

Measuring Torque Ripple in Electric Machines

Agenda

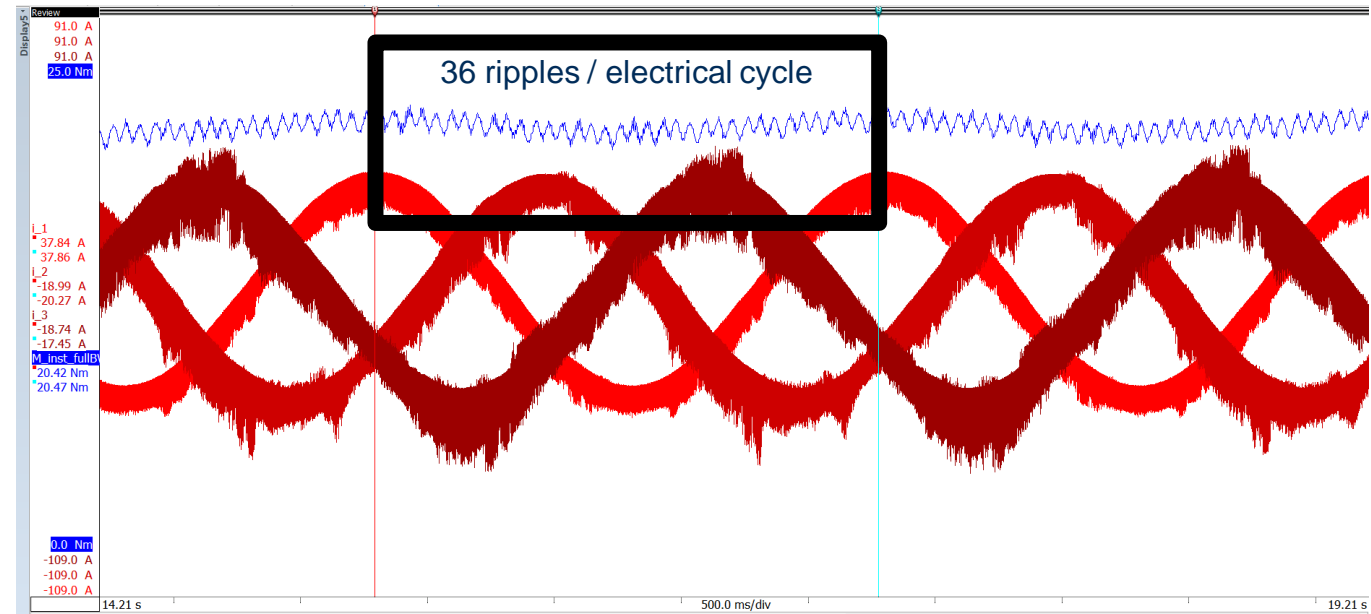
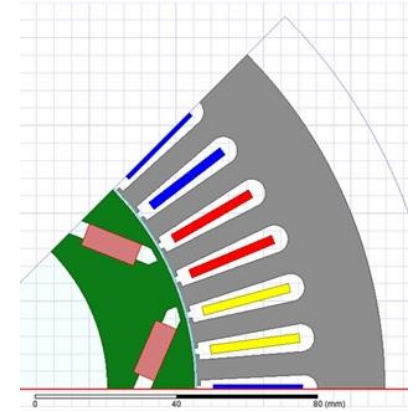
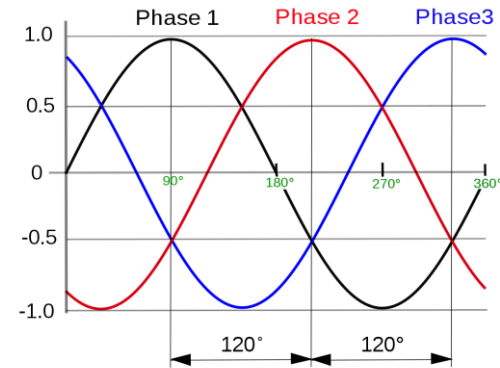
1. Torque ripple review
2. Measuring considerations for torque ripple
3. Torque ripple examples
4. Frequency analysis
5. Measure

eDrive testing

Torque Ripple Review

Torque Ripple from AC Motors

- Cyclical disturbance in torque
- Caused by construction
 - Magnets
 - Slots
- Caused by excitation
 - 3-phase excitation
 - Inverter switching
- Ripple frequency is proportional to speed



