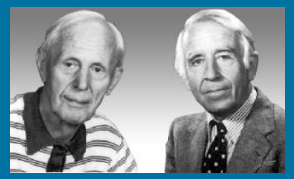
eDrive NVH

HBM eDrive Testing

Oct 2019

Agenda

1. eDrive overview
2. Challenges in electric propeller testing
3. Measuring high fundamental frequencies
4. System level electric aircraft tests
5. Electro-mechanical aircraft tests
6. High voltage testing



PER V. BRÜEL AND VIGGO KJÆR

Brüel & Kjær

HBM

KARL HOTTINGER

HBK – merger of two great companies into one test and measurement powerhouse

The global leader in **sound and vibration** test and measurement with a 75 year history

Designs and sells the **entire measurement chain**

A premium brand, recognized for **quality, reliability and performance**

Technology and market leader in measuring, testing, and analysis with a focus on **durability, reliability, structural design, industrial control and weighing**

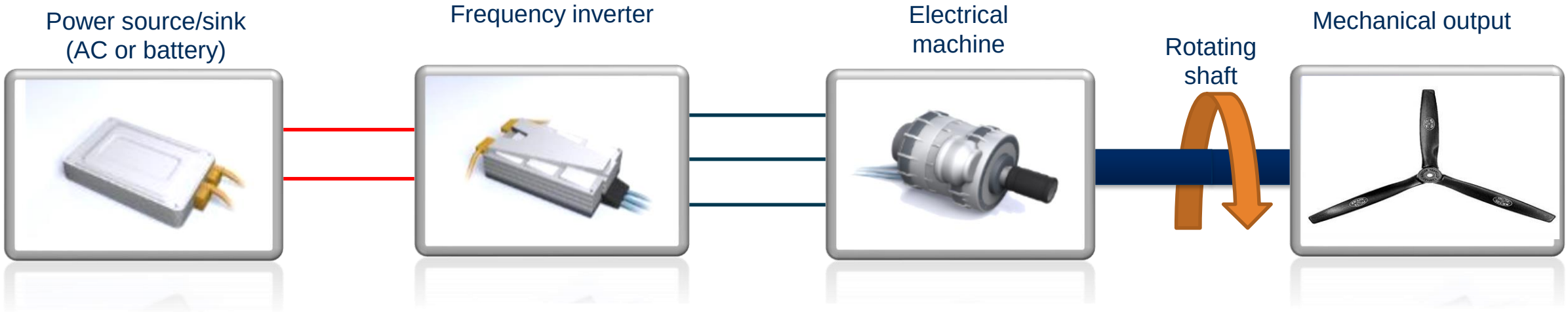
Global player offering the **complete measurement chain** from sensor to instruments to analysis SW and engineering services in our key disciplines

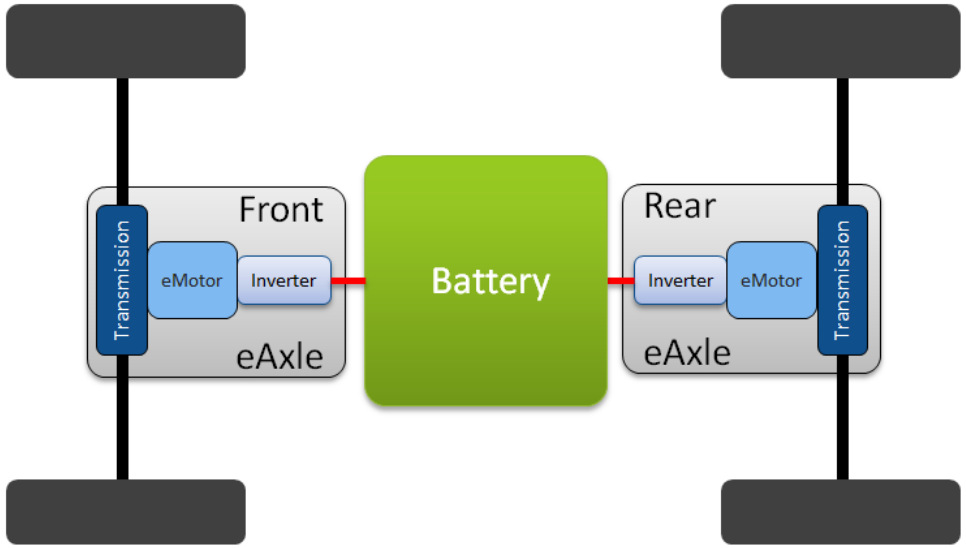
FOCUS BUSINESS AREAS	KEY FIGURES	OUR CULTURE
• Automotive, aerospace and telecom/audio • Sound and vibration • Noise	• 1000+ employees • A global company with 1/3 of business coming from USA, Europe and Asia respectively	• Today, the engineering spirit prevails • High focus on creating the best technology • Informal and “family style” culture

FOCUS BUSINESS AREAS	KEY FIGURES	OUR CULTURE
• Automotive, Aerospace, Transportation • Weighing, Industrial and Machine Building • Durability Design and Validation	• **1900 people** • 29 subsidiaries and sales offices worldwide • Balanced sales split between Europe, US and Asia	• Reliability and accuracy • Integrity and respect • Results you can trust • These values drive our behaviour as a company

Introduction to Vibration In Electric Machines

Simple Measurement Chain - Electric & Mechanical Measurements





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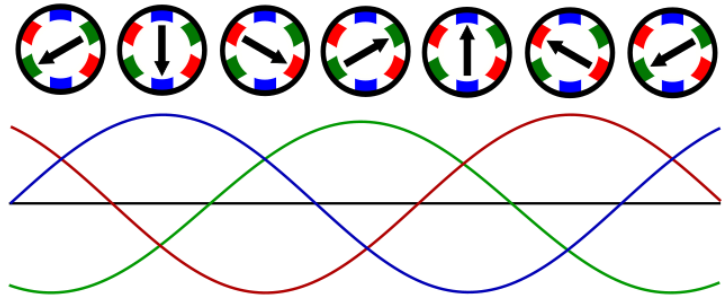
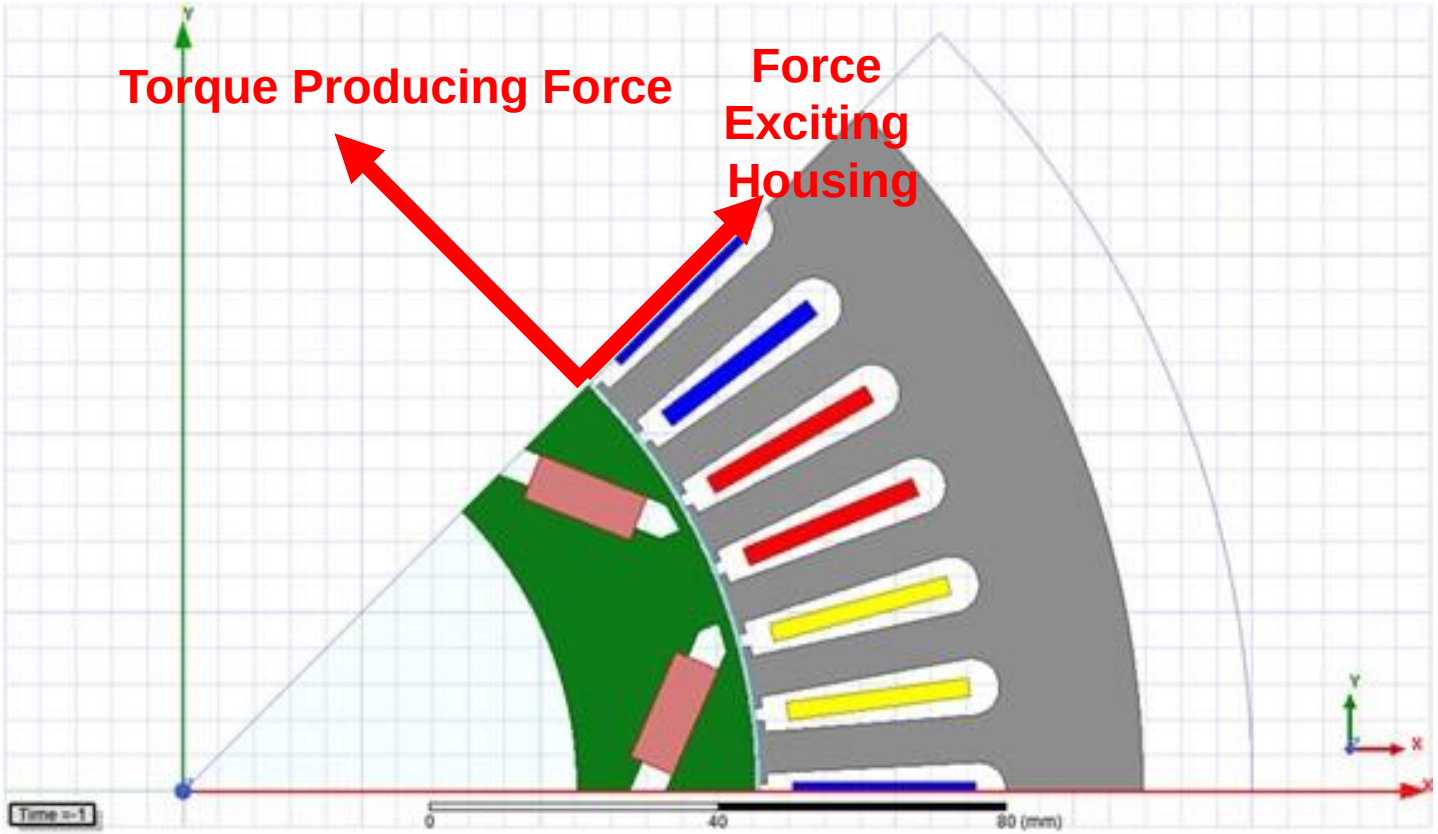
Motor construction – Sources of vibration



