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Presenter

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- Ph.D. Physics – University of Wisconsin-Madison
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Krista Tweed

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Measuring Torque Ripple Accurately

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Agenda

1. Introduction
2. What is torque ripple
3. Why we care about torque ripple
4. Measuring torque ripple

HBK

- eDrive Power Analyzer
  - Accuracy
  - Dynamics
  - Expandability
  - Traceability
  - High sample rate
  - Time alignment for mechanical and electrical measurements

- World class torque cells
  - Accuracy up to **.02%**
  - Bandwidth up to **6 kHz**

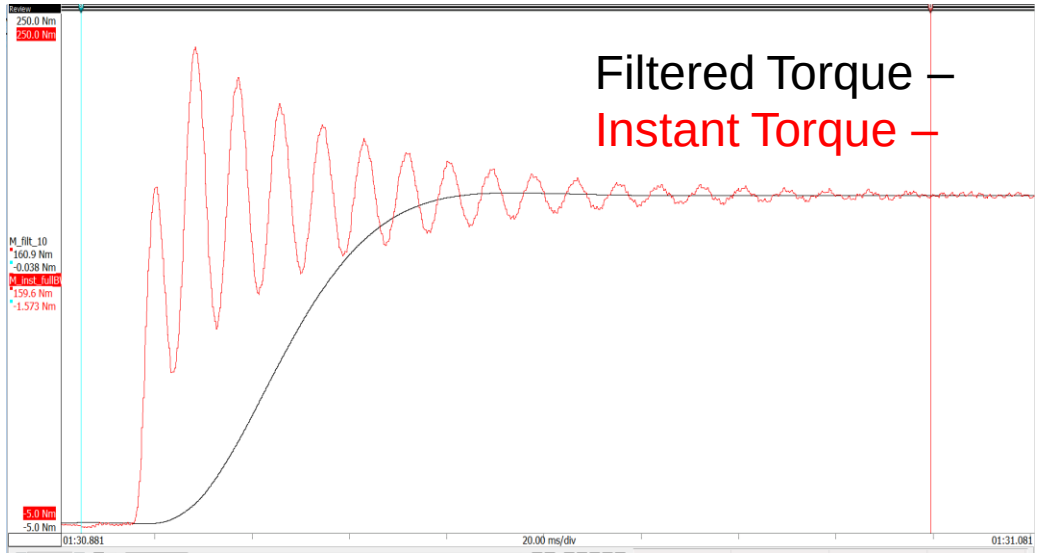
- Torque ripple
  - High accuracy torque cell shows subtle changes in torque
  - High bandwidth shows high frequency details
  - High sample rate and time alignment let you analyze the time and frequency data

HBK products for torque and power

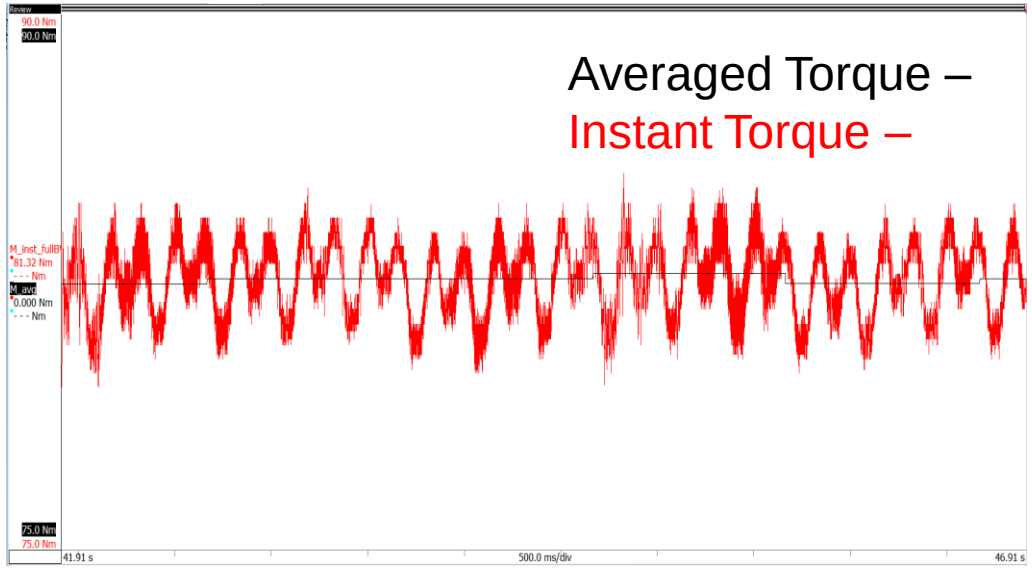
What is Torque Ripple

Torque ripple is → Dynamic torque in a steady state

- Torque is not a static
- Sometimes we view torque as a filtered quantity
- Comes in pulses
- Has cyclical nature
- Transient behavior



