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VIRTUAL CONFERENCE
EV ENGINEERING

Measuring Torque Ripple And Its Effects On Electric Power And Noise & Vibration

Mitch Marks
Business Development - Electrification
HBK

Ed Green
Principal Staff Engineer - Sound and Vibration Engineering Services
HBK

Presenters

- Mitch Marks
  - BSEE, MSEE – University of Wisconsin – WEMPEC
  - Joined HBM in 2017 (became HBK)
  - Business Development – Electrification
  - Previous experience:
    - Motor manufacturing
    - Controls
    - Traction motor testing

- Ed Green
  - Ph.D. Purdue University – Ray W. Herrick Laboratories (1995)
  - Joined Bruel & Kjaer Sound & Vibration Measurement A/S in 2011 (became HBK)
  - Principal Staff Engineer at HBK Sound and Vibration Engineering Services
  - Previous experience:
    - High Voltage Product Engineer
    - Research Engineer

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Agenda

1. Introduction to Torque Ripple
2. Frequency Content of Torque Ripple
3. Why We Care About Torque Ripple
4. Measuring Torque Ripple
5. Torque Ripple’s Correlation to Noise and Vibration
6. NVH Case Study – Simulation of Different Motors into a Car
7. NVH Case Study – Permanent Magnet Synchronous Traction Motor

HBK - Comprehensive Equipment and Service

- Dynamic Power Analyzer
  - Accuracy
  - Dynamics
  - Time alignment for mechanical and electrical measurements

- Highest accuracy torque cells
  - Accuracy up to **.02%**
  - Bandwidth up to **6 kHz**

- World Famous Microphones & Accelerometers for over 75 years

- Testing Services
  - Measurement, troubleshooting, test design, target cascading, source path contribution analysis, simulation
  - North America, Europe, and Asia

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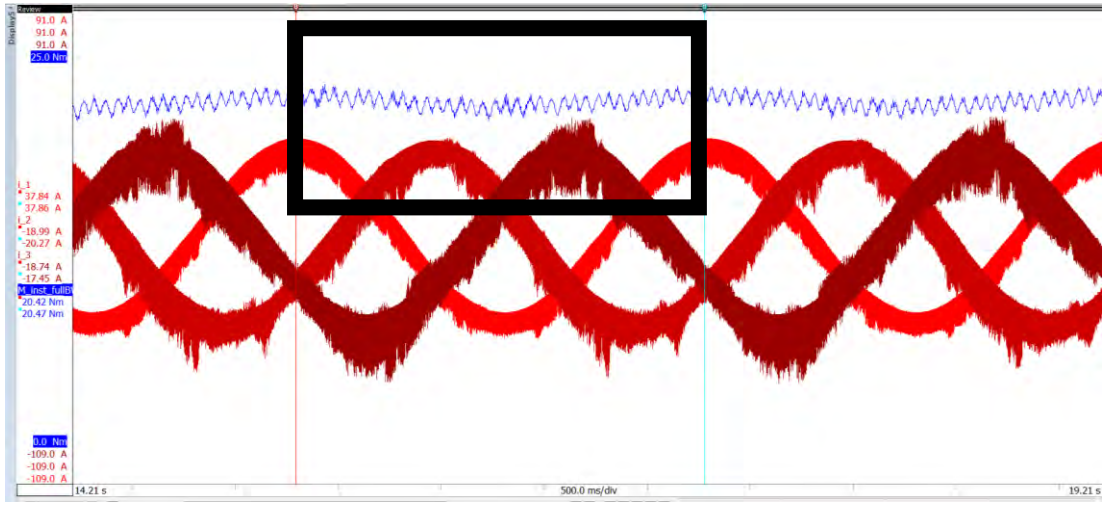
Introduction to Torque Ripple

Torque Ripple is a Periodic Disturbance in Torque

- Torque is not a static
- Torque ripple has a frequency and amplitude
- Ripple is proportional to frequency
- Torque ripple has several potential sources
- Many test stands show heavily filtered torque

36 ripples / electrical cycle



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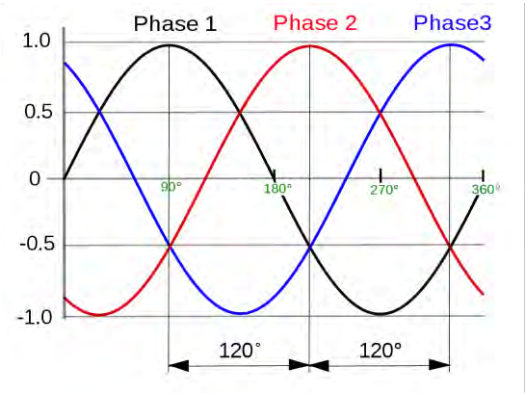
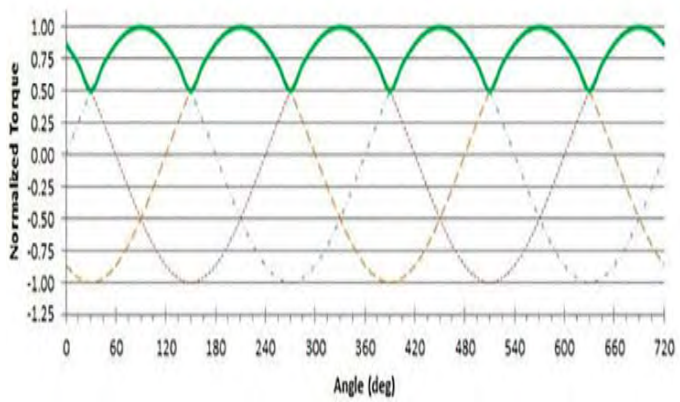
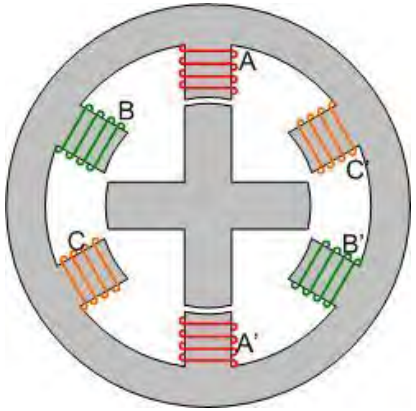
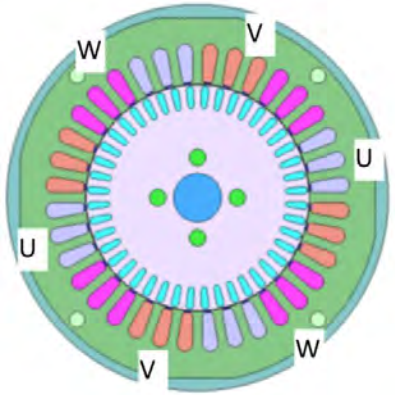
Torque Ripple Sources

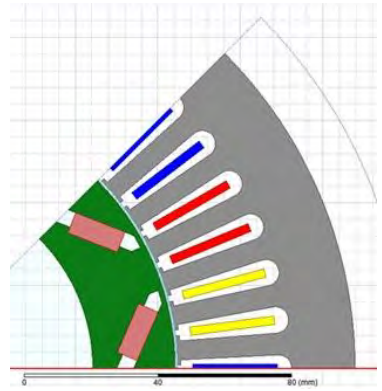
- Electrical excitation
  - 3, 6, n phase excitation
  - Inverter switching
  - Harmonics
- Machine construction
  - Magnets
  - Slots
- Mechanical resonances
- Machine alignment
- Loading