Three phase motor excitation in red and resultant torque ripple in blue

Why Torque Ripple Matters

- User experience
 - Sometimes you can feel torque ripple
 - Sometimes you want to feel torque ripple
 - Vibration can be very hazardous
- Vibration, noise, and fatigue
 - Torque ripple results in vibrations
 - Causes gear chatter
 - Torque ripple can excite structures
- Accurate efficiency measurements



eDrive testing

Measuring Torque Ripple

Equipment needed

- Torque sensor that has accuracy and bandwidth to observe bandwidth
- Noise immune torque communication
 - Analog signals are susceptible to noise in a PWM environment
 - HBM torque cells use a frequency output that reduces susceptibility to noise
- Acquisition system that records torque at a rate sufficient for bandwidth
- Acquisition system that correlates to other signals of interest
 - Electrical
 - Vibration



Accuracy, Bandwidth & Time Alignment for Efficiency

Internal Combustion Engine

- Engine efficiency 30-40%
- A 3% error in an engine gives 39% instead of 36%
- We believe this!

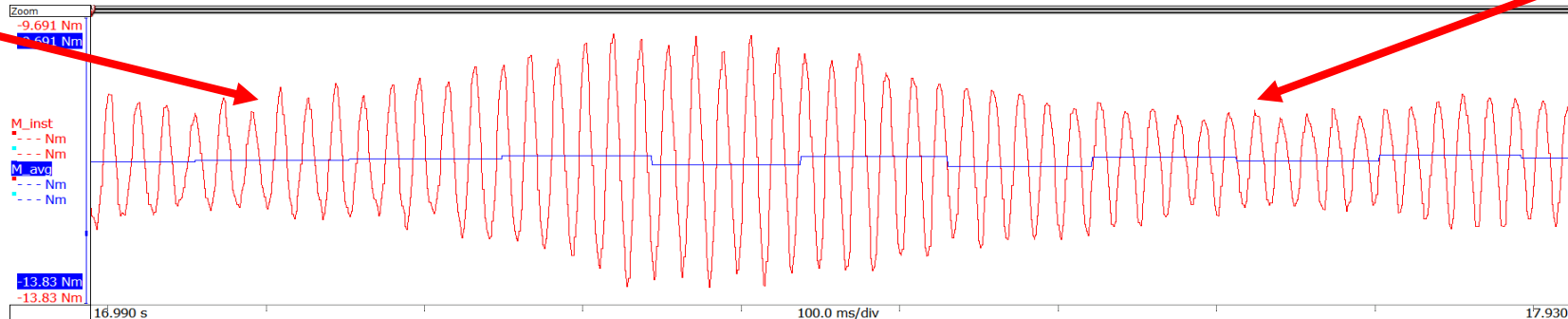
Electric Motor

- Motor efficiency 85-98%
- A 3% error in a motor gives 101% instead of 98%
- This is impossible!

- Need highly accurate torque and speed that accounts for **SMALL** disturbances in the average
- 80 kW @ 20k RPM \rightarrow 2093 Rad/sec x 38.22 Nm \rightarrow .25 Nm offset is 500 W \rightarrow .625 %