Transient torque fluctuations and high speed torque ripple

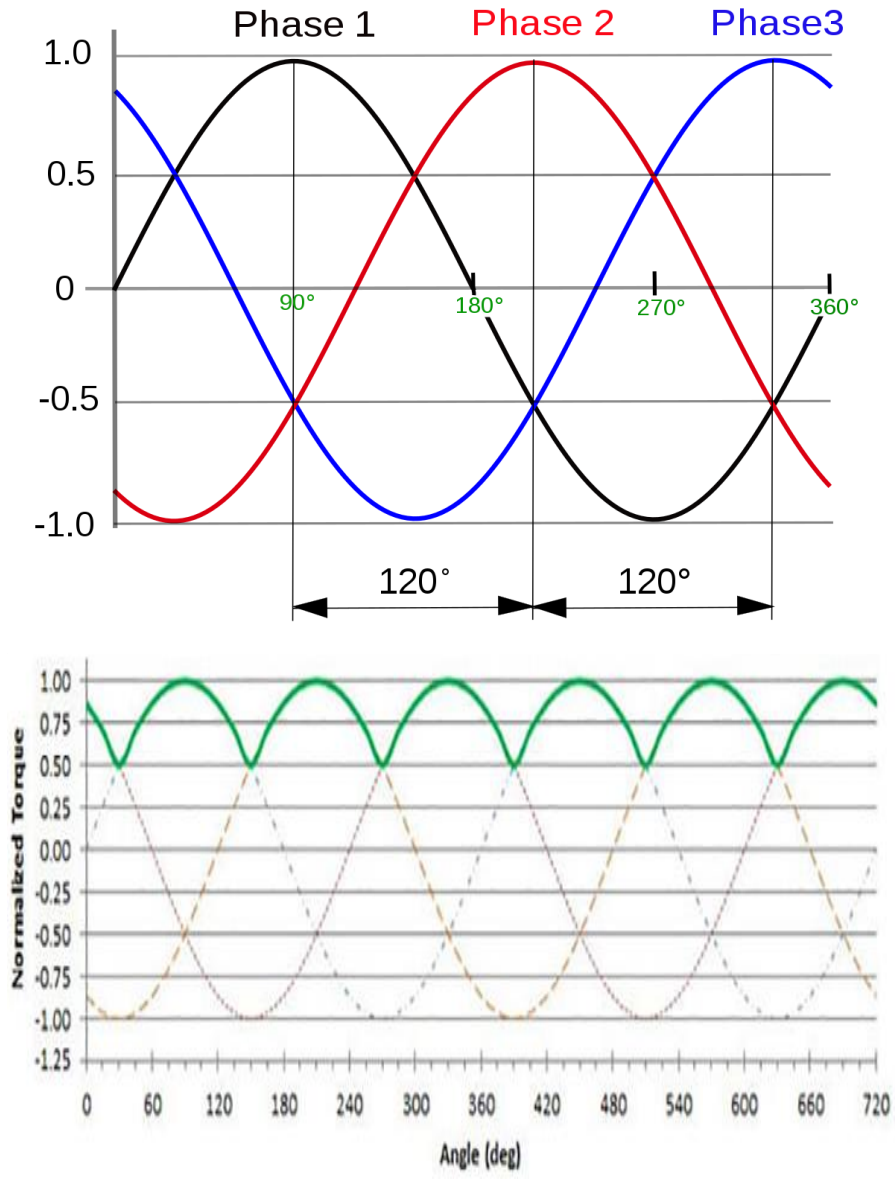


Slow speed torque ripple for a PM machine

Where does torque ripple come from?

AC excitation

- Non – zero torque
- Not “DC” torque
- Torque follows the peaks of the currents
- Responds to any harmonics in the ripple
  - Control technique
  - Switching frequency
- Frequency and amplitude are proportional to phases and RPM



Three phase excitation and the resulting torque output

Where does torque ripple come from?

Permanent Magnet

- Magnet interaction with stator
- Cogging torque
- IPM/SPM → Cannot turn magnets off