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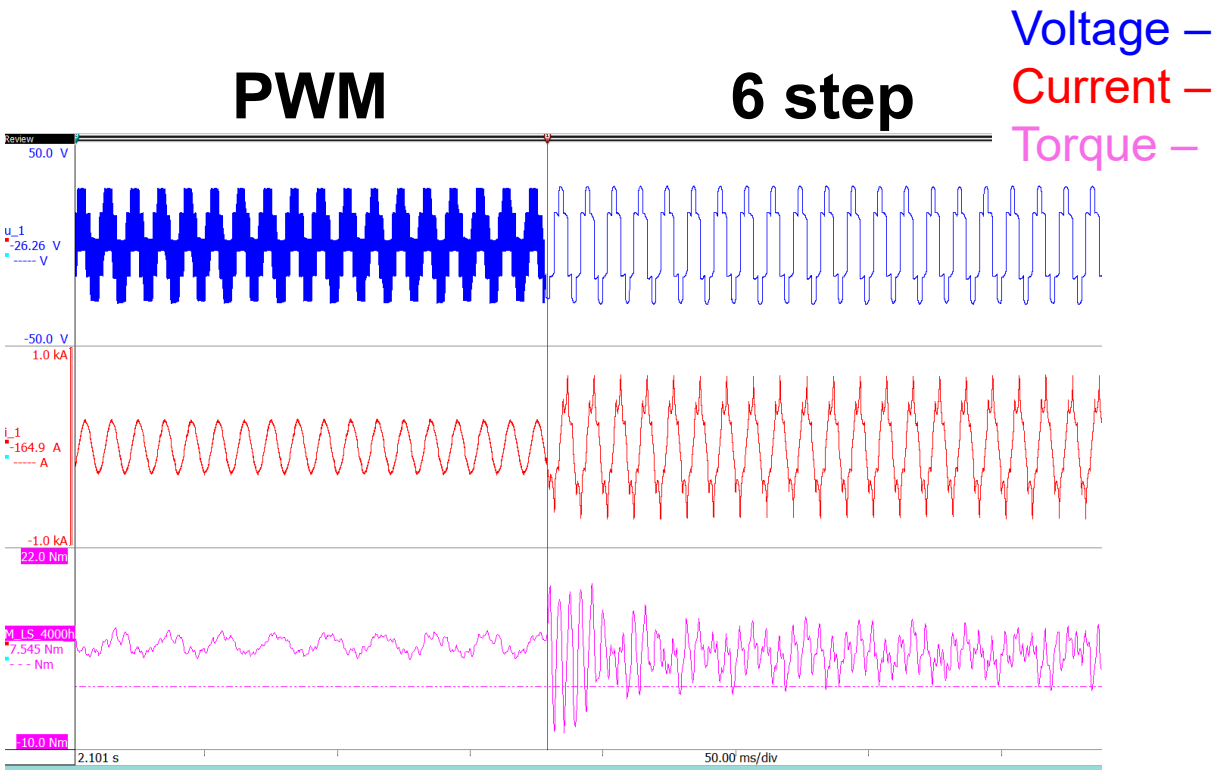
Frequency Content of Torque Ripple

Inverter Voltage Influence on Mechanical Torque

- Torque has frequency component
- Inverter control type effects torque
  - PWM excitation on the left
  - 6 step excitation on the right
- These effects will result in NV at the machine and down stream



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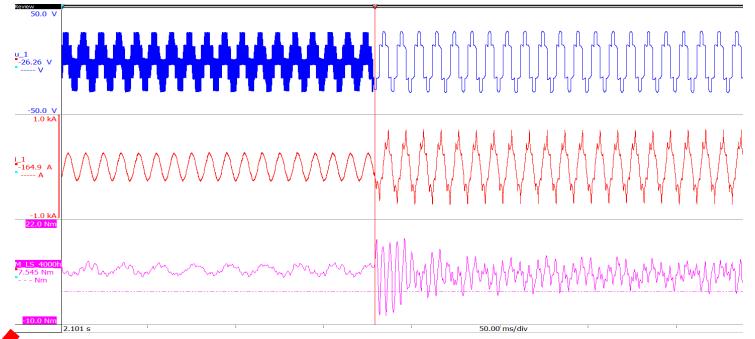
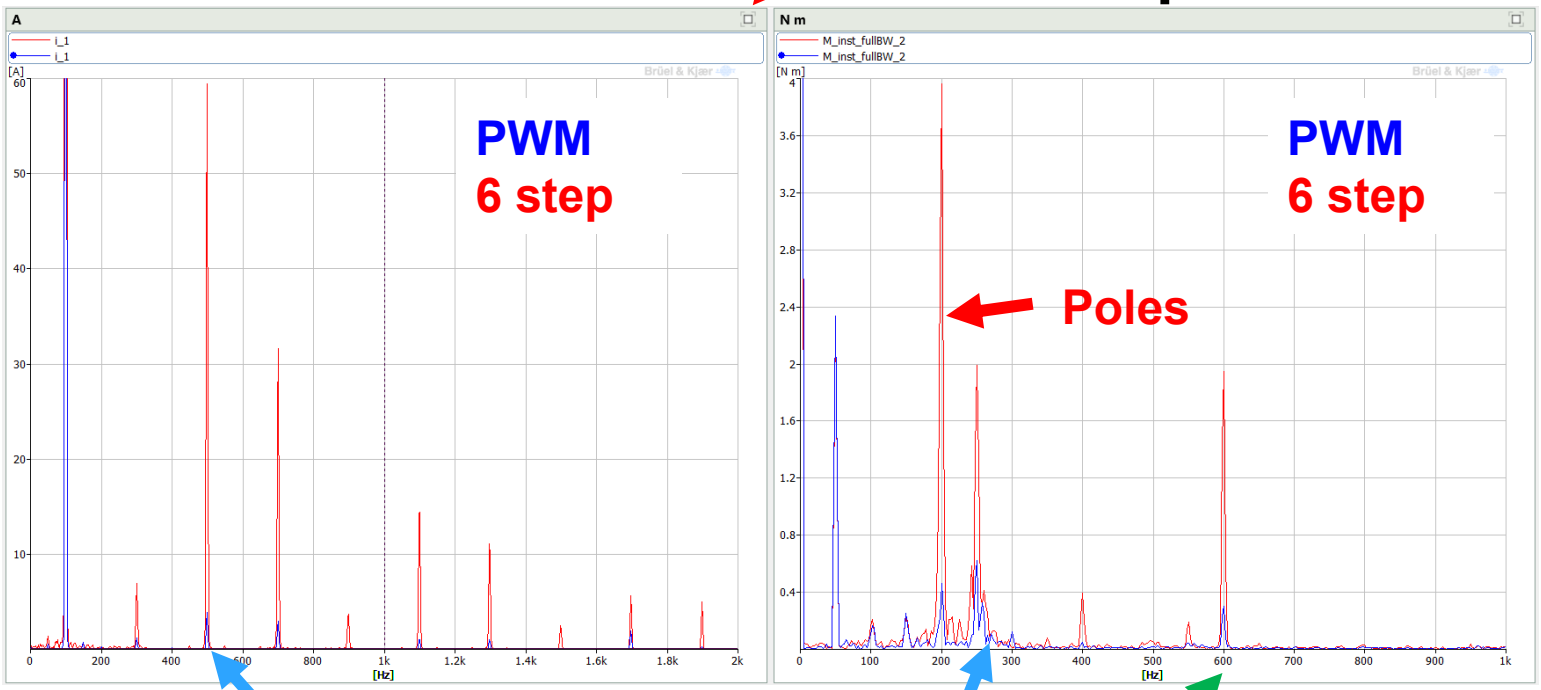
Voltage, Current, and Torque Frequency

- Electrical and mechanical fundamentals are related by pole count
- One control technique has significantly more harmonic content than the other
  - Electrical harmonics effect torque harmonics
- Frequency analysis of torque ripple can be used for correlation



Current **Torque**



5th electrical harmonic

Switching

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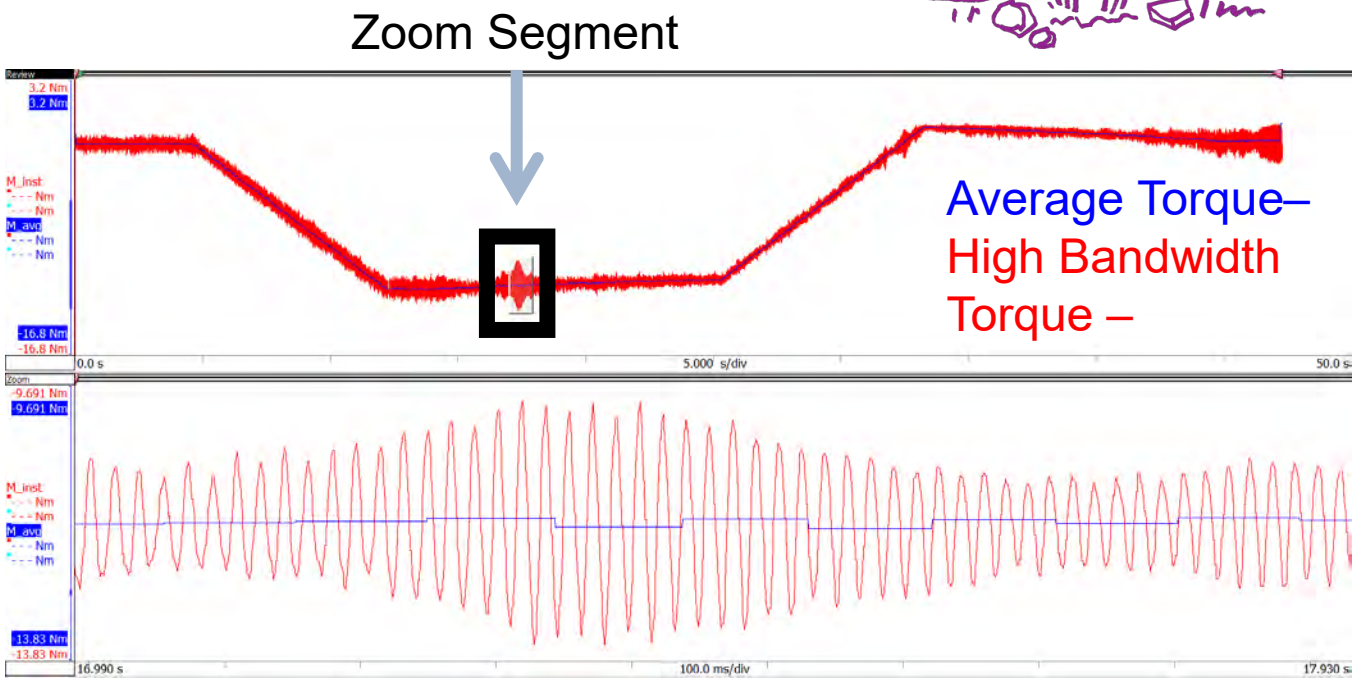
Why We Care About Torque Ripple