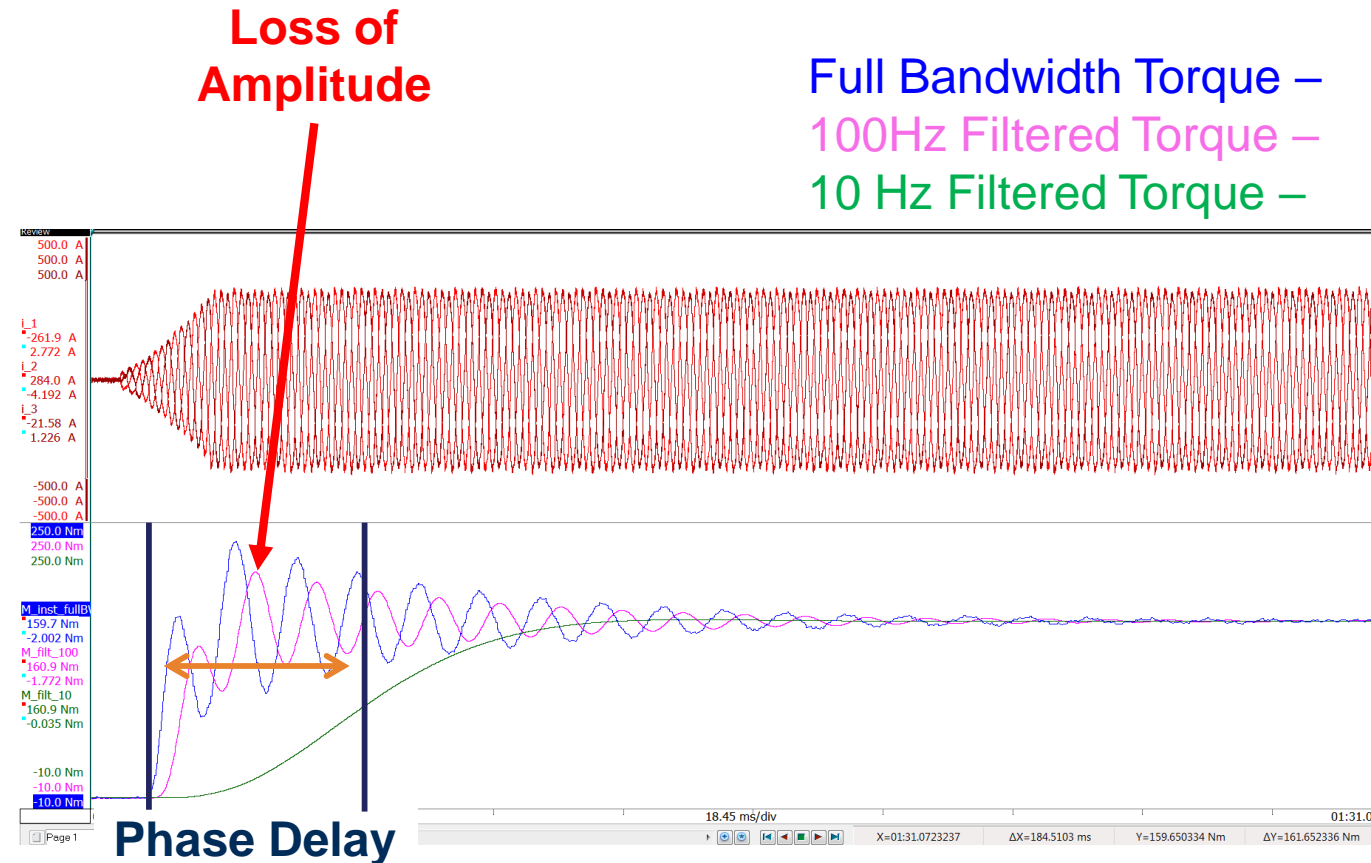
Bandwidth allows for phase alignment with power signals

Accurate measurement of peaks



Accuracy, Bandwidth & Time Alignment for Transients

- Test machine at 7500 RPM with load step from 0 to 150Nm
- Filtered version loses amplitude info and has phase delay
- Highly filtered has large phase delay and loses all amplitude/freq info
- Phase delay can come from filters in torque cells
- Time alignment is necessary for control calibration