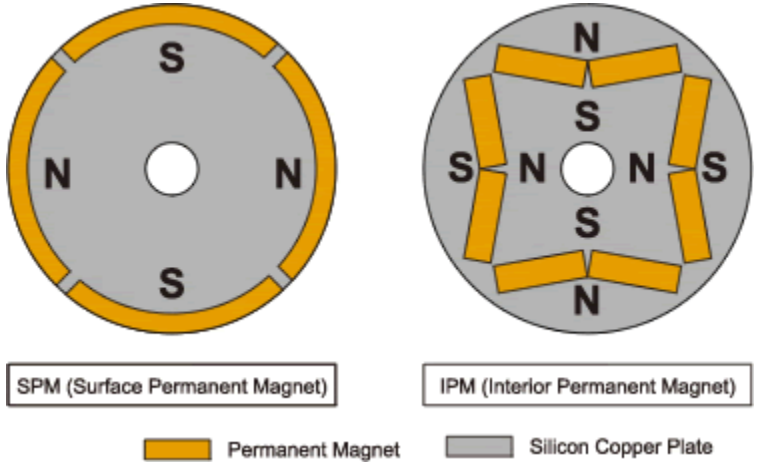
Switched Reluctance

- Pulsed current
- Hard torque pulses

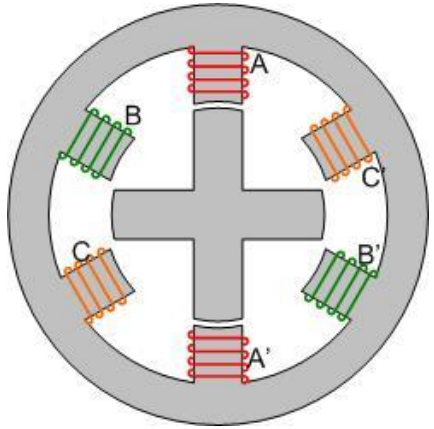
Induction Machine

- Magnets induced on rotor
- Interact with stator magnets

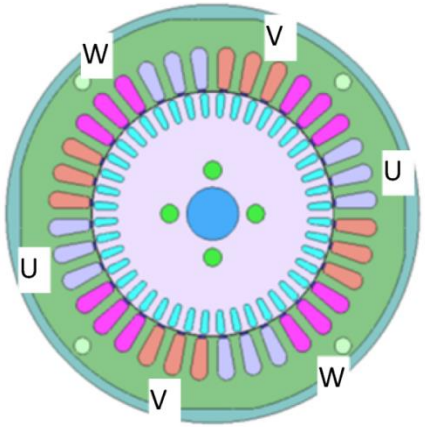
Permanent Magnet Motors



Switched Reluctance



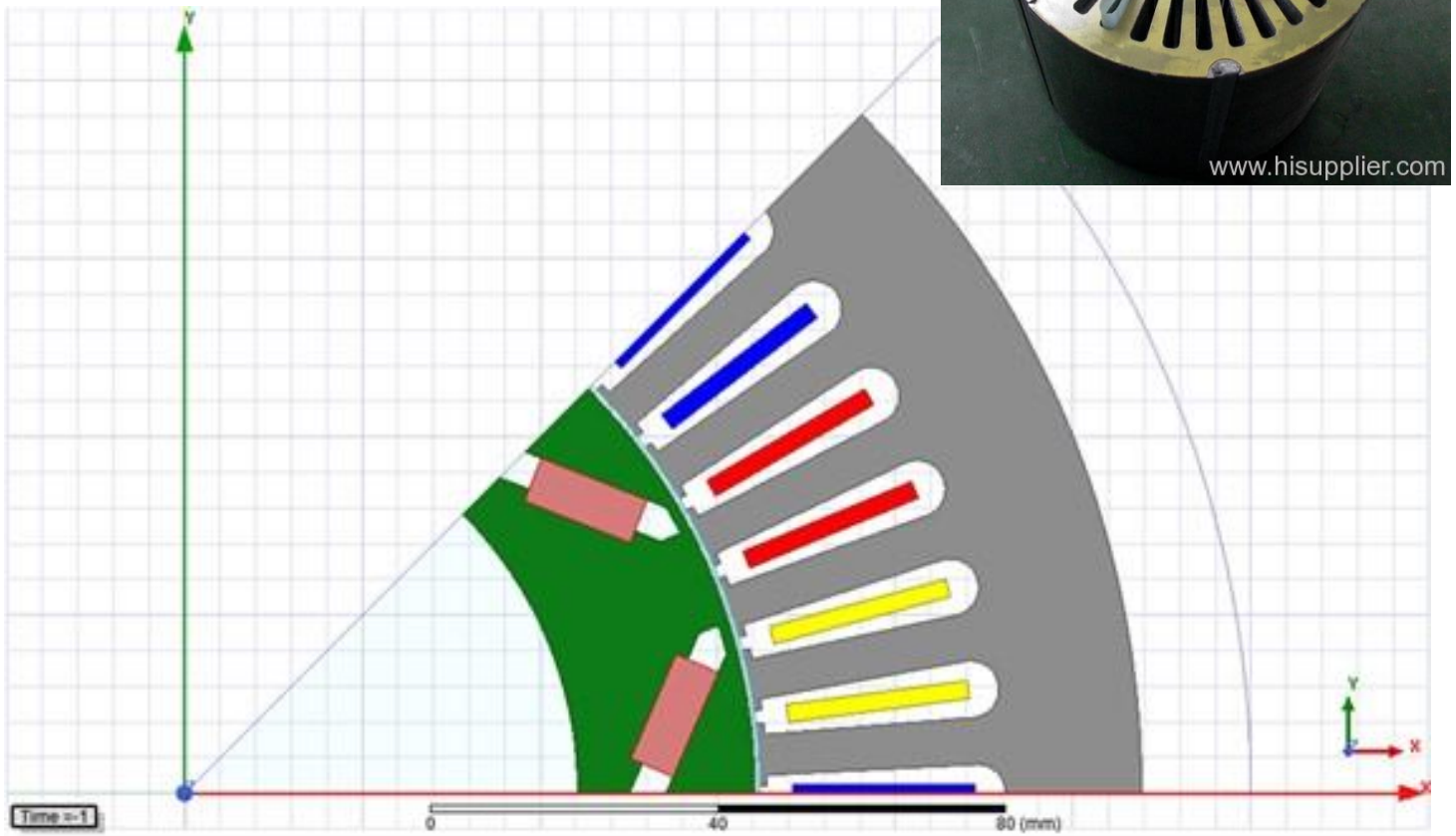
Induction Machine



Different machine types will have different types of torque ripple

Stator Slots

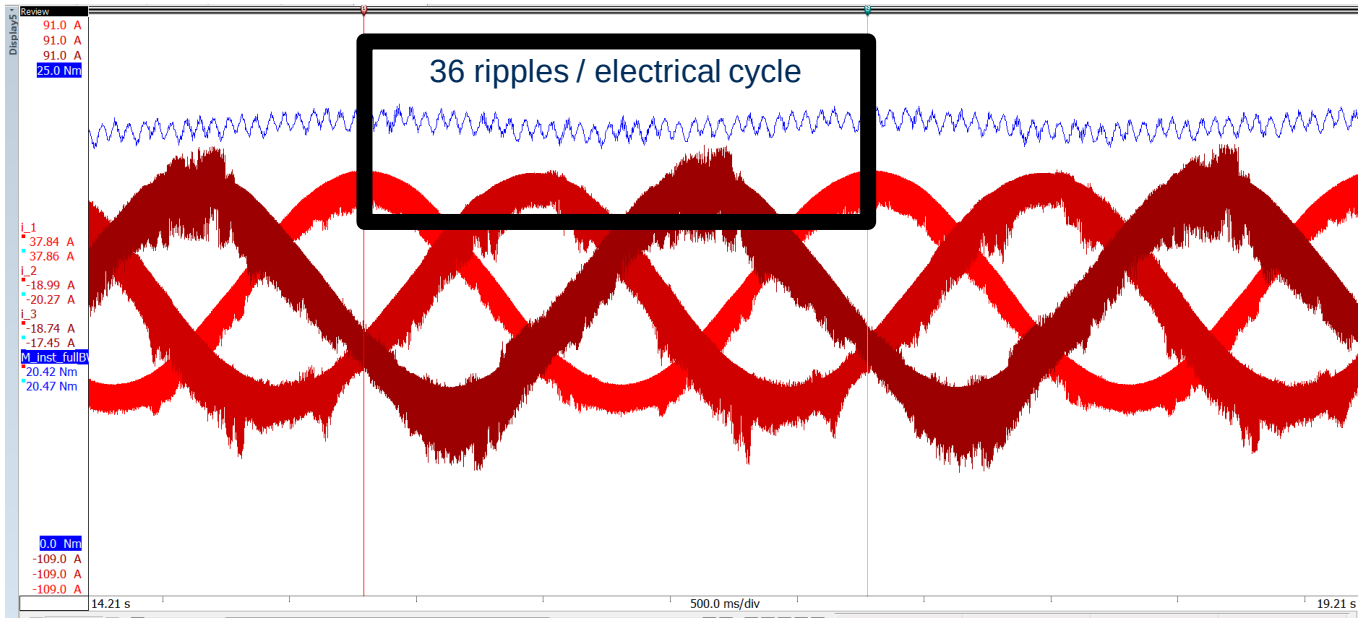
- Magnets want to stick to slots
- This makes a disturbance in torque
- Think about trying to spin a motor rotor and feeling it stick



Motor stator with iron teeth for windings

Torque Ripple from PM Motors → Slow Speed Test

- Slow speed test
- Many ripples → PM / Excitation / suppression techniques
- Ripple is a function of construction
- Ripple is proportional to frequency



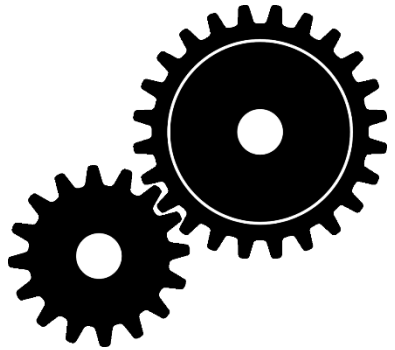
Three phase motor excitation in red and resultant torque ripple in blue