Vibration, Noise, and Fatigue

- Torque ripple results in vibrations
  - Gear chatter in gear boxes
  - Lifetime and durability concerns
- Torque ripple can excite structures
  - Result in noise
  - Result in resonant vibrations
- Motors spin at high speed – objectionable whining noise



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Efficiency Measurements in Motors

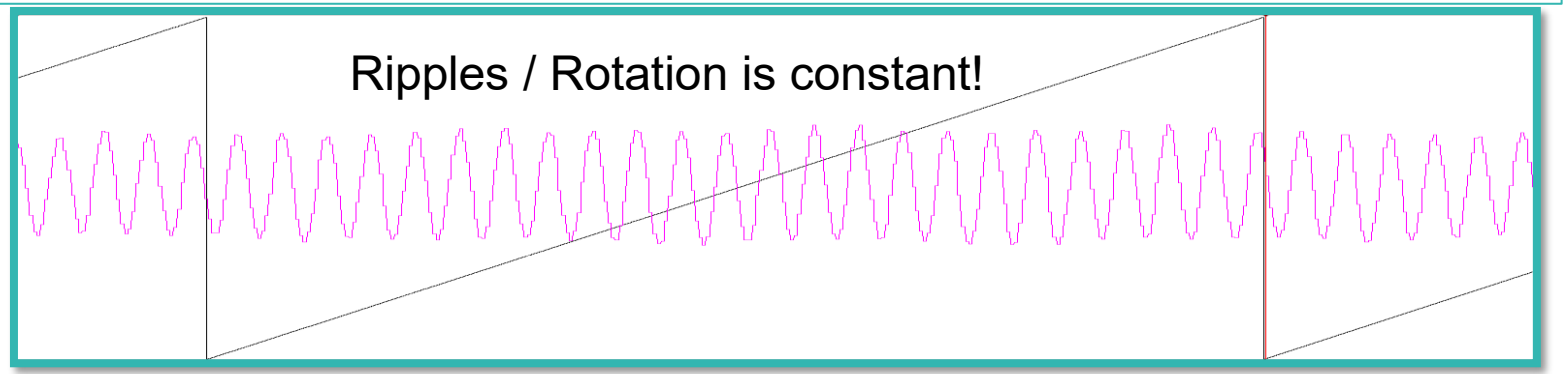
Internal Combustion Engine

- 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 → 2093 Rad/sec x 38.22 Nm → .25 Nm offset is 500 W →.625 %



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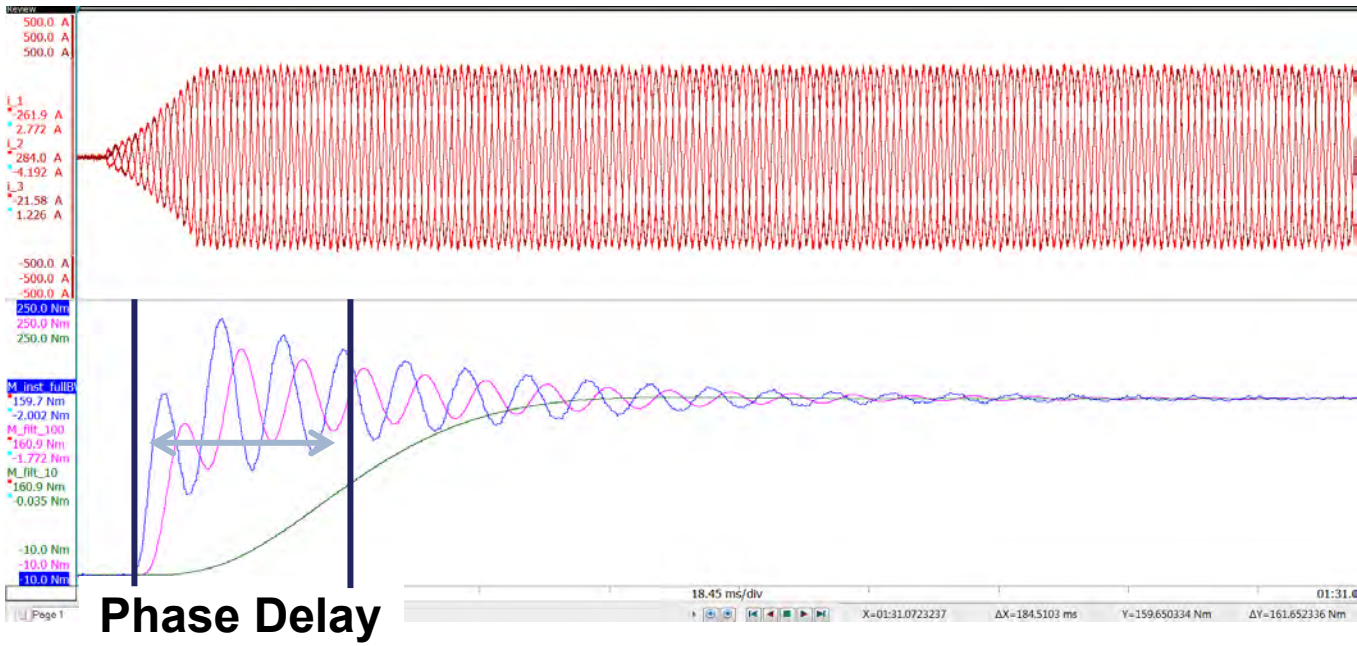
Measuring Torque Ripple

Accuracy, Bandwidth, and Time Alignment for Transients

- Accuracy lets you trust small values from large capacity sensors
- Low bandwidth and filtering augment phase and amplitude information
- Time alignment is necessary for control calibration
- Filters augment data used for efficiency
  - Results in very slow tests
  - Results in incorrect data

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



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Millbrook Revolutionary Test Facilities