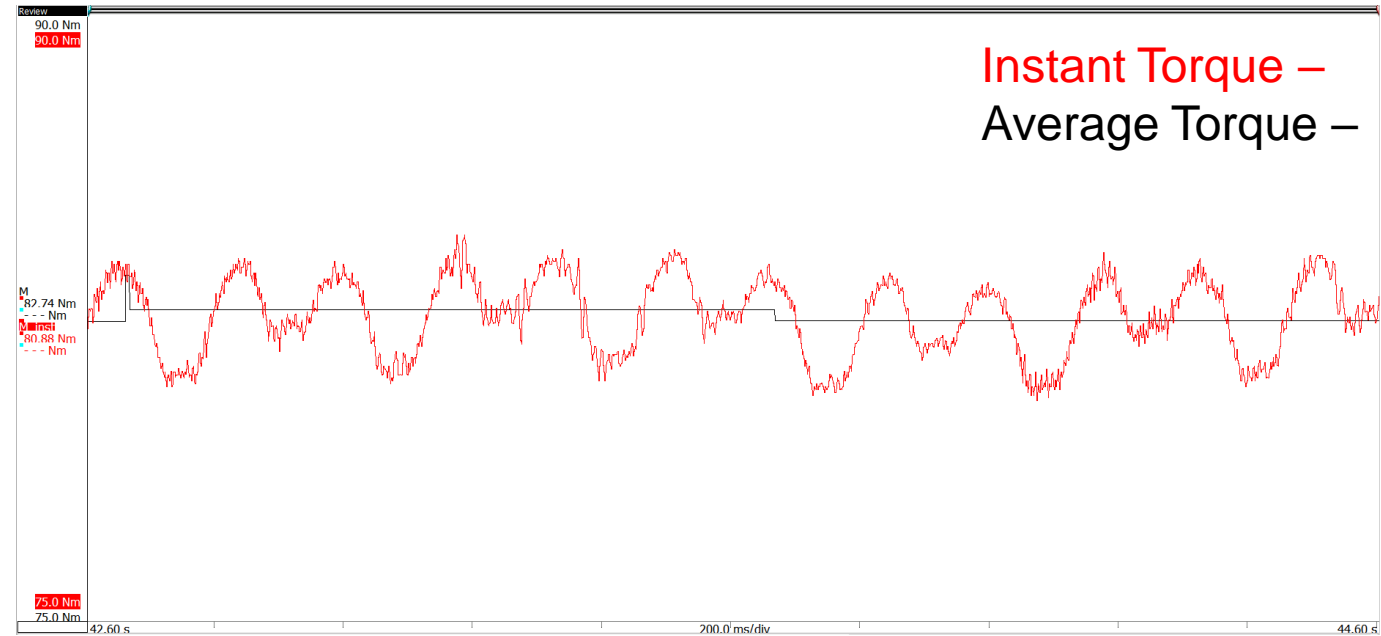
Top – three phase excitation for an electric machine with a load step
Bottom – cyclical torque with different filter rates

eDrive testing

Torque Ripple Examples

Torque Ripple from PM Motors

- Requires accuracy and bandwidth
 - Accuracy to trust the amplitude
 - Bandwidth to see the frequency content
- Characterize magnets under different loading conditions
- Rotor structure can be identified from the torque response
 - V shaped IPM
- Understand cogging torque and percentage of torque ripple