Why we Care About Torque Ripple

Noise and Vibration

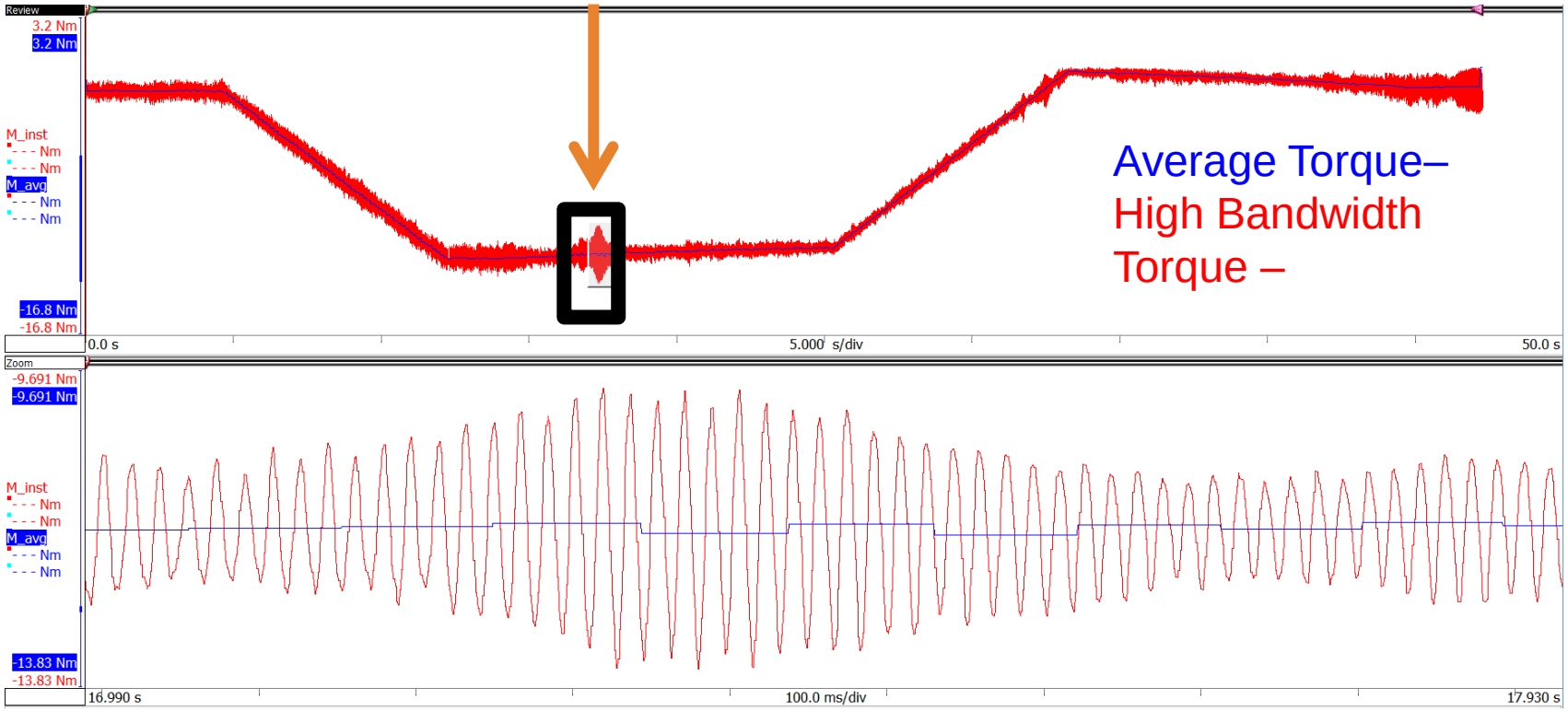
- Potentially a very high percentage of total torque
- Results in difficult vibrations
- Ripple frequency is proportional rotor construction and electrical frequency
  - Control technique
  - Ripple frequency * switches
- Machines up to 20k rpm for automotive
  - High frequency vibration & noise

Gearbox



- Frequency and amplitude information
- Gear chatter
- Lifetime issues

Zoom Segment

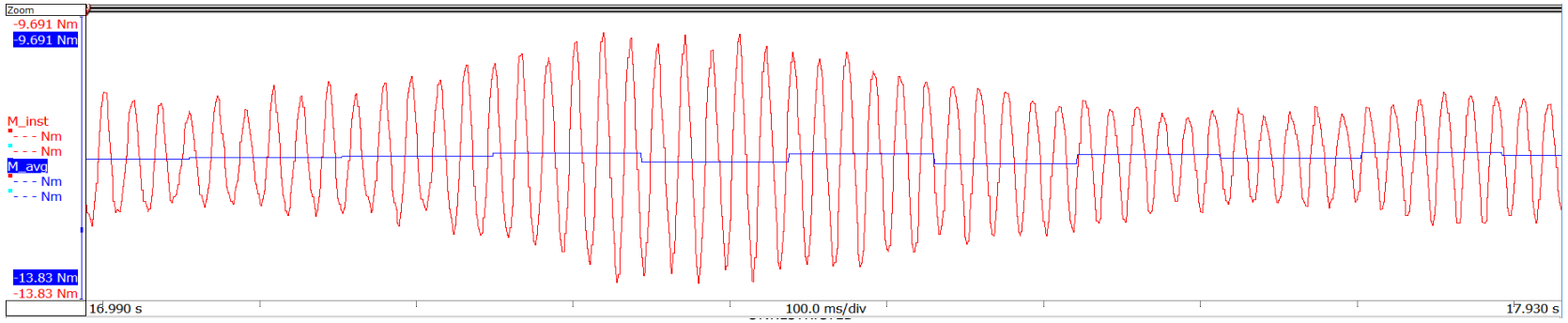


Instantaneous and averaged torque from the output of a gearbox

Why motors care about torque so much → Efficiency

Internal Combustion Engine	Electric Motor
• Engine efficiency 30-40%	• Motor efficiency 85-98%
• A 3% error in an engine gives 39% instead of 36%	• A 3% error in a motor gives 101% instead of 98%
• We believe this!	• This is impossible!