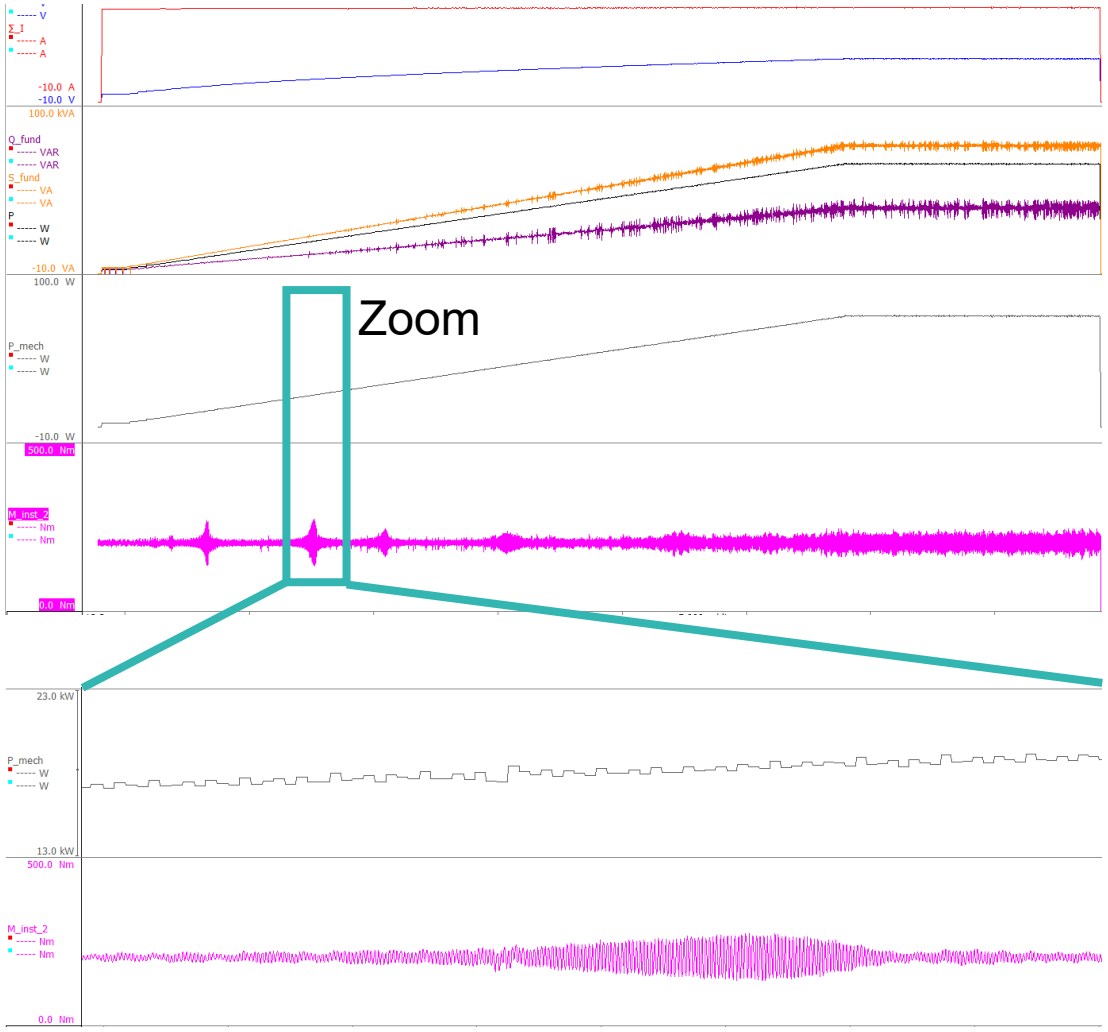
- Testing facilities in Livonia MI, Hayward CA, Leyland UK, and Bedford UK
- 19 year history offering testing solutions
- Specialized in electric motors, axles, transmission, and gear box testing
- All locations have access to:
  - Permanent magnet machines
  - High speed machines
  - eAxle rig
  - 90 degree gearbox (20k RPM)

Key Elements in a Torque Ripple Test Stand – MRE

- High performance dynamometers
  - Featuring induction load machines
  - Stiff speed control & great disturbance rejection
  - Closed loop control featuring EtherCAT
  - Variety of test profiles available
- High end instrumentation
  - HBM T12HP
  - eDrive Power Analyzer
- Experienced eMotor testing staff
  - Maximize run time
  - Bring electrification industry knowledge to traditionally mechanical customers
  - Knowledgeable in high speed operation

Speed Ramp

- Speed ramp with a constant torque
  - Measure power
  - Measure torque
- Torque ripple can effect measured output power with incorrect measurement time
- Torque ripple problems may not be obvious to engineers measuring power
- Power is typically measured over a long period where torque ripple averages out



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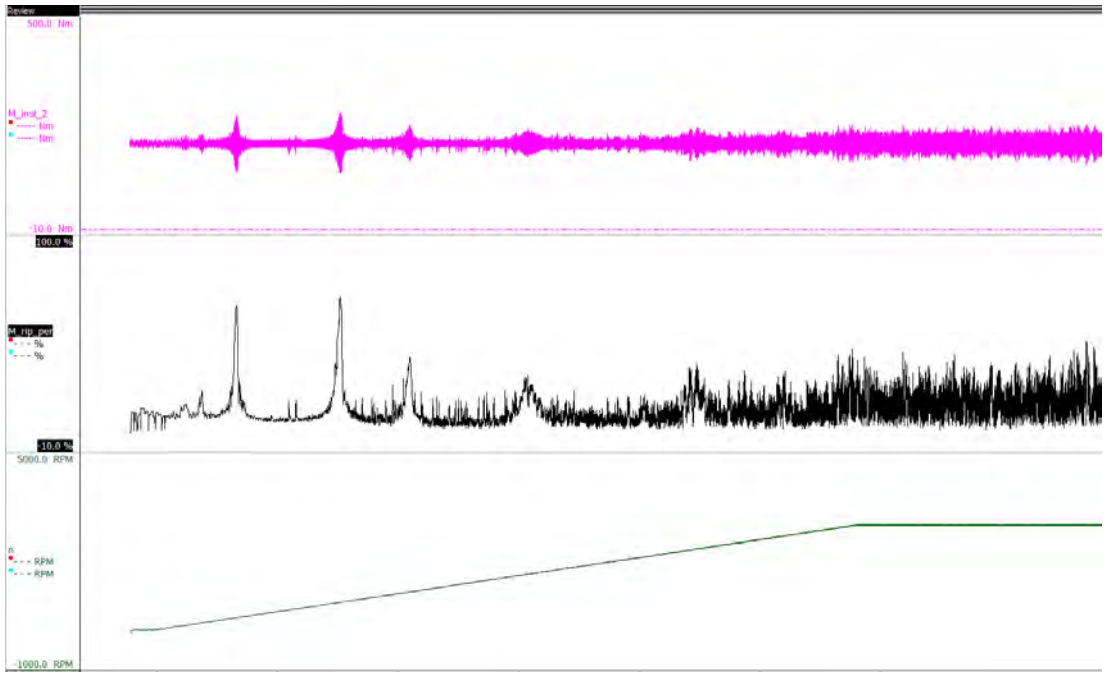
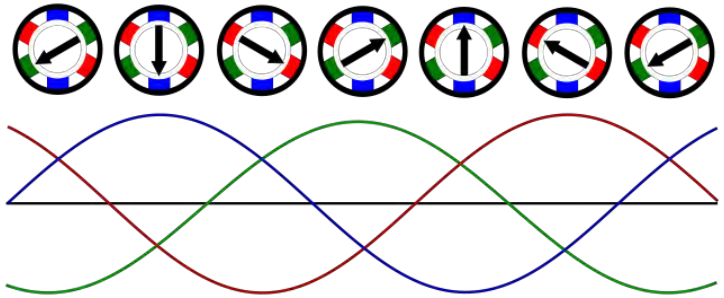
Torque Ripple Data – Time Domain

- Speed ramp with fixed torque
- Note torque ripple & torque ripple percentage
- 2 obvious resonant points
- Up to 70% torque ripple at certain points
- Normal 5% torque ripple
- Good opportunity to bring in the NVH team