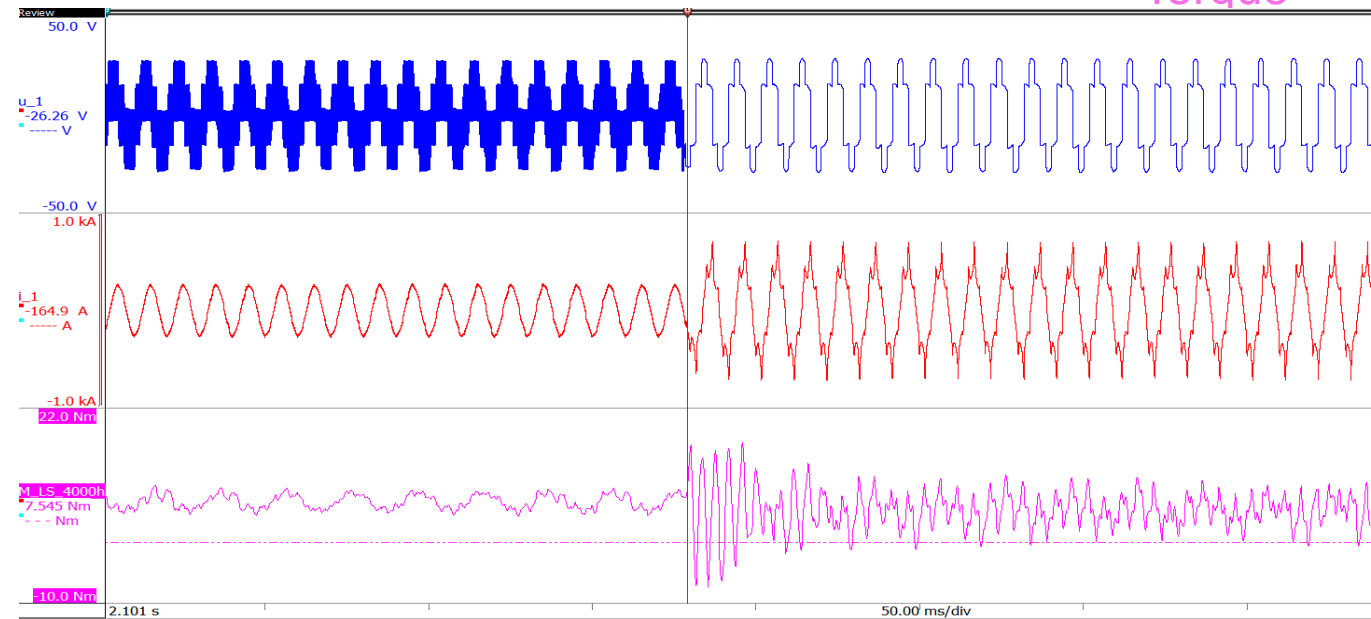


Steady state slow speed torque ripple

Torque Ripple from PM Motors → control change

- Control changes are a good opportunity to look at torque transients
- Ripple frequency increases with control change
- Negative torque swings
- Switching frequency effects torque ripple frequency
- Torque has frequency content