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



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User experience

- Sometimes you can feel torque ripple
  - Vehicle
- Sometimes you want to feel torque ripple
  - Drill clutch
- Vibration can be very hazardous
  - Vibration on a wing

Power tools and aircraft driven by electric machines

Measuring Torque Ripple

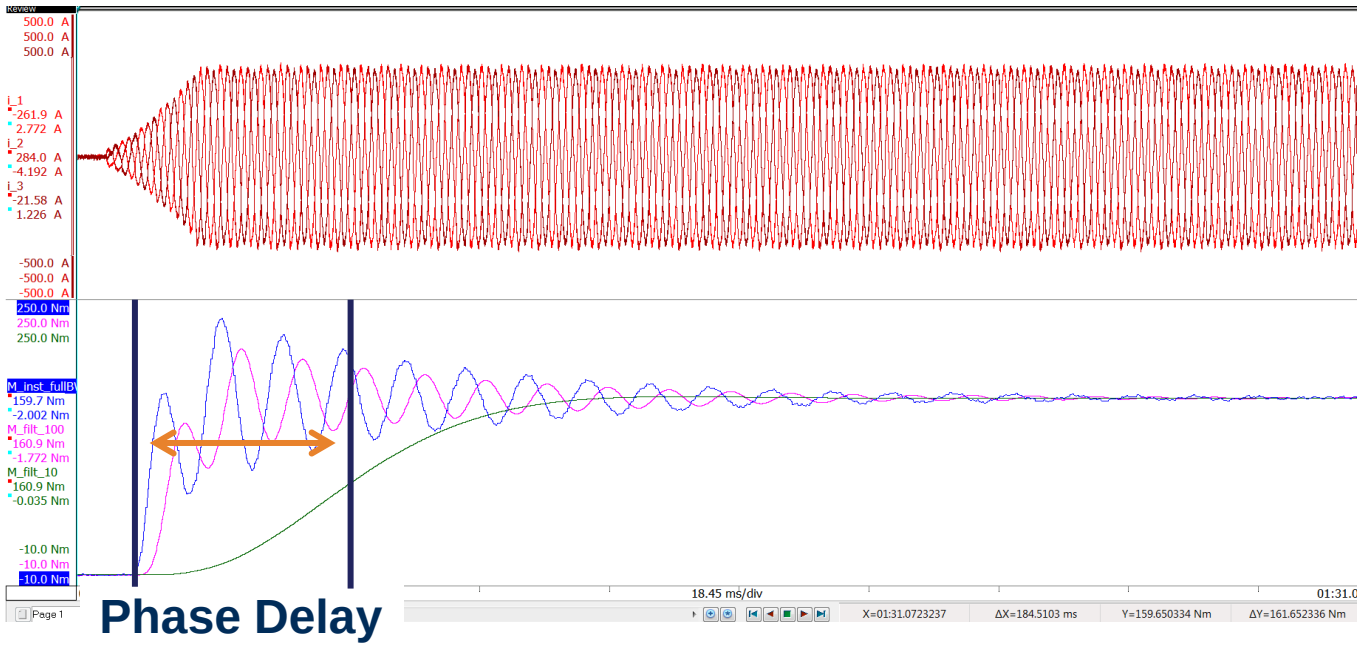
Equipment needed

- Torque sensor that has accuracy and bandwidth to observe the torque ripple
- 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

Bandwidth

- Filtered version loses amplitude info and has phase delay
- Highly filtered has large phase delay and looses all amplitude/freq info
- Phase delay can come from filters in torque cells