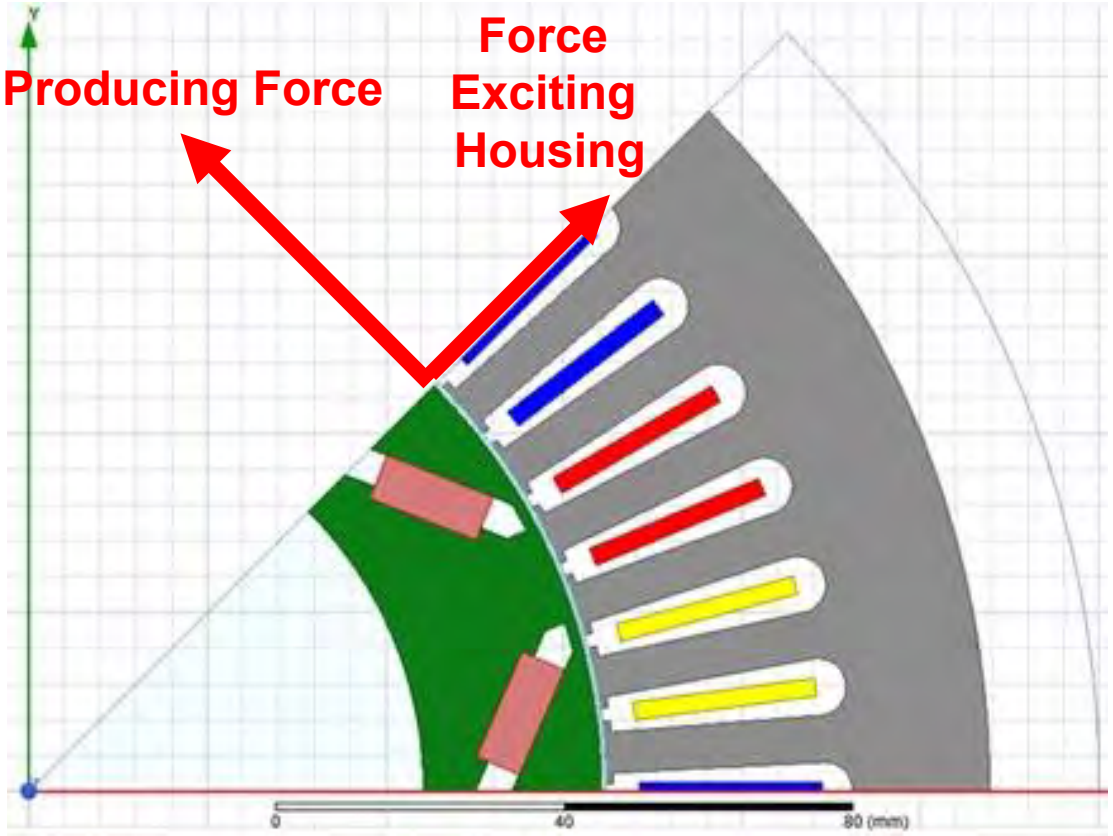


Torque Ripple’s Correlation to Noise and Vibration

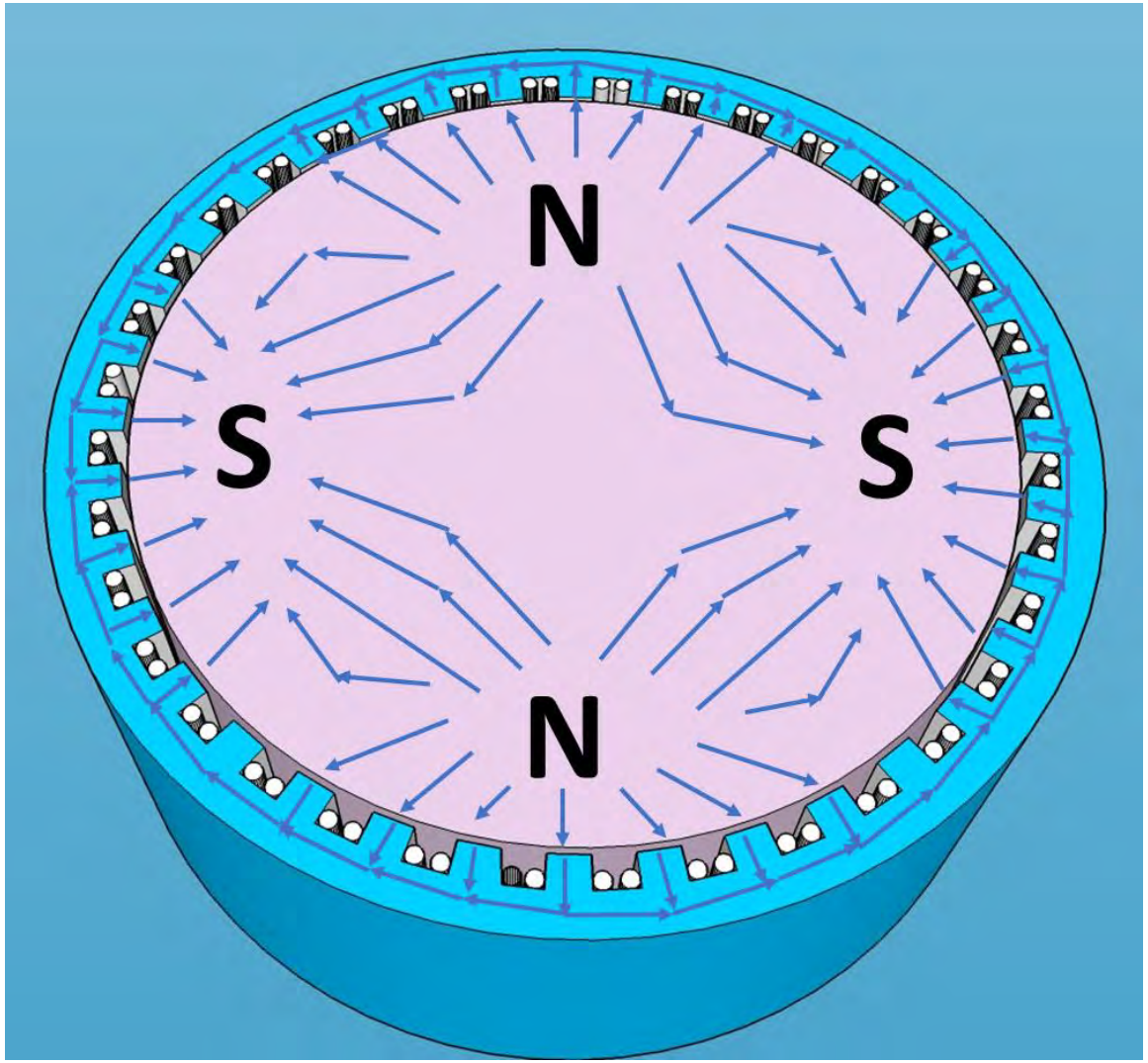
Motor Construction – Sources of Vibration



- Torque follows the envelope of AC excitation
  - Slow speed ripple proportional to electrical frequency
  - Function of winding distribution
- Permanent magnets interact with slot teeth
  - Magnets want to stick to iron
  - Function of magnets
  - Function of slots
- Forces not in the direction of torque can excite housing
  - Interaction of rotor and stator produce a rotating radial force which can be much stronger than the tangential force that produces the desired torque
  - Radial forces mechanically excites the stator producing vibration/sound



Motor Construction – Sources of Vibration *(cont.)*



- Consider the simple synchronous motor. The rotor is a powerful magnet, the stator is iron, and they are separated by as small of a gap as possible

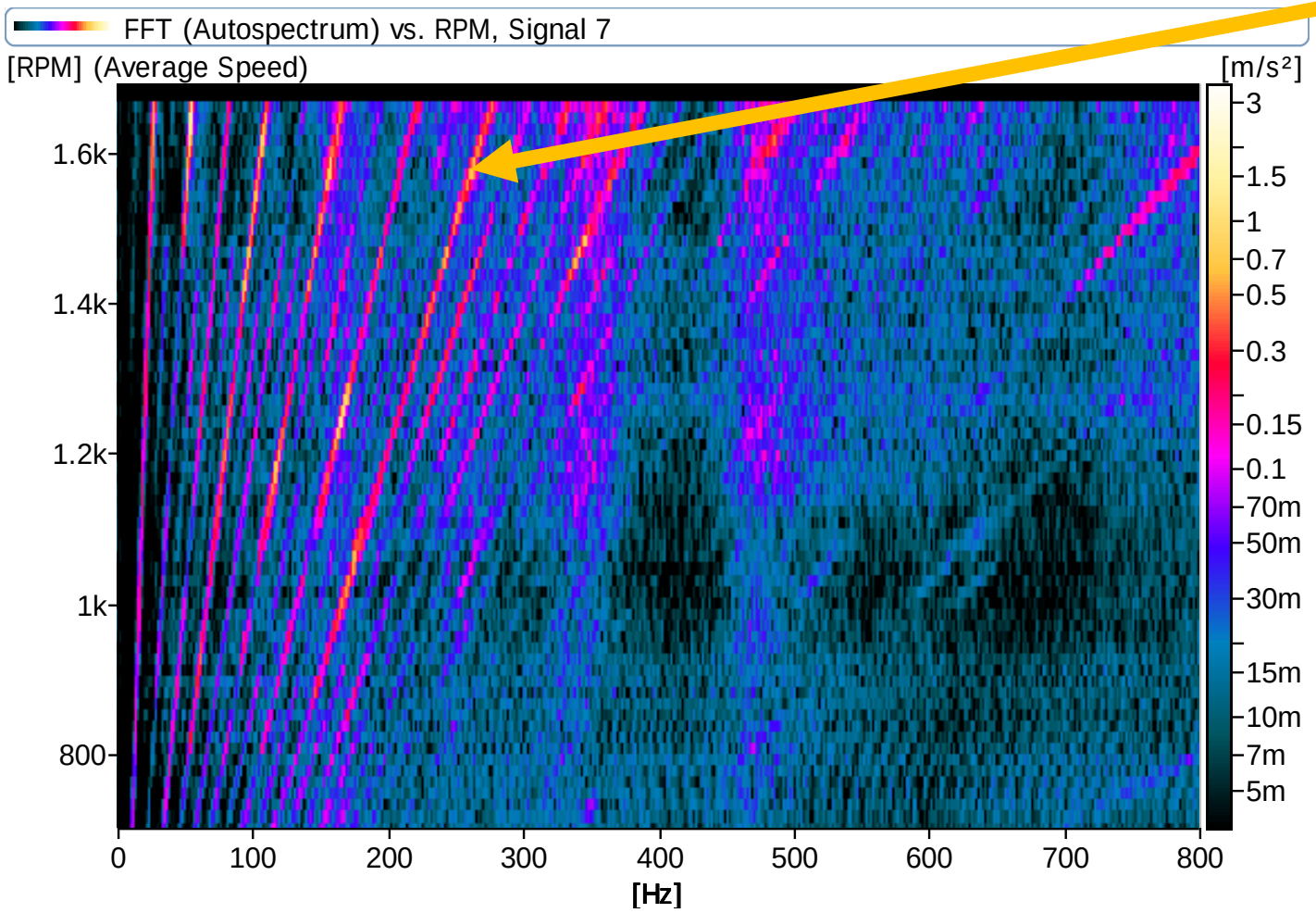
- **Radial forces and lesser tangential forces produce stator vibration and motor torque ripple which increase as load increases**