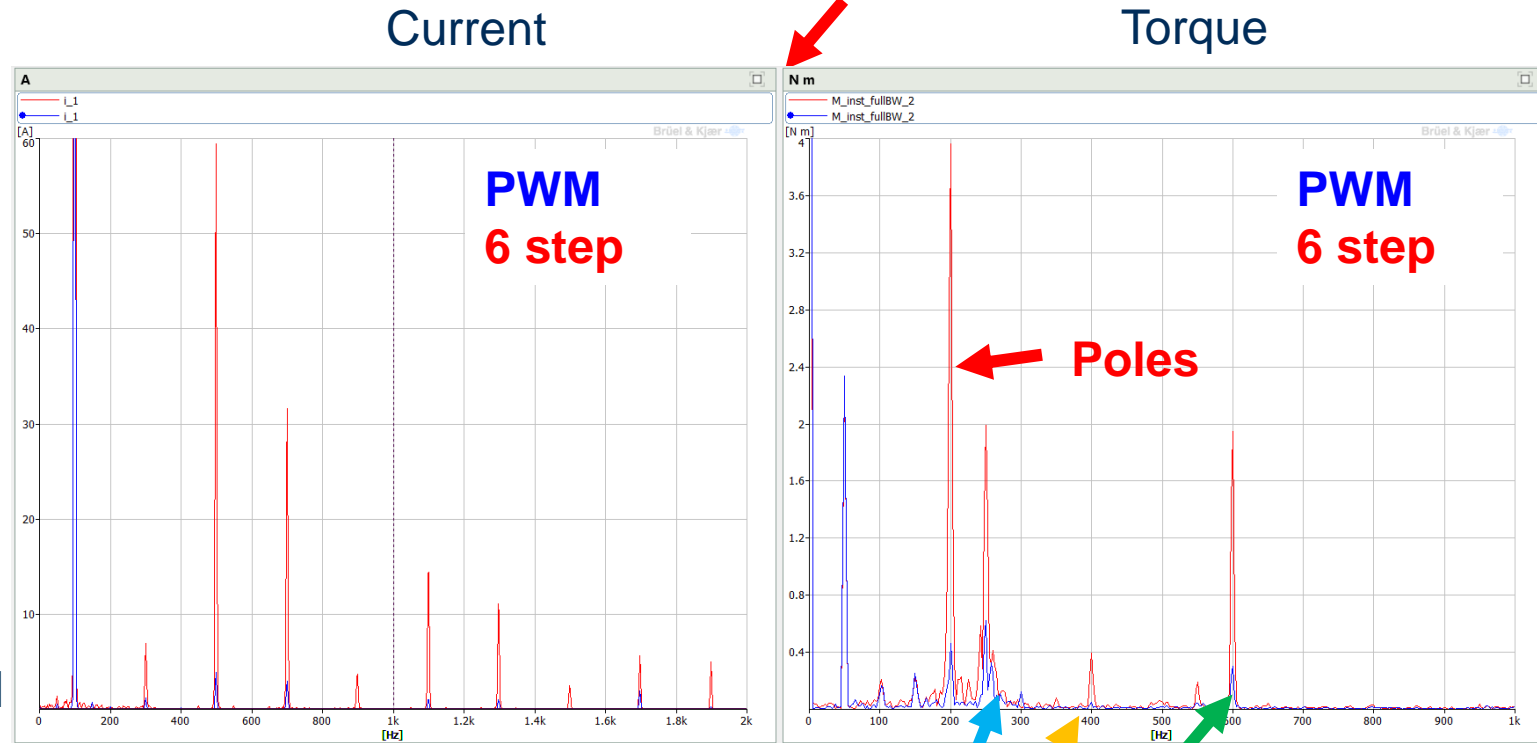
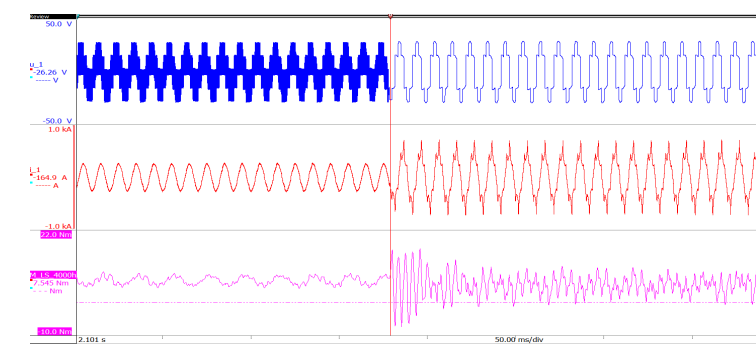
Voltage –
Current –
Torque –



Top – voltage for a PWM to 6 step control change
Middle – Current for a PWM to 6 step control change
Bottom – Torque for a PWM to 6 step control change

Voltage, Current, and Torque Frequency Content

- Fundamental and rotational current and torque are similar
- 6 step current has significantly more current harmonic content in PWM
 - 5th, 7th, 11th, ...
- Torque has significantly more harmonic content during 6 step
 - 4x, 5x, 8x, 10x, 12x rotational frequency
 - Linked to current