Full Bandwidth Torque –
100Hz Filtered Torque –
10 Hz Filtered Torque –

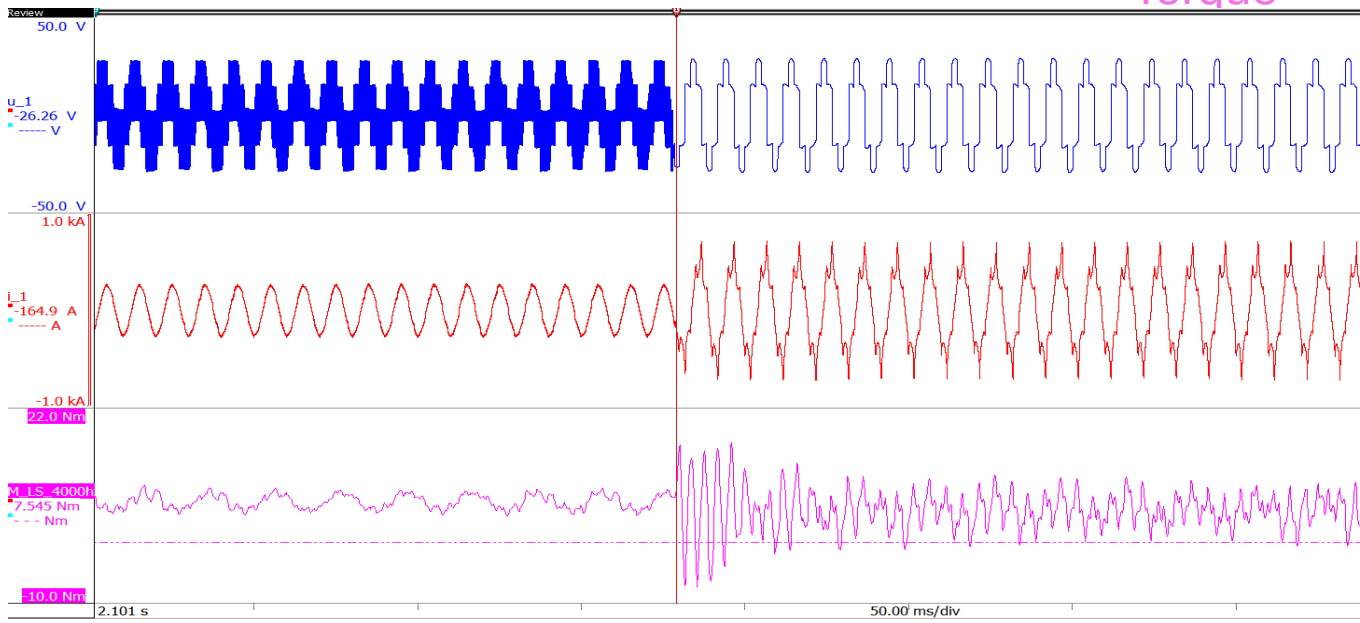


Top – three phase excitation for an electric machine with a load step
Bottom – cyclical torque with different filter rates

Torque Ripple from PM Motors → control change

- Control changes are a good opportunity to look at torque transients
- Change from PWM to six step (smooth sine wave to jagged)
- Ripple frequency increases with control change
- Negative torque swings

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

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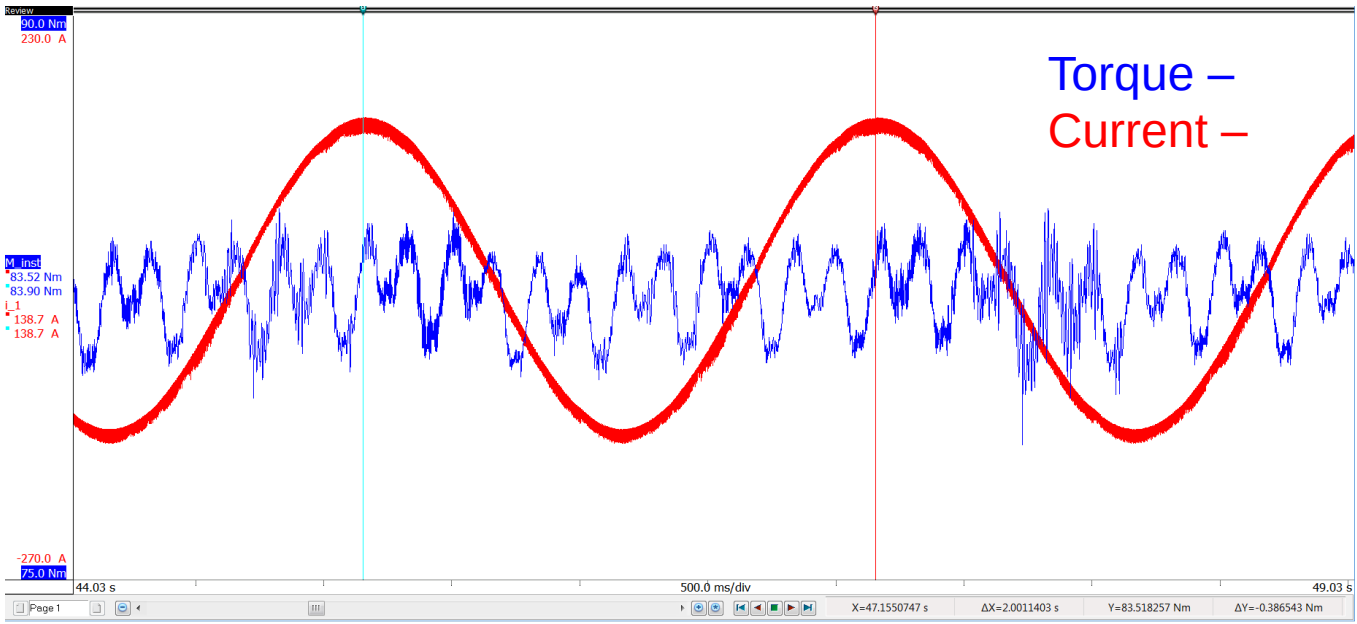
Torque Ripple from PM Motors