- **The fundamental excitation frequency is:**

$$f_{ex}(Hz) = \frac{pN}{60}$$

***p* is number of pole pairs**
***N* is the rpm**

Noise and Vibration – Basic Mechanisms



- For this synchronous motor, expect strong vibration 10th order (ten pole pairs)
- Many other orders are present due to many things like slot geometry, mechanical imperfections and deformations, magnetic imperfections, and current imperfections

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Impact of Automotive Torque Ripple

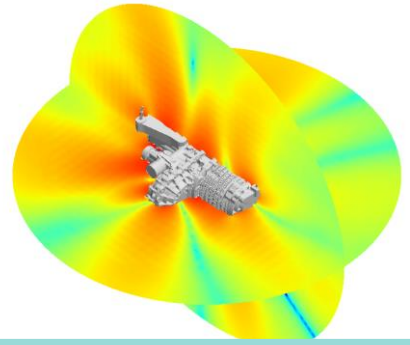
- The torque ripple is resisted at the engine mounts and suspension attachments
- Dynamic force inputs into the body
- Noise, vibration, and shudders

NVH Case Study – Simulation of Different Motors into a Car

Hybrid Model for Virtual Powertrain NVH Evaluations

Romax TECHNOLOGY

Mount Forces



Acoustic Source Strength

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$$\frac{P}{F_1}, \frac{P}{F_2}, \dots$$

$$\frac{P}{Q_1}, \frac{P}{Q_2}, \dots$$

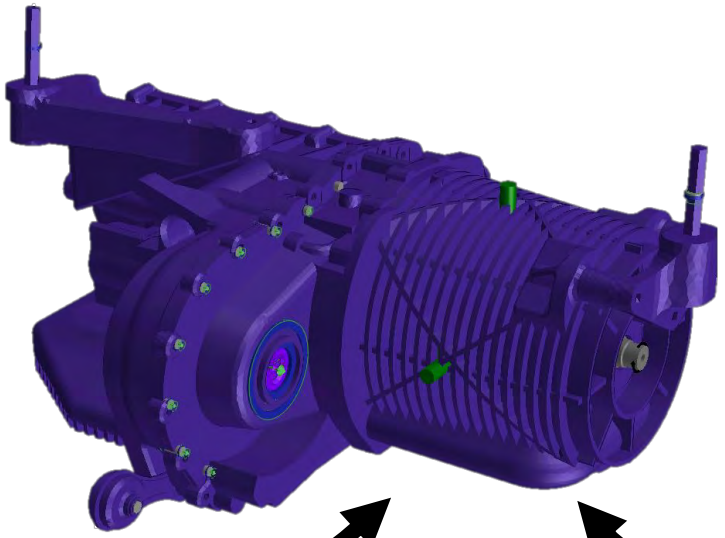
Measured Data

Virtual Vehicle

Model Variants

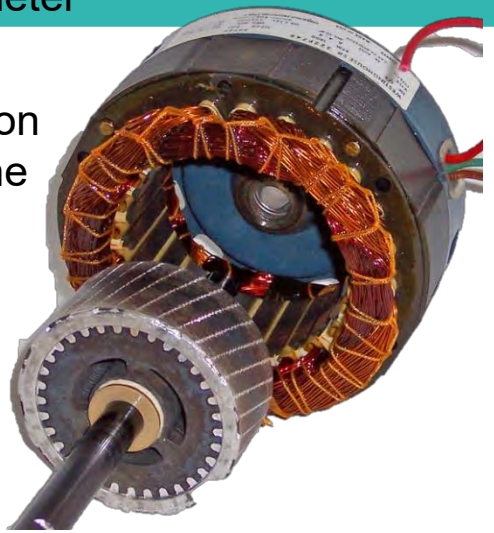
Simpler, and cheaper to construct, more robust but potentially noisier and more difficult to control

Switched Reluctance Machine

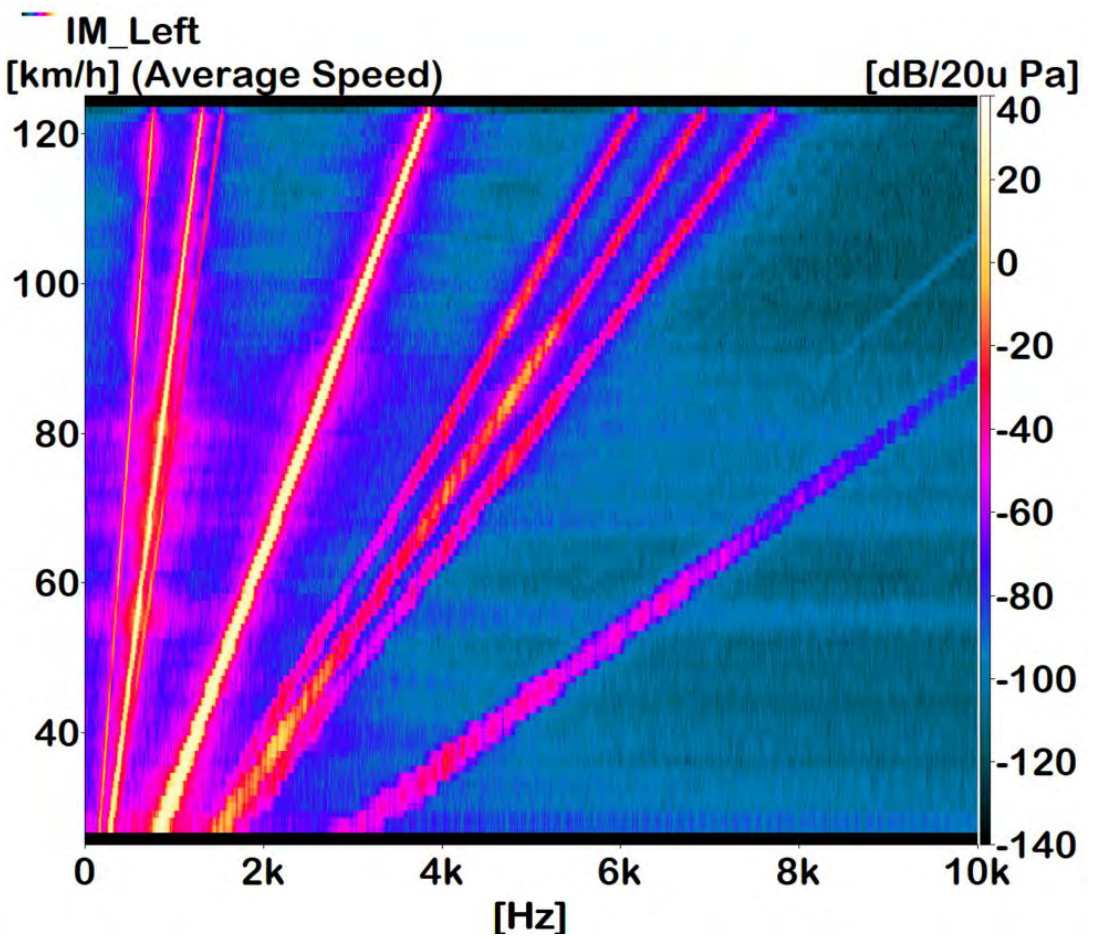


More complex windings, lower torque density, mature technology, and potentially quieter