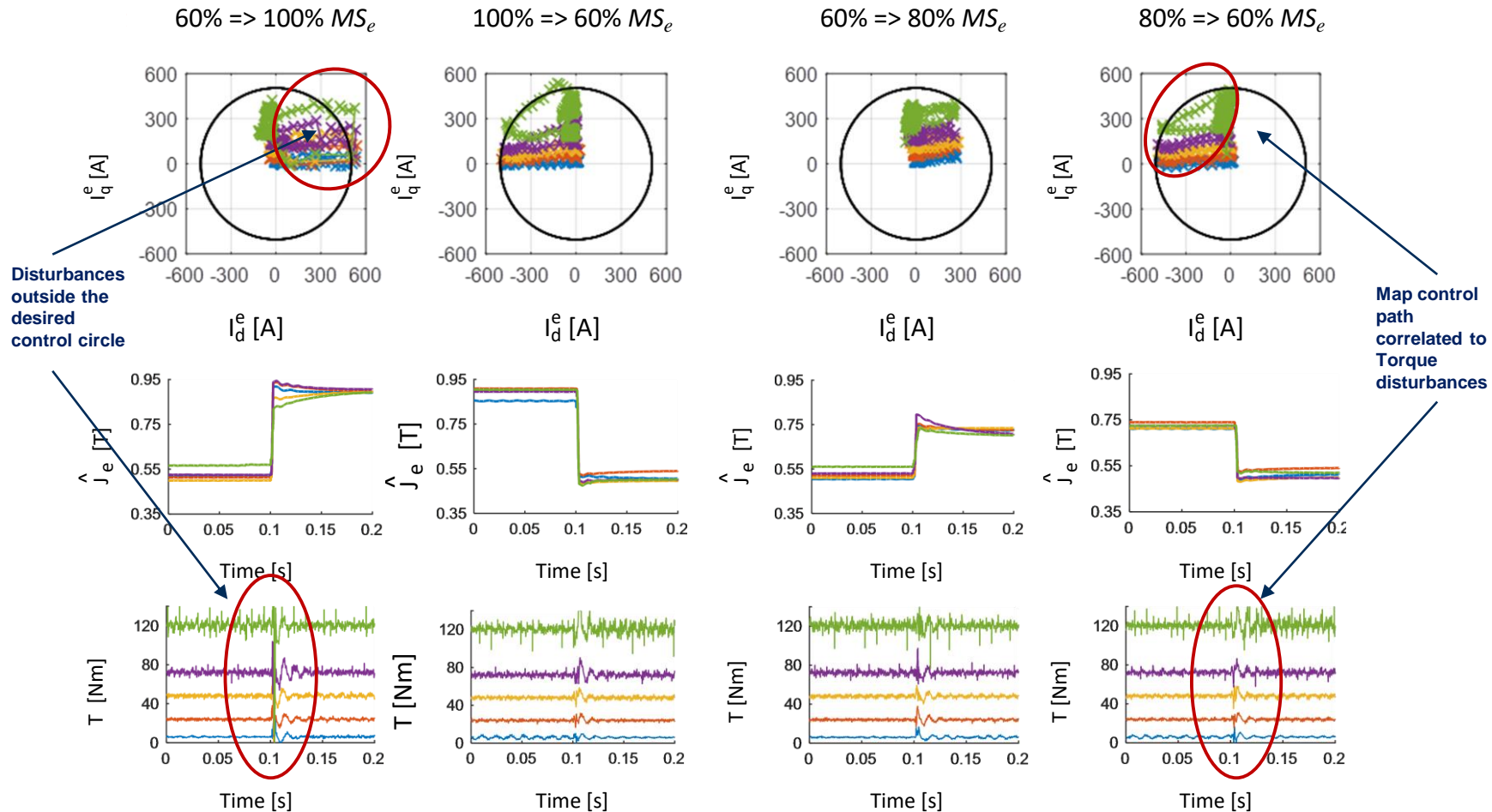
Frequency spectrum comparing current and torque during PWM and 6 step operation

5th electrical harmonic
Construction
Switching

Comparing electrical and torque signals during control change

Transitions:

MS change for increasing and decreasing MS_e level combinations at 2000 rpm, over a range of torque conditions



Questions?



Mitch Marks

Business Development at HBK -
Hottinger, Brüel & Kjær



HBK Electric Power Test

