance of the same due to stator slots distribution. The effects of torque ripple are undesirable and periodically change with the rotor position. The results are speed oscillations which degrade the performance of the machine. In addition, torque ripple can excite the mechanical drive train and therefore produce unwanted acoustic noise and vibration.

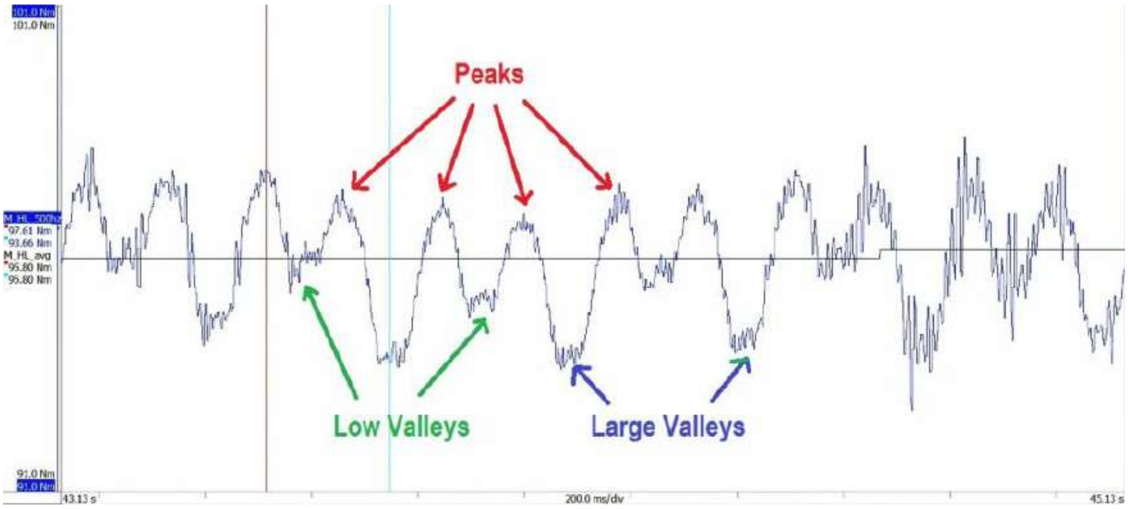

Fig. 3 – Cogging-torque waveform matches the geometry of the machine magnets

Figure 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, which is in this case 2% of the rated torque. A successful torque measurement requires a transducer with high accuracy and resolution. This means that someone looking for a torque transducer should pay attention, especially when the specifications of values that are related to full scale such as linearity incl. hysteresis and coefficient of temperature of the zero point TC0 are of greater significance. This is even more important, if also taking into account the design factors regarding nominal and max. peak torque of the electric machine. 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.

4. Control Change

In figure 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.

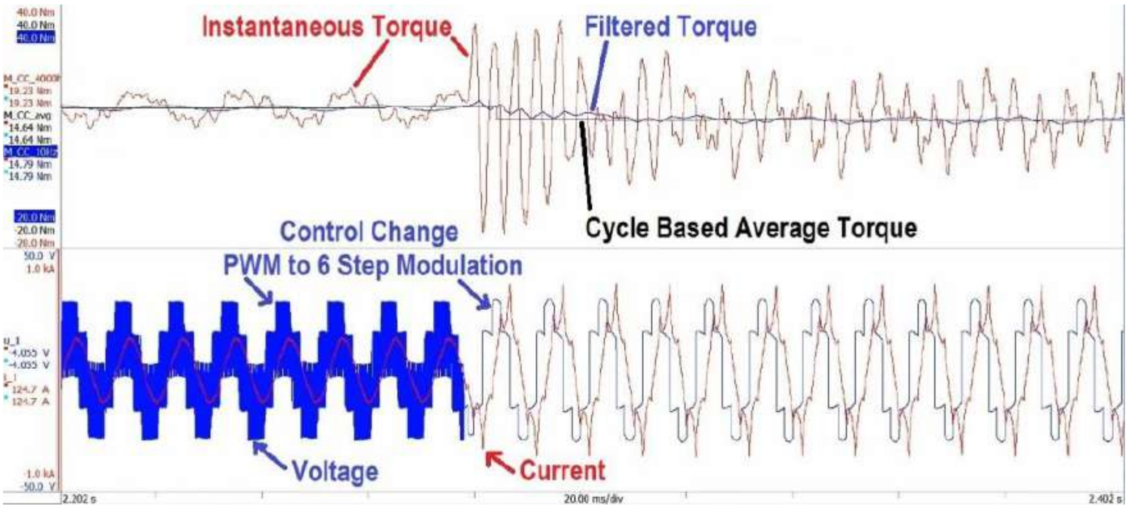

Fig. 4 - Torque during a control change from PWM to six-step modulation

5. Conclusion

Design factors of the electric machine regarding e.g. the ratio of max. peak torque vs. nominal torque have an impact on the selection of the nominal torque of a torque transducer, which can be 2-3 times higher. In combination with unwanted torque ripple in the signal, which is only a few percentages of the rated torque at a certain load point, it is obvious that the torque transducer that is used must have a very good accuracy and resolution to deliver the information needed for investigation.

For dynamic tests, the torque must be measured instantaneously with a high measurement bandwidth of the signal to get the full information provided by the system. The HBM eDrive system, consisting of HBM's T40B or T12HP torque transducers and the Genesis HighSpeed DAQ system, gives users the ability to acquire both mechanical and electrical signals on a common time basis.

This allows you to understand how the inverter PWM signals being input into the electric machine effect the mechanical torque output and associated vibrations. The eDrive samples torque at a sufficiently high rate to obtain the full bandwidth of the sensor. Having the full bandwidth allows us to look at transients and torque ripples, in addition to taking a very fast average of the torque measurement.