Induction Machine



Interior Sound – Induction Motor Run-up to 80mph



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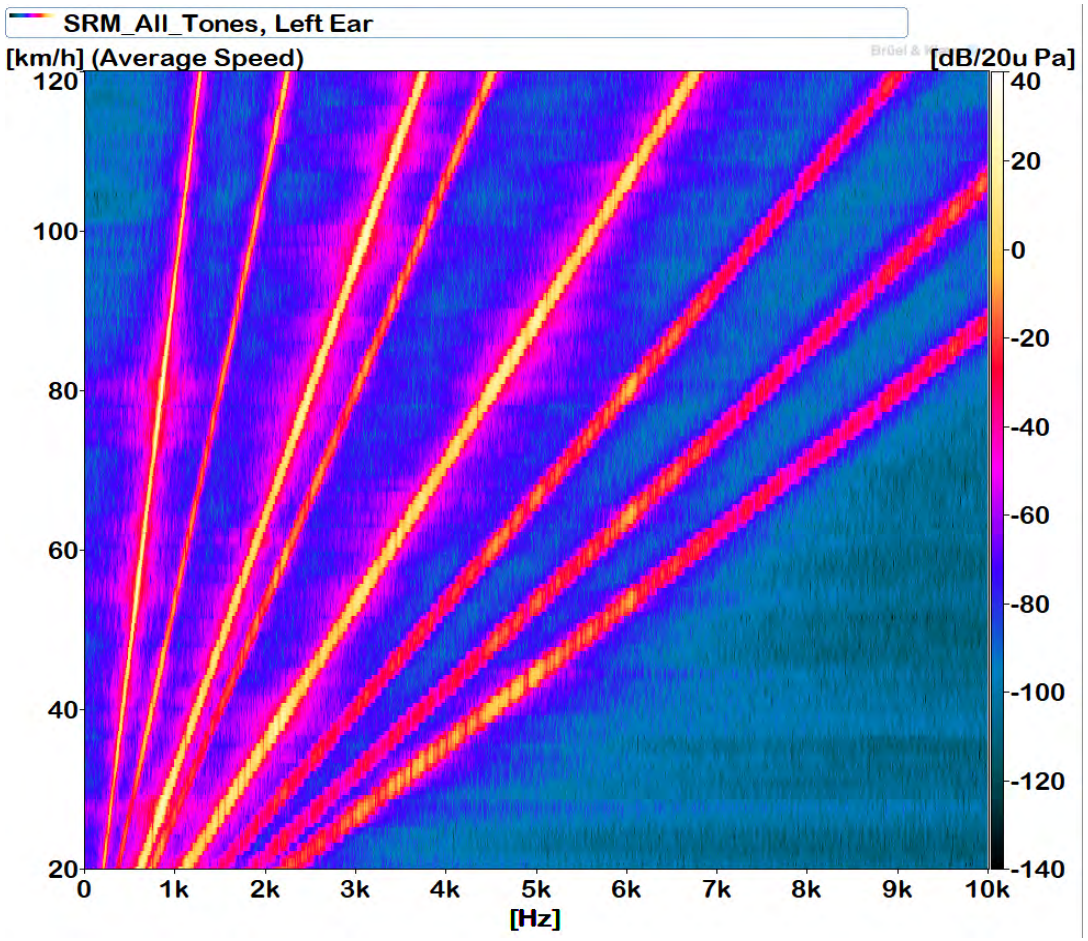
Interior Sound – Switch Reluctance Motor Run-up to 80mph



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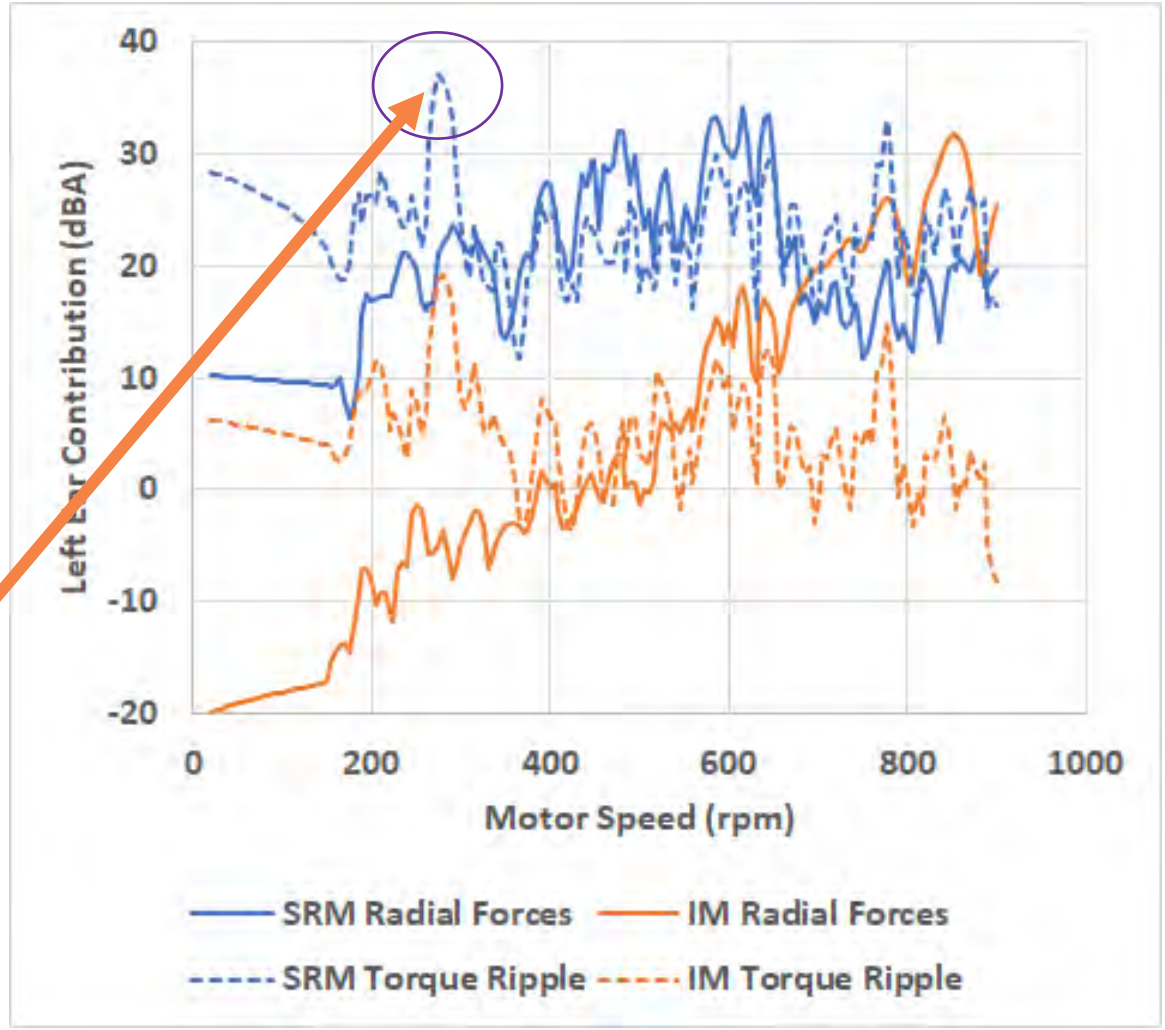
IM vs. SRM Overall Level

- Great insight into noise produced by radial forces versus torque ripple – **torque ripple produces similar noise** (solid versus dashed line).
- The tones from the switch reluctance motor generates higher loudness than the induction motor (blue versus orange).
- The torque ripple for the switch reluctance motor has a high contribution around 300 rpm exceeding the gear noise at that speed.



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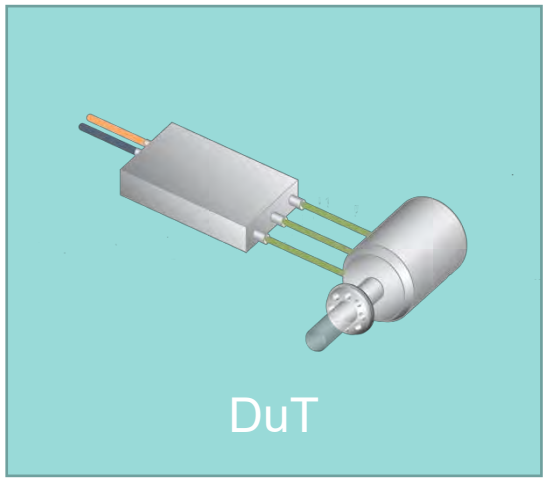
NVH Case Study – Permanent Magnet Synchronous Traction Motor

Problem: Customer was Interested in Initial Torque Ripple Characterization for NVH

- Machine was suspected to have a torque ripple issue
- Desired initial investigation
- Torque ripple is a new concept to NV engineers
- Torque ripple analysis may require new investments for an NV group
- Four pole pairs