- 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

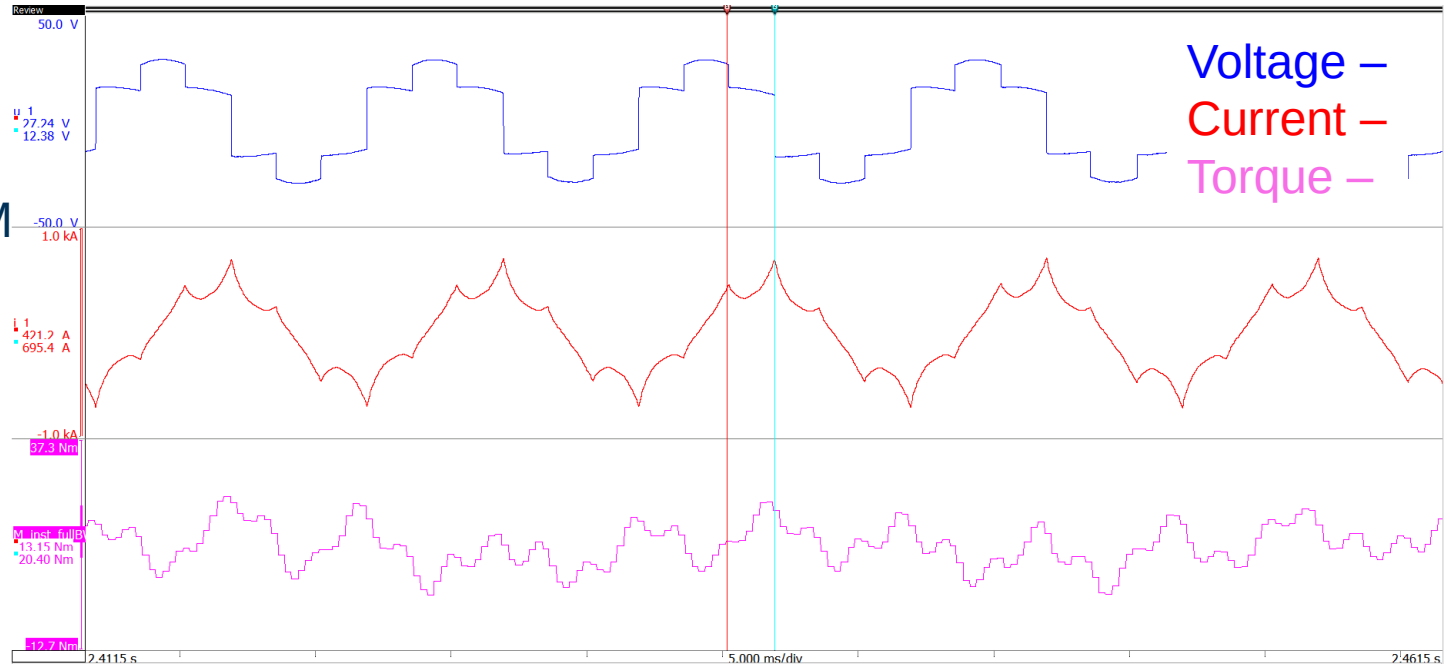


Single motor pole for a PM machine highlighting iron slots and widnings

Inverter operation

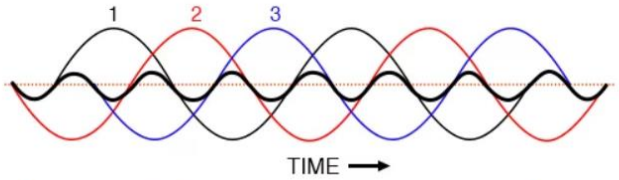
- Inverter often creates AC with a Pulse Width Modulated voltage
  - Pulses of different length create a sine wave
  - Unequally timed pulses result in multiple frequencies of NV
- PWM voltage → PWM current → PWM Magnet → PWM torque → PWM NV
  - Noise and vibration at switching rate
- Many more controls than PWM

PWM to Synthesize Sinusoidal Output



Voltage, current, and torque highlighting the correlation between the 3 values

Three Phase Machine Electrical Harmonics



Third harmonics for phases 1, 2, 3 all coincide when superimposed on the fundamental three-phase waveforms.

- Sinusoids eliminate 2n harmonics
- 3 phases eliminates 3n harmonics for **balanced load**
- Positive harmonics (ABC) are in the direction of rotation
- Negative harmonics (CBA) are in the negative direction
  - **Cause reverse torque**

Fundamental	**A** 0°	**B** 120°	**C** 240°	**A-B-C**
3rd harmonic	**A'** 3 x 0° (0°)	**B'** 3 x 120° (360° = 0°)	**C'** 3 x 240° (720° = 0°)	*no rotation*
5th harmonic	**A"** 5 x 0° (0°)	**B"** 5 x 120° (600° - 720° - 120°) (-120°)	**C"** 5 x 240° (1200° - 1440° - 240°) (-240°)	**C-B-A**
7th harmonic	**A"'** 7 x 0° (0°)	**B"'** 7 x 120° (840° - 720° + 120°) (120°)	**C"'** 7 x 240° (1680° - 1440° + 240°) (240°)	**A-B-C**
9th harmonic	**A""** 9 x 0° (0°)	**B""** 9 x 120° (1080° = 0°)	**C""** 9 x 240° (2160° = 0°)	*no rotation*

Direction of rotation for 3 phase motor harmonics

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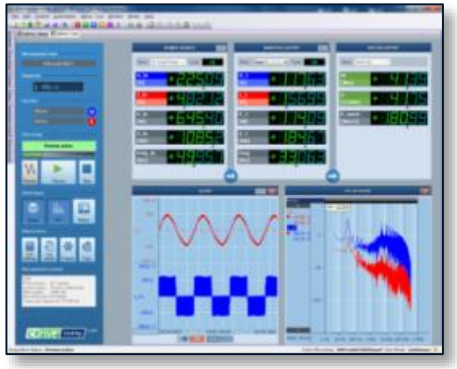
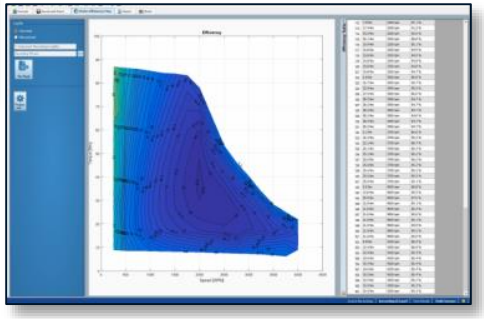
Characterizing NVH for Electric Machines

eDrive Value

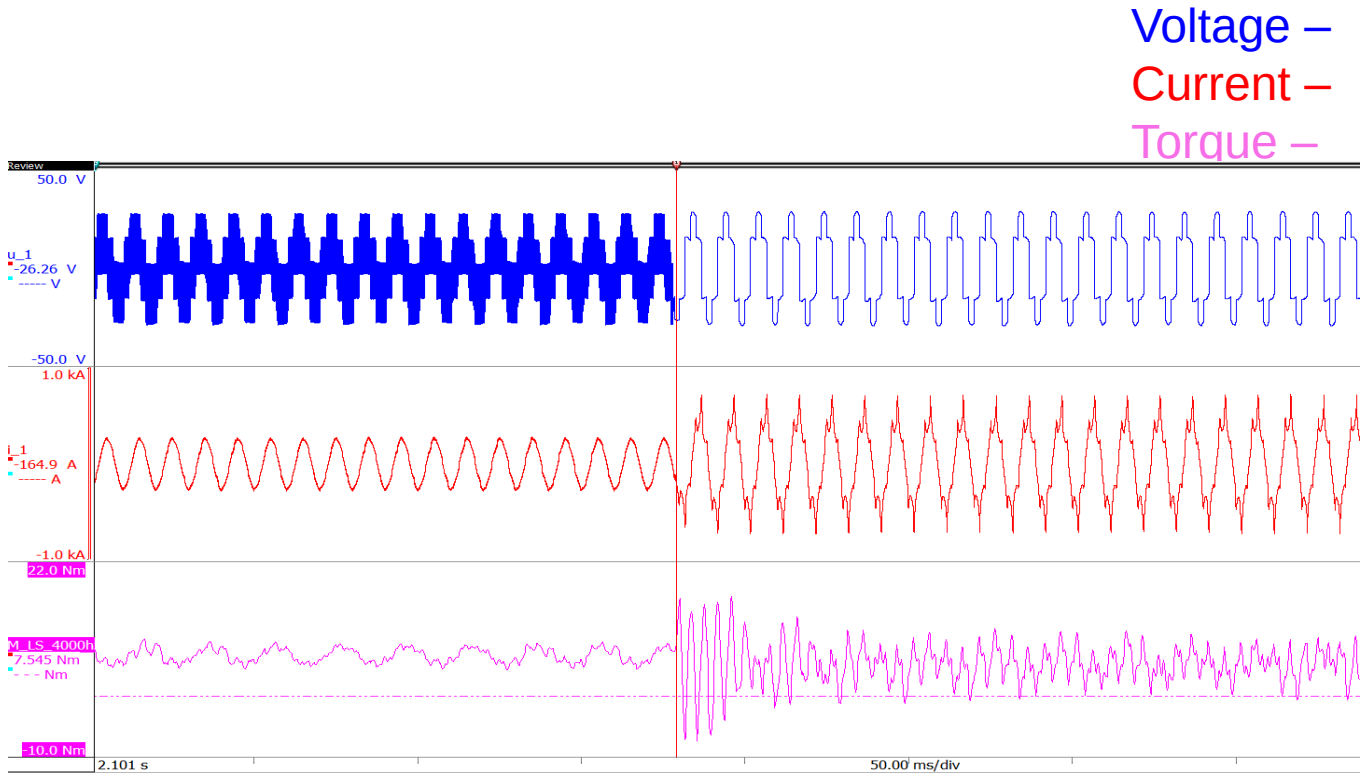
- The HBK **eDrive solution** streamlines and simplifies data collection of electro-mechanical signals
- High accuracy power measurements
- Future proof your testing capabilities
- **Auditable Tests**
- Full data streaming / raw data collection – Know where your results came from
- Simplifies measurement chain
  - Sensors → Aquisition → Software





Inverter Voltage Influence on Mechanical Torque

- Torque has frequency component
  - AC excitation
  - Slotting effects
- 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



Voltage, current, and torque for a control change in a 3 phase machine highlighting the dependence of torque on excitation

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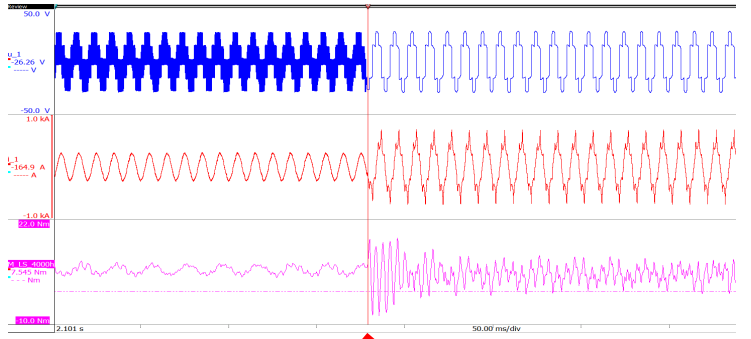
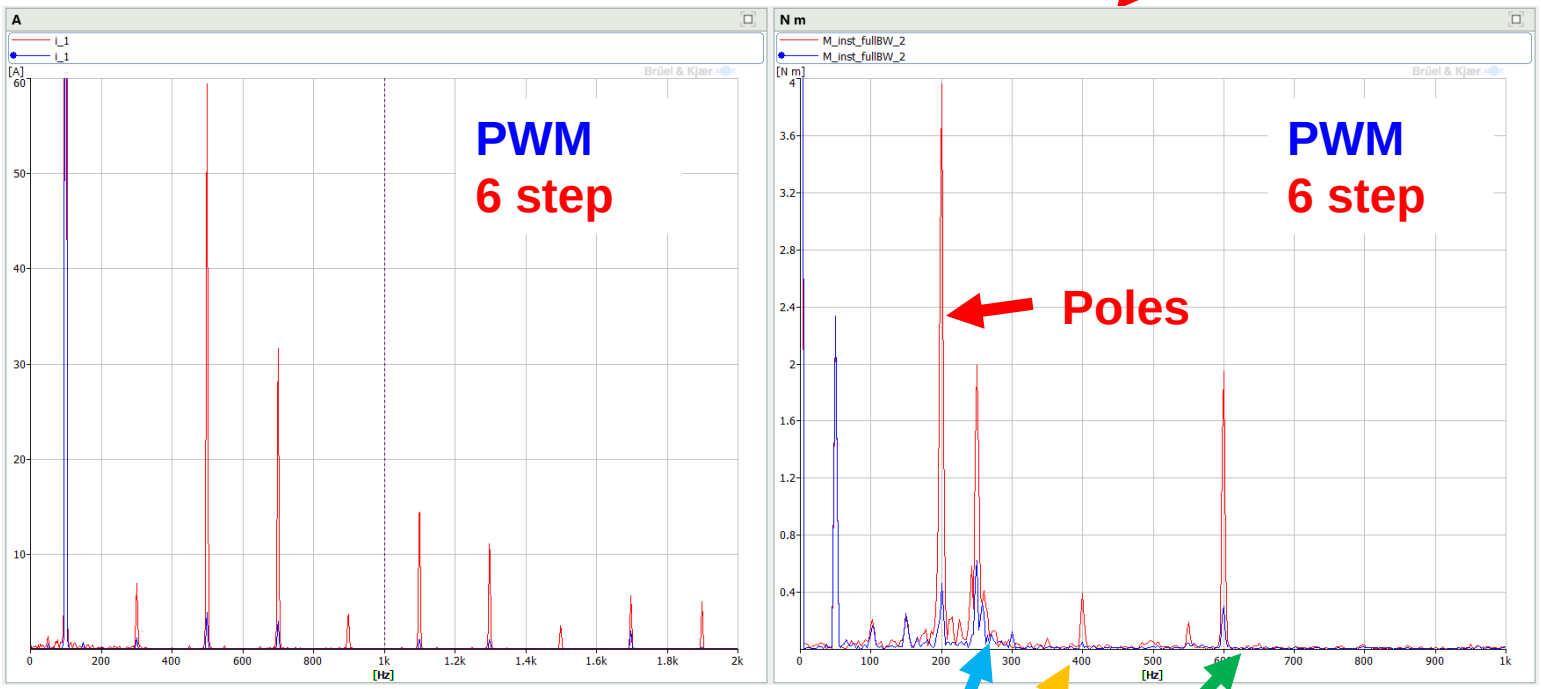
Voltage, Current, and Torque Frequency Content

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





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

5^{th} electrical harmonic

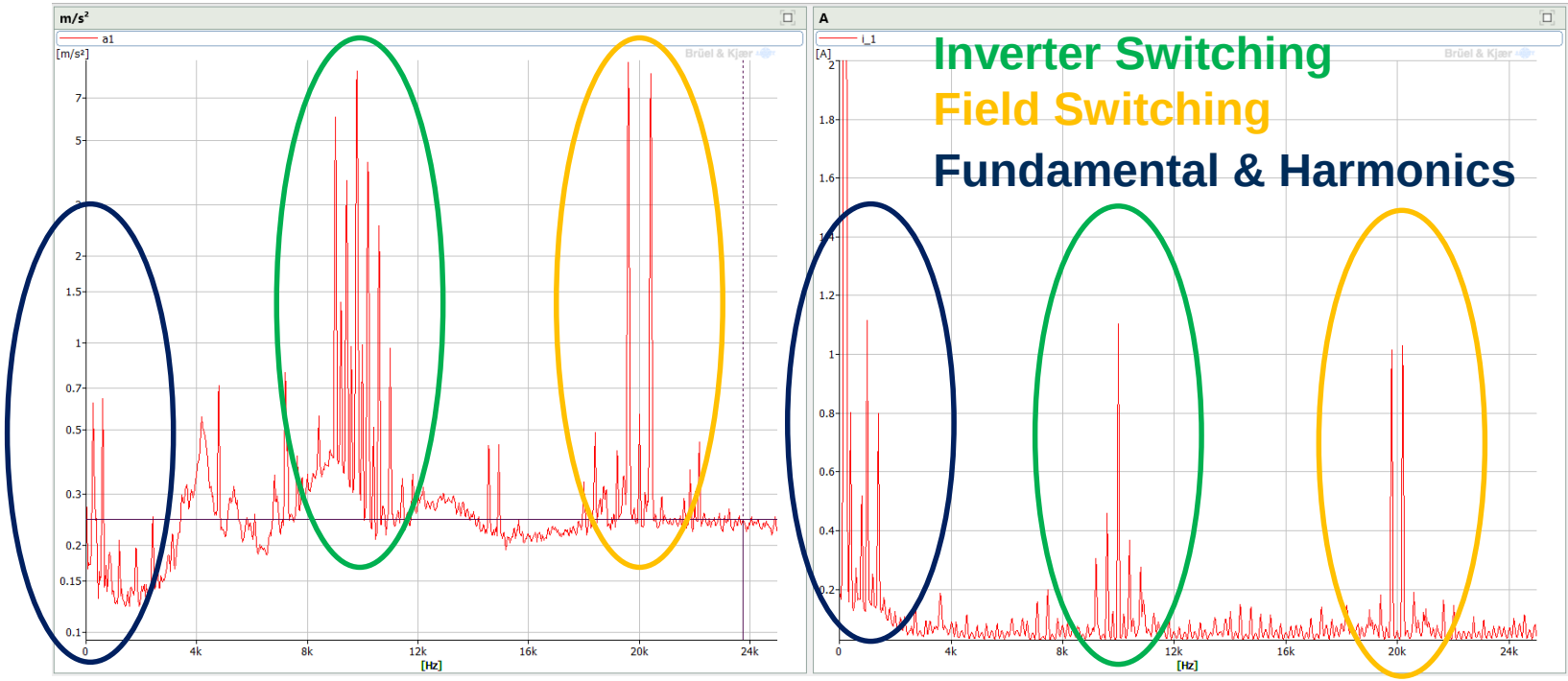
Construction

Switching

Current Causes Vibration

Or is it?!?!?!?

- Some machine vibrations are caused by the current
- Rotational frequency shows vibration from the harmonics of the fundamental
- High frequency vibration from switching
- Very similar to the torque signature
- Torque sensors limited to 6kHz bandwidth



Frequency spectrum comparing current and vibration for a steady state machine operation

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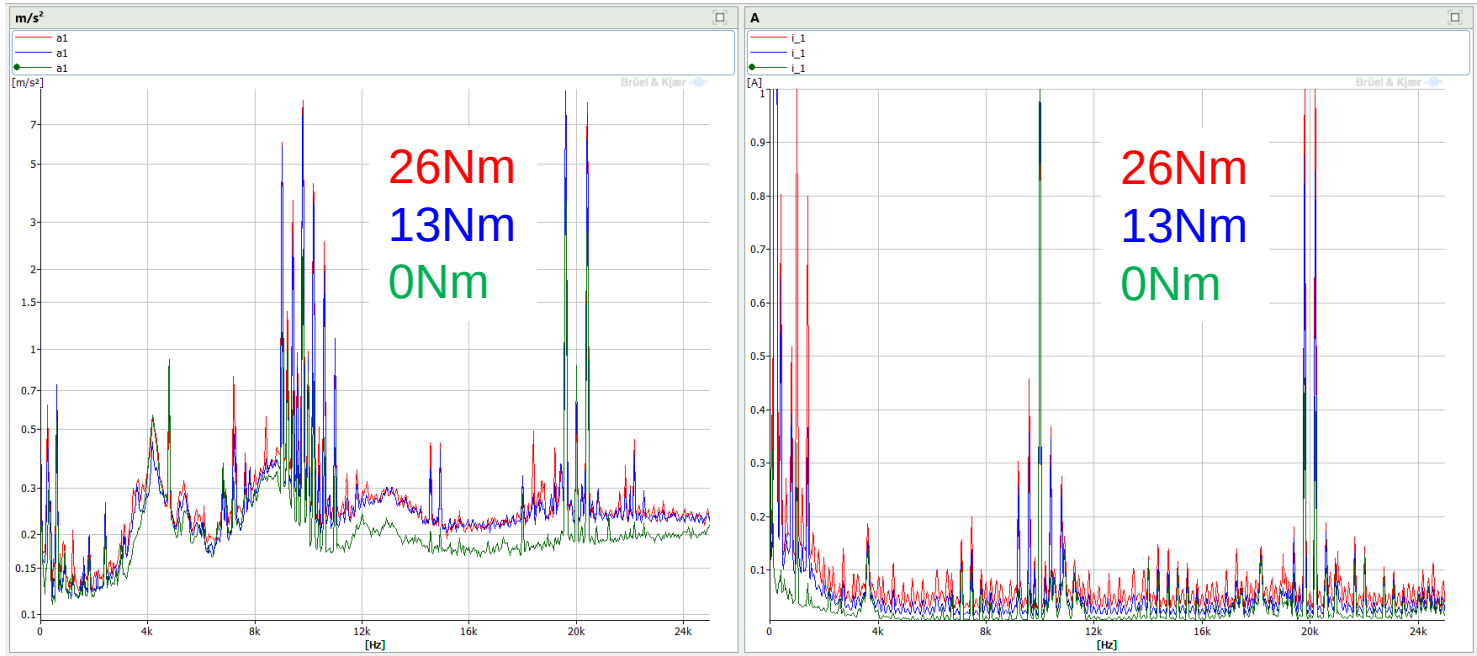
Torque Loading Influences Frequency Spectra

- Fundamental shows a torque dependence
- Inverter signature shows strong torque dependence
- Gear mesh orders also enhanced under high torque
- Switching is always there but has stronger presence with loading

Vibration

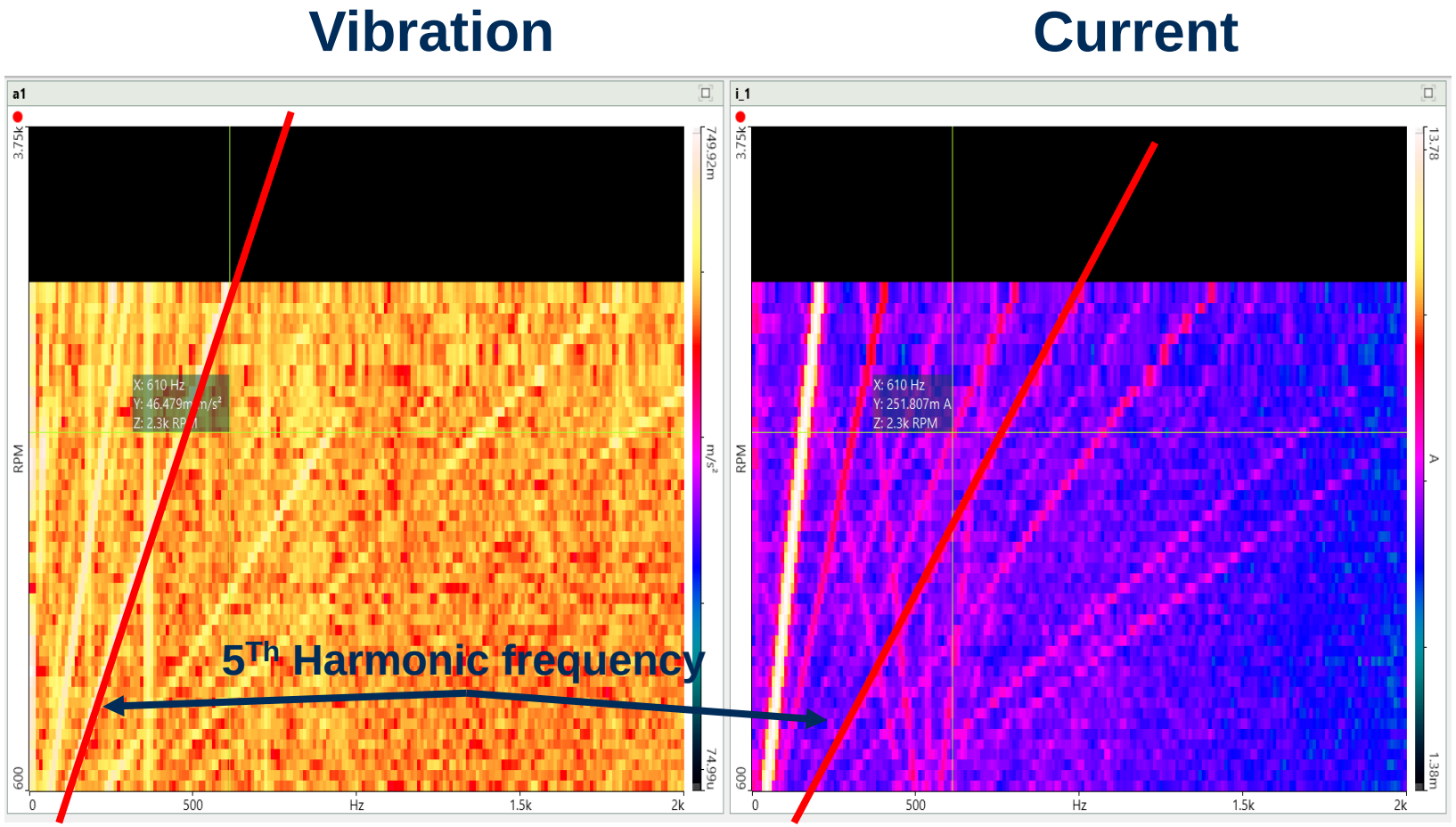
Current



Frequency spectrum comparing current and vibration for a steady state machine operation at 3 loading points

Ramps & Spectrum Plots

- Ramp up and down of speed at a given torque/ control
- Plot of amplitude (z), vs frequency (x), vs speed (y)
- Easy way to graphically see the influence of speed on current/vibration
- Follow fundamental & harmonics

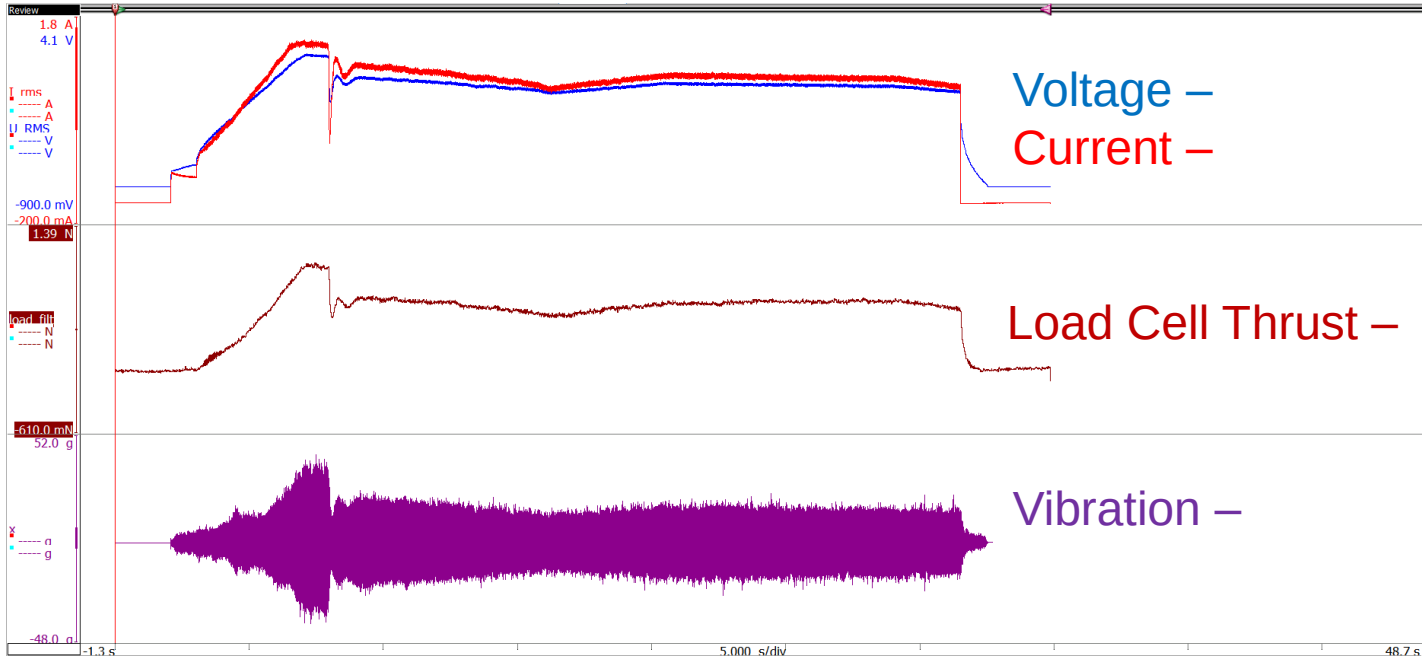


Spectrum graph showing vibration bands and current bands for the rotational frequency of a ramp test

Why Measure Both?

Benefits of combined testing

- Single test to do both
  - **Reduction costs**
- Communication between groups
  - **Faster development**
  - Easier communication to vehicle simulation
- Sound design
- Fatigue characterization
- Failure testing
- Resonance tracking
- End of line characterization



Propeller motor startup with load and vibration measurements

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Case Study

Characterization of a Traction Motor

Test Machine

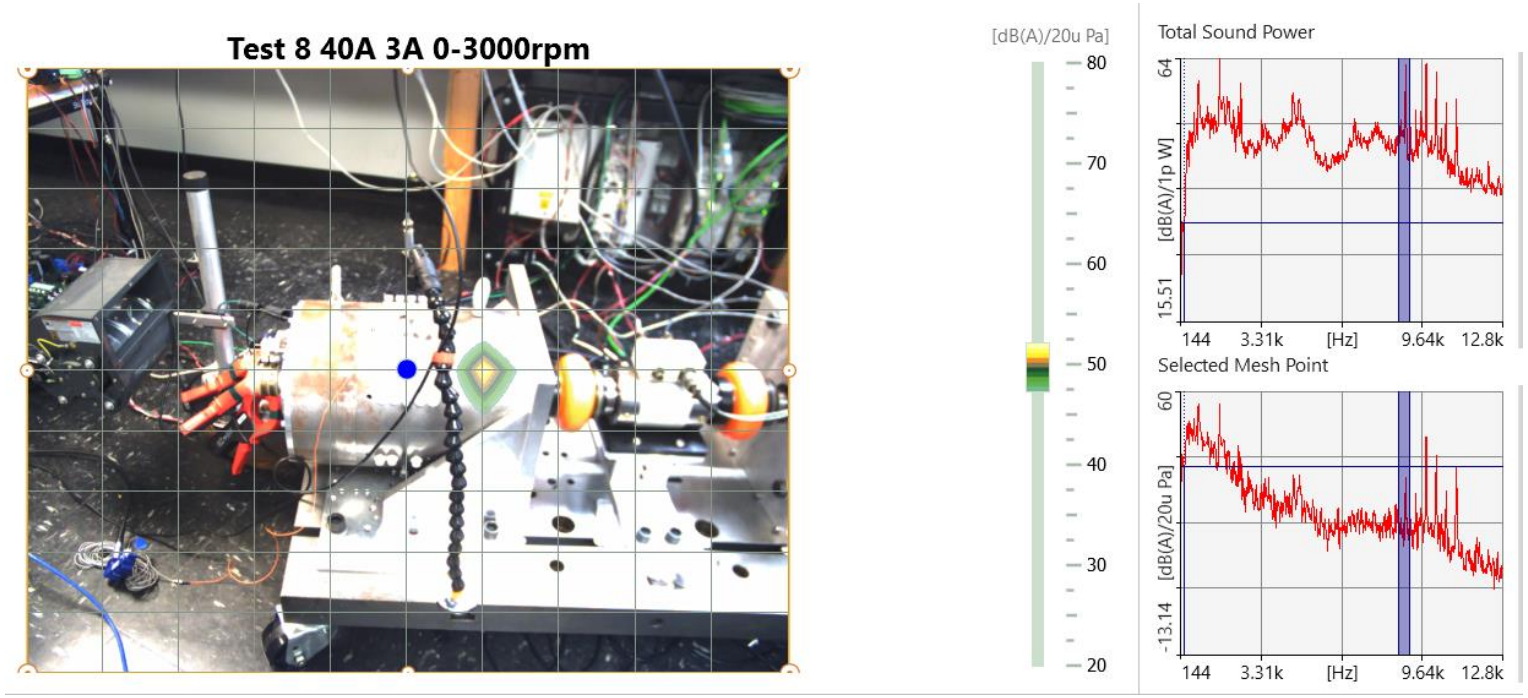
- Three phase traction motor
- PM & wound field excitation
- Eight poles

Tests Run

- Point by point efficiency map
- Ramps at different loadings

Measured Quantities

- Inverter voltage & current
- Torque and Speed
- Vibration
- Noise



Acoustic Camera picture for the DUT at IIT

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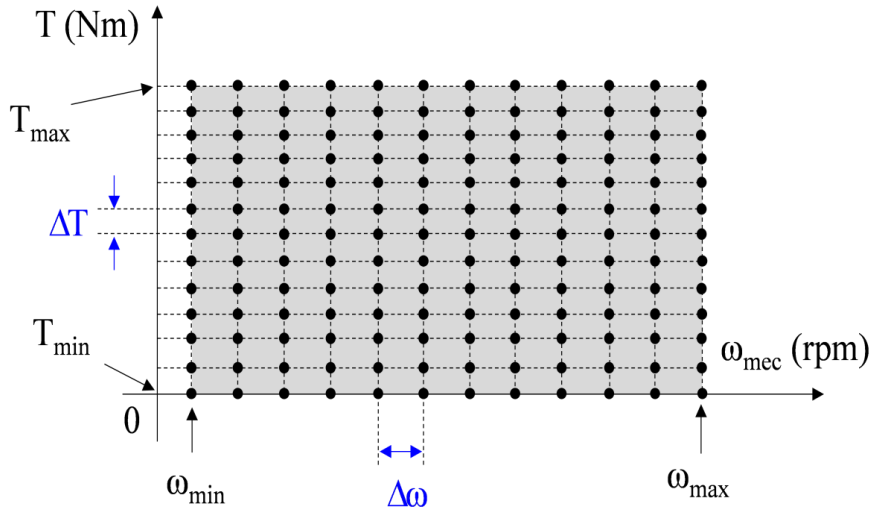
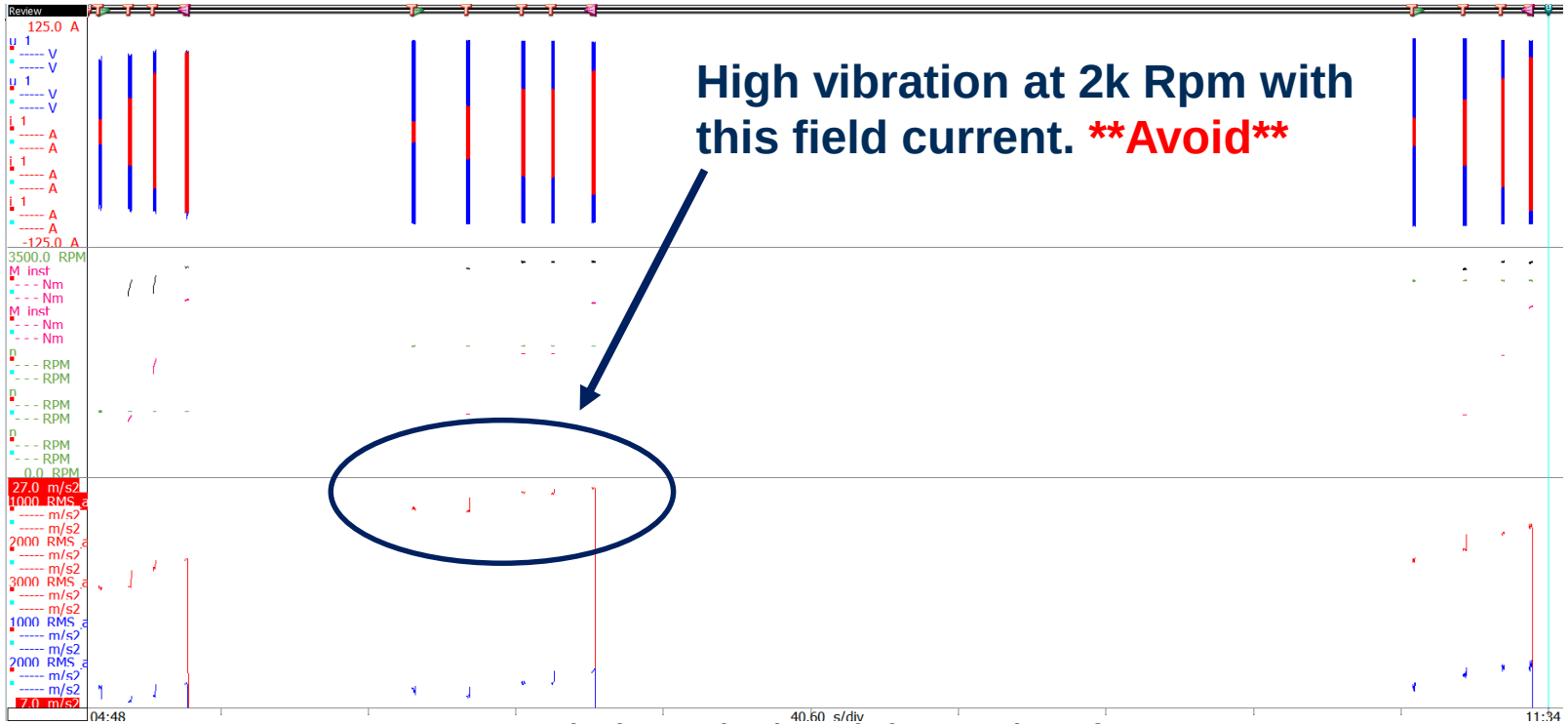
Efficiency Mapping With Vibration

Efficiency Mapping

- Series of static torque and speed points where efficiency is measured
- Record many signals
  - torque & speed
  - Voltage & current
  - Control
  - Vibration
- Can monitor how control effects vibration
  - Avoid certain states
  - Faster communication with other teams



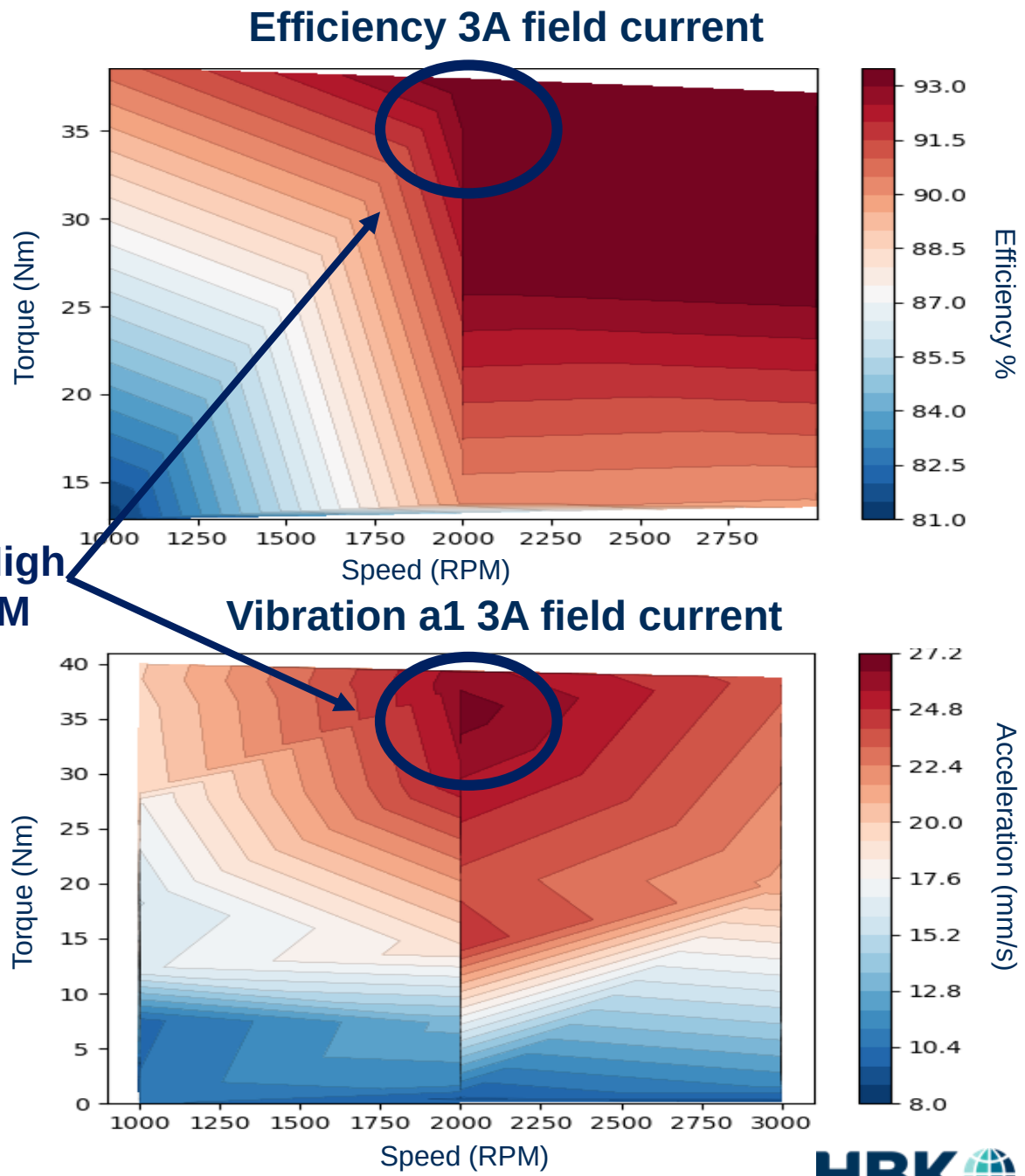
Voltage –
Current –
Torque –
Speed –
Efficiency–
RMS accel1 –
RMS accel2 –



Recorded & calculated data points for motor efficiency map

Efficiency & Vibration Mapping

- From these acquired points a “Efficiency Map” is often generated
  - X – Speed (RPM)
  - Y – Torque (Nm)
  - Contour – Efficiency %
- Gives an idea of where the optimal operation is
- Can also be plotted for RMS vibration
  - Shows general trend of the vibration
  - Identifies hot spots
- Allows for analysis of system level interactions

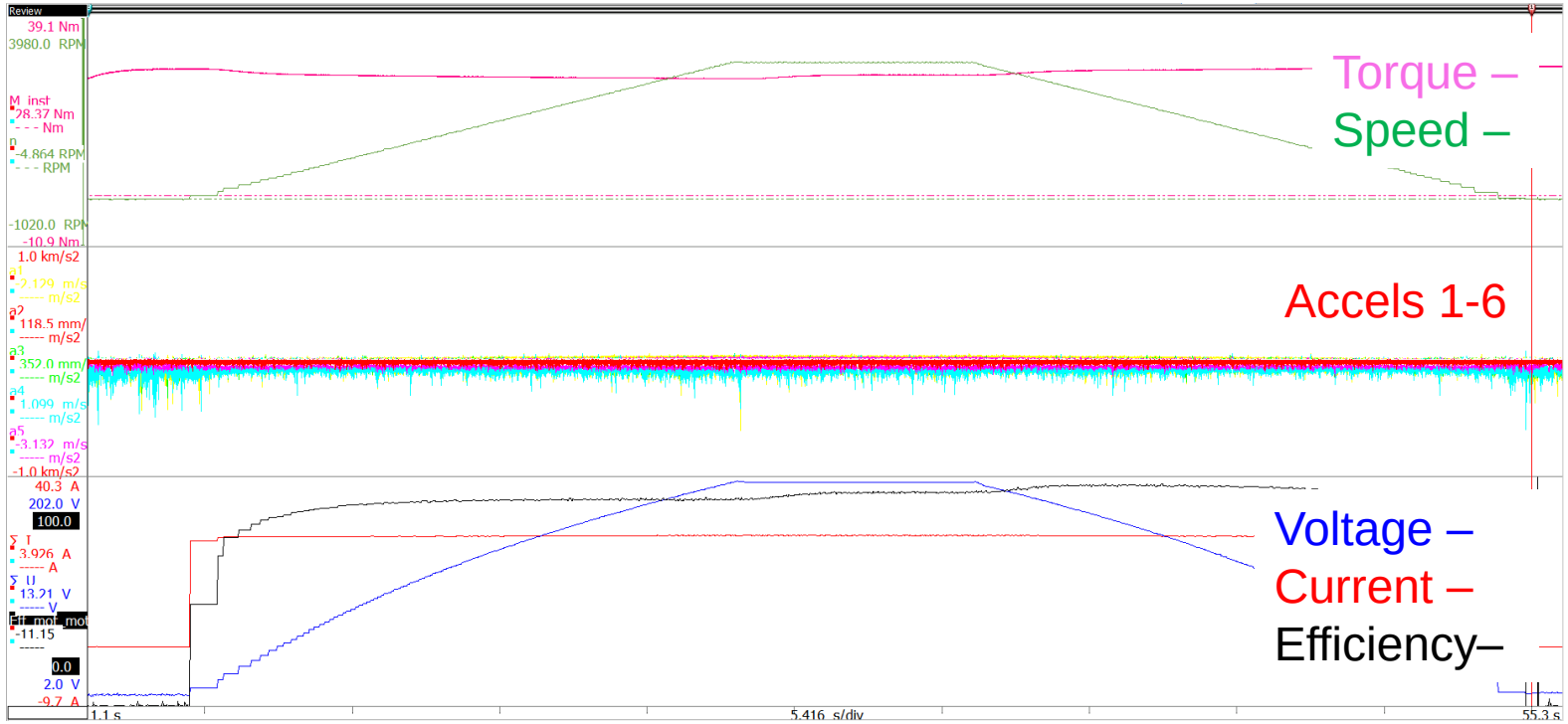


Efficiency and vibration heat maps for DUT

Ramps With Efficiency

Speed Ramp Testing

- A ramp test involves setting a fixed torque and ramping speed
- Record:
  - Accelerometers
  - Microphones
  - Torque & Speed
  - Voltage, Current, Efficiency
- Understand how speed and loading effects vibration
- Electrical allows us to also include control, efficiency, and state into these tests



Speed Ramp of DUT recording V, I, M, n, and accelerometers

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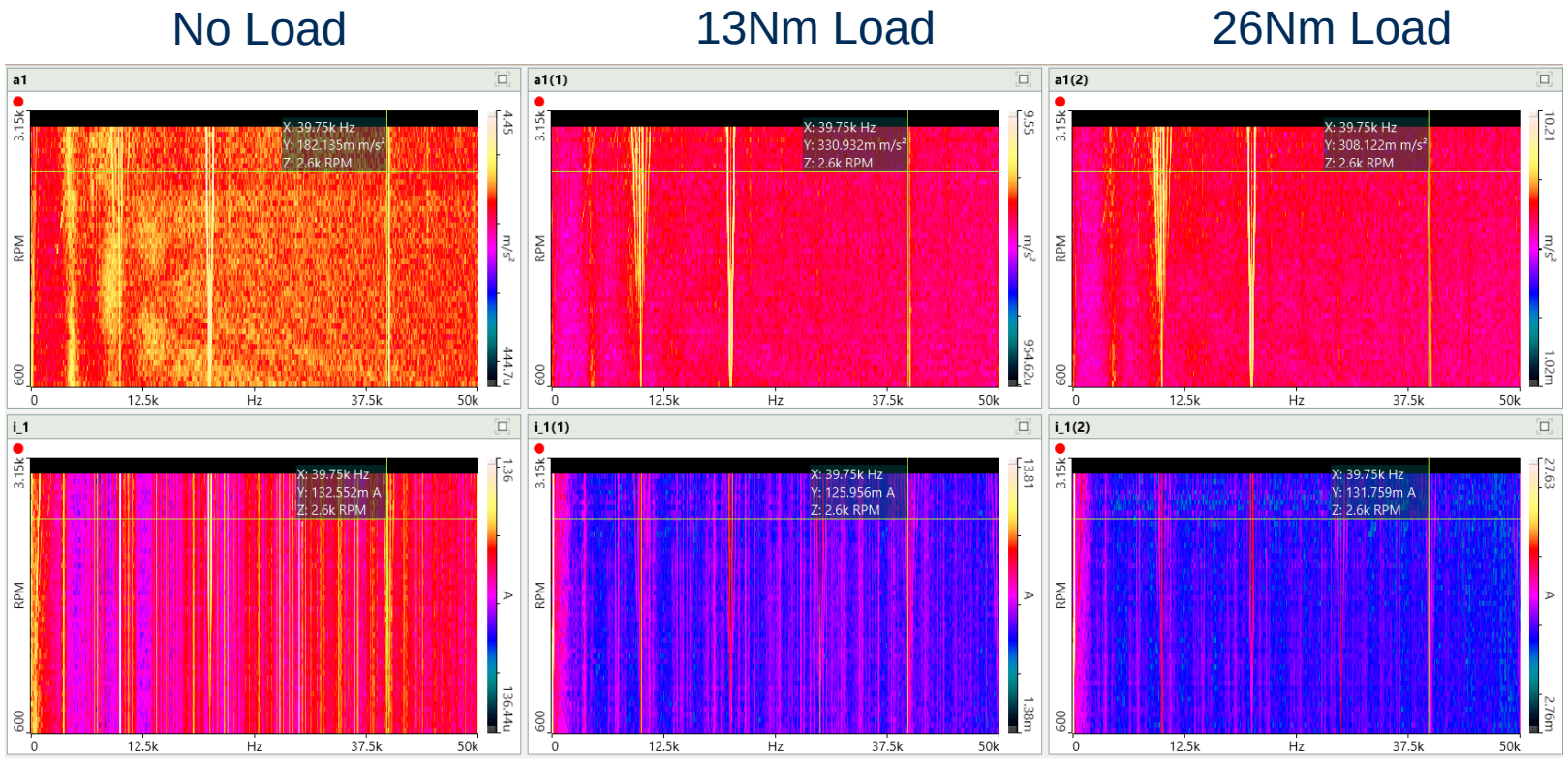
Frequency spectrum from Ramps Test

- A ramp test is often portrayed with a spectrogram showing:
  - X - Frequency (Hz)
  - Y – Speed (RPM)
  - Contour – Amplitude
- 3 ramps are plotted. 0, 13, 26 Nm from 0 to 3k RPM
- Acceleration and current are shown
- We can see fundamental, switching frequency, and field frequency shown in both spectra



Full spectrum plots of acceleration and current for 3 loading points during ramp tests from 0-3000RPM

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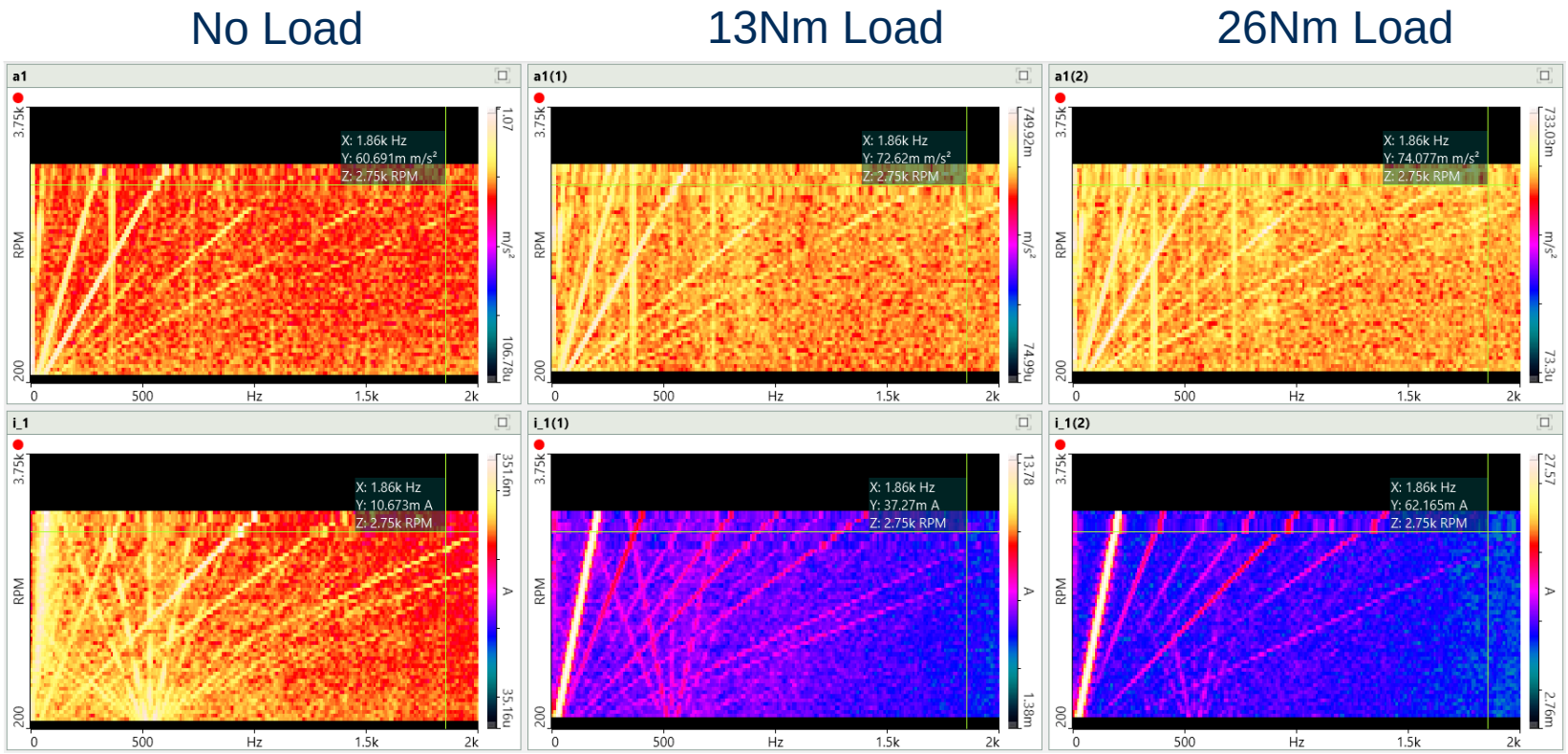
Fundamental Frequency Current and Vibration Spectrum

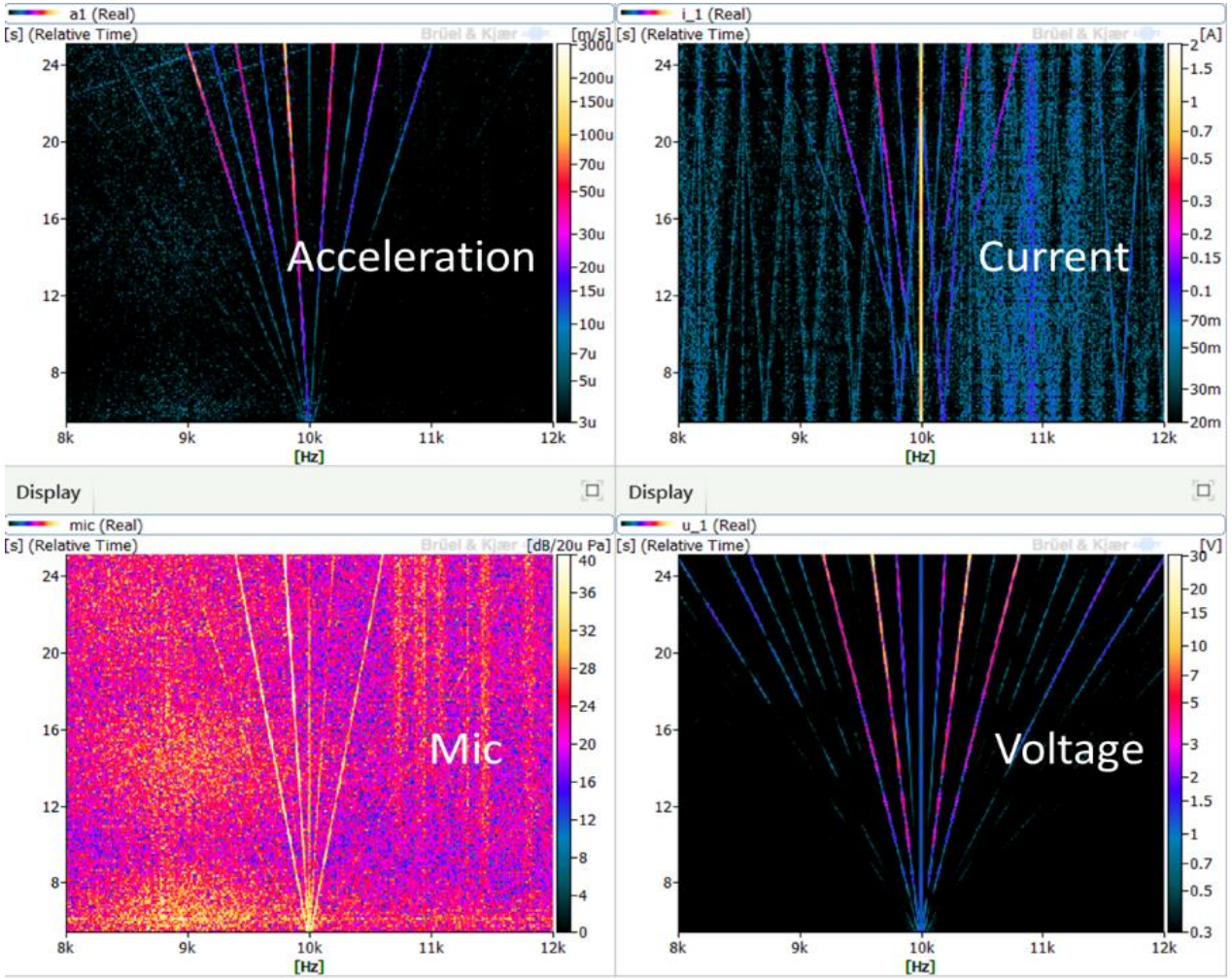
- Zoom on the fundamental spectra for vibration and current
- The fundamental of current has a majority of the amplitude
- Fan blades show the correlation between current and vibration
- Interesting fan around 500 in the current → Possibly causes vibration resonance



Fundamental spectrum plots of acceleration and current for 3 loading points during ramp tests from 0-3000RPM

Noise Analysis of the Machine

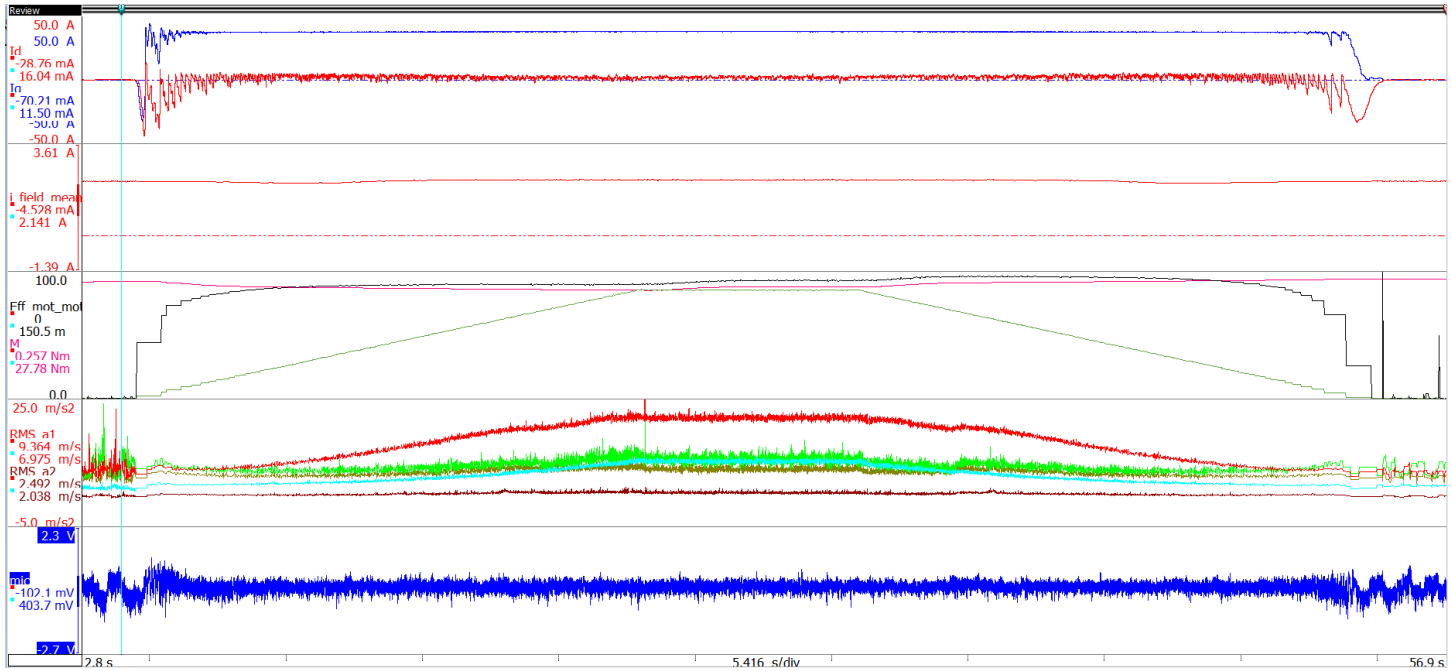
- Test took place in acoustically noisy environment
- Accel has superior signal to noise
- Some orders show
- Clear traces of switching noise
- For this environment, inferring noise level based on prior acceleration/mic correlation would be best



Spectrum plots of acceleration, microphone, and current for full loading ramp tests from 0-3000RPM

Electrical Analysis of Motors and Drives During Sweeps

- Representative of real-world situations to understand transient behavior
- Efficiency can be measured with a dynamic measurement technique
  - Cycle Detect
  - Available for live traces
  - Available for real time feedback to automation system
- Opportunity to understand how calibration influences:
  - Efficiency
  - Noise
  - Vibration



Ramp test showing state, efficiency, noise, vibration, and control variables during a ramp test.

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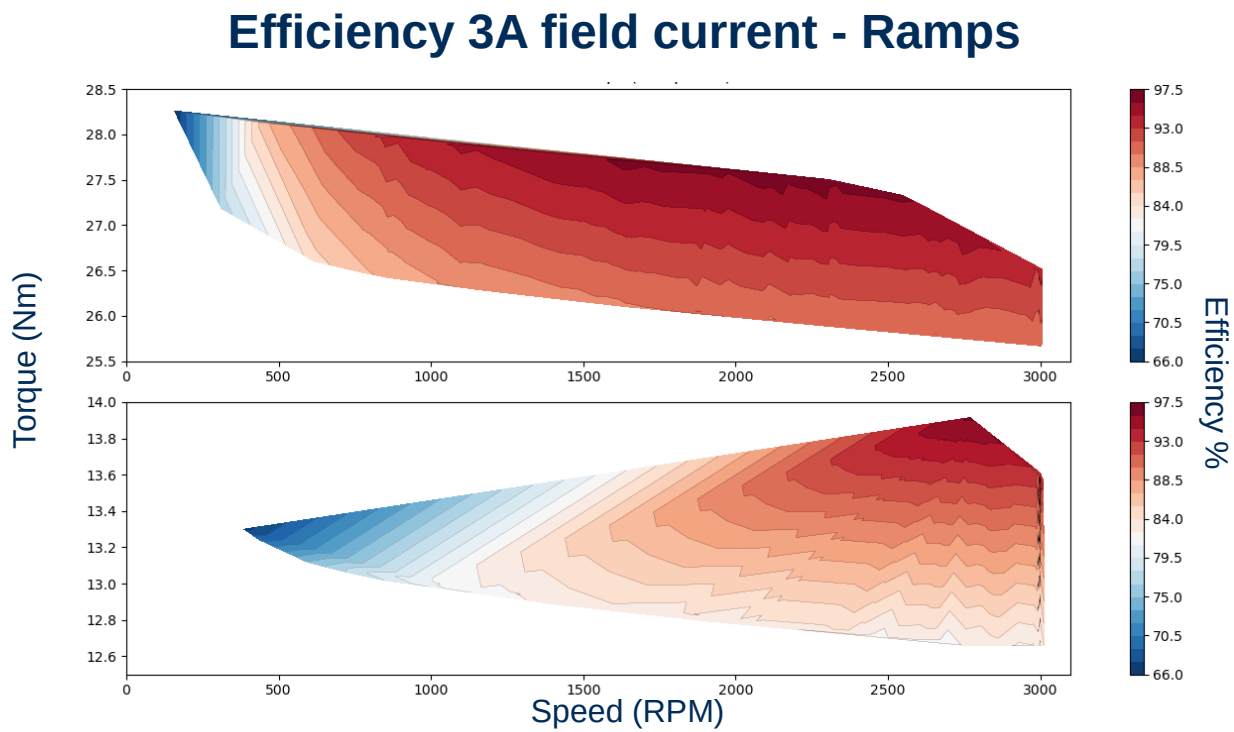