- Test rig capable of holding a speed
- Ripple characterization
- Load rig to different torques
- Spin at different speeds
- Look at % ripple for each

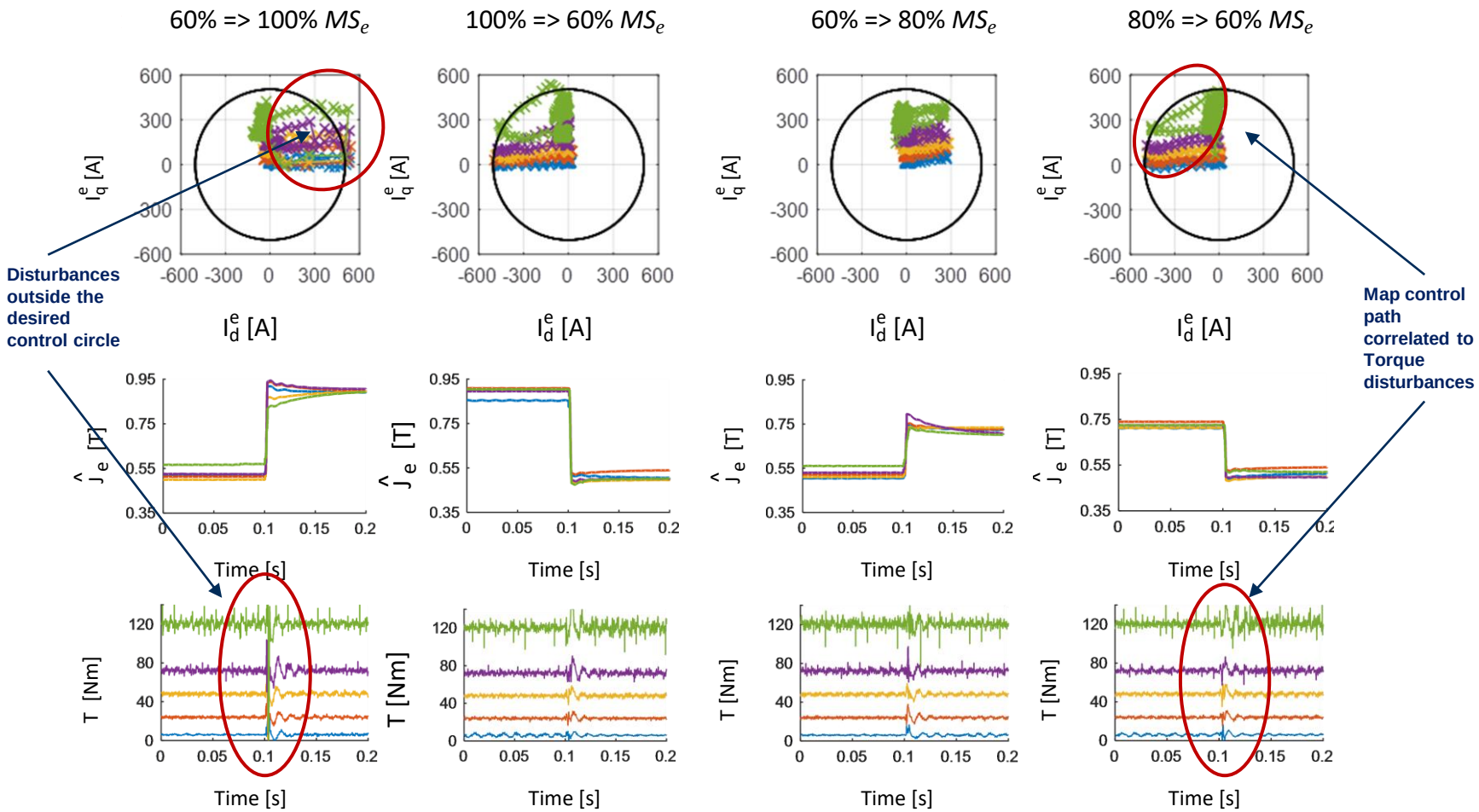


Steady state slow speed torque ripple

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



The HBM eDrive components for advanced power analysis

- GEN DAQ configurable, expandable mainframes
  - Up to 51 power channels
  - Continuous streaming or storage per set point in real time
  - Support for up to 6 torque transducers
- 3 channel Power card
  - Voltages up to ± 1500 V DC
  - Sample rate 2 MS/s @ 18 bit
  - Accuracy 0.015% rd. + 0.02% rg.
  - On board DSP with user programmable math
- High accuracy HBM torque and current transducer
- Options
  - EtherCAT and CAN FD interfaces
  - Various inputs for NVH, temperatures, CAN, 250MS/s

Learn more at
https://www.hbm.com/eDrive

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Thank You

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Questions?

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