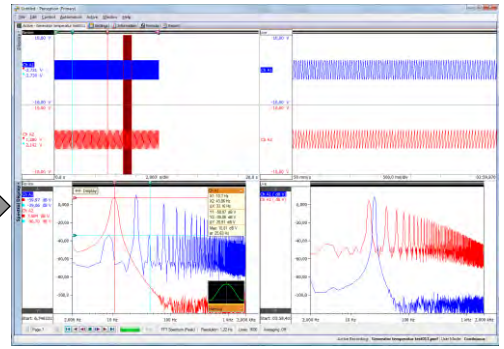
Electric Powertrain and NVH Testing



Voltage
Current
AND
Acceleration

ALL
synchronously and
continuously
recorded with eDrive

Time domain and
FFT display
in Perception



Post process analysis in
BKconnect

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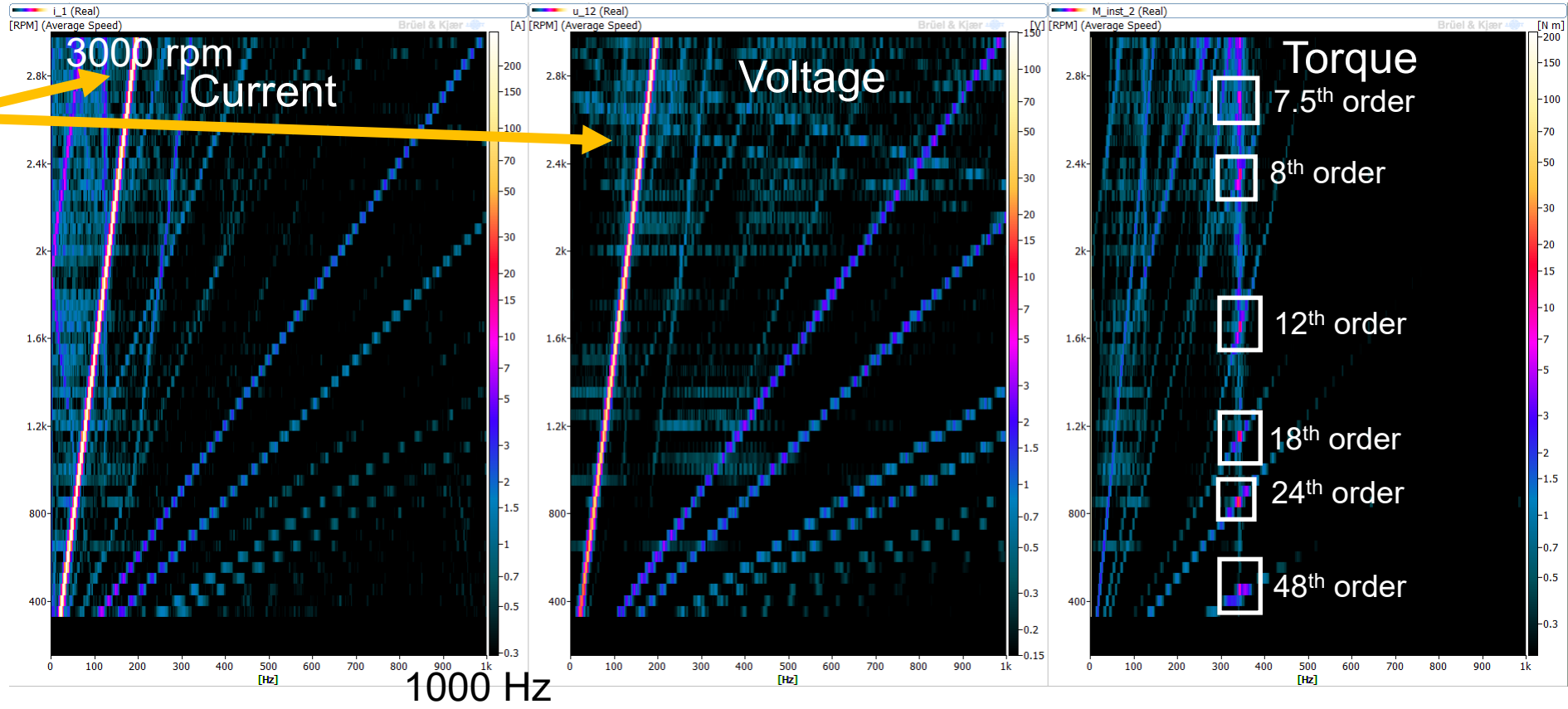
Torque Ripple Colormaps for 200 Nm Load

- Strong lines at 4th order for current and voltage as expected



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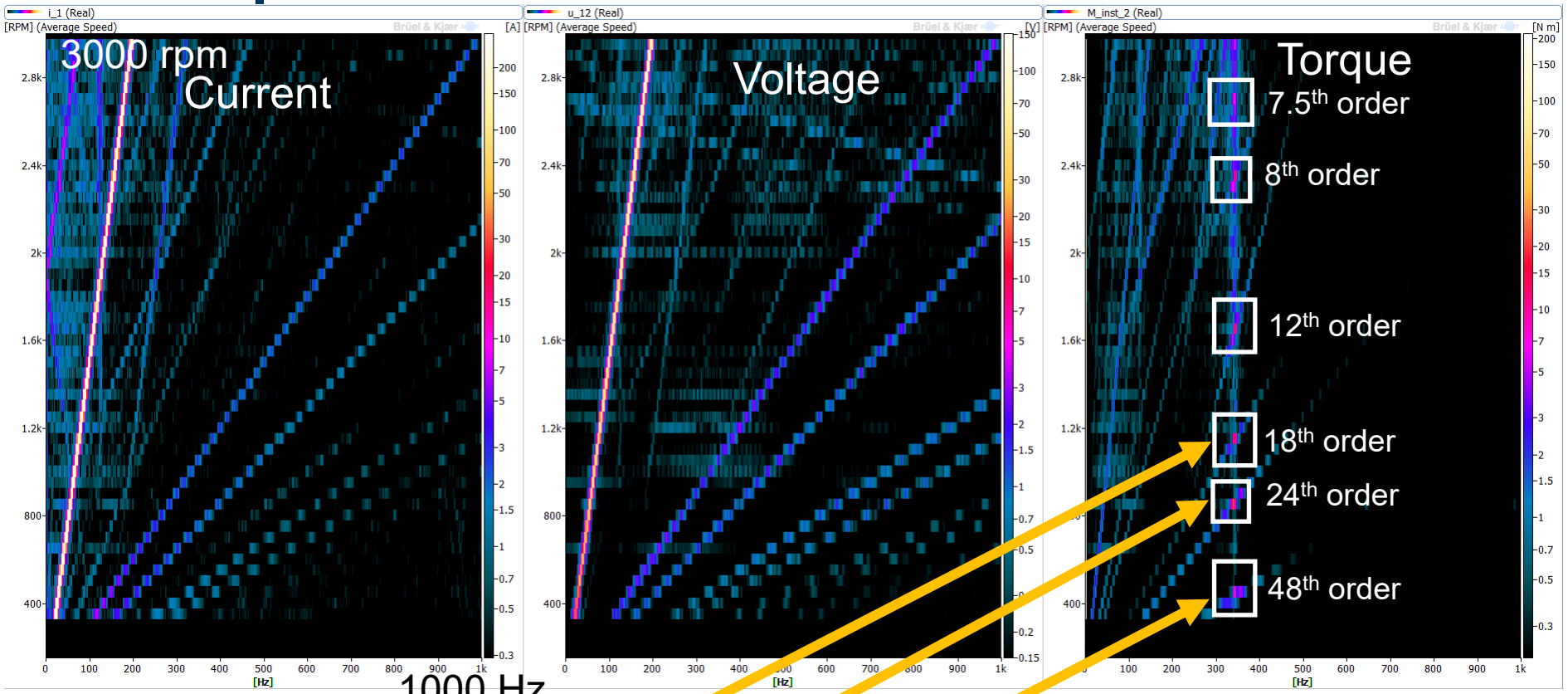
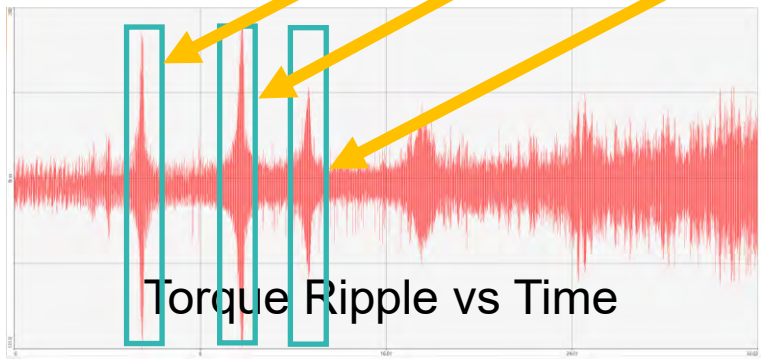
Torque Ripple Colormaps for 200 Nm Load

- In this case torque ripple is caused by strong 340 Hz resonance excited by several high orders
- **Simultaneous measurement of NVH quantities and current and torque provides the complete picture**



1000 Hz



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THANK YOU - QUESTIONS?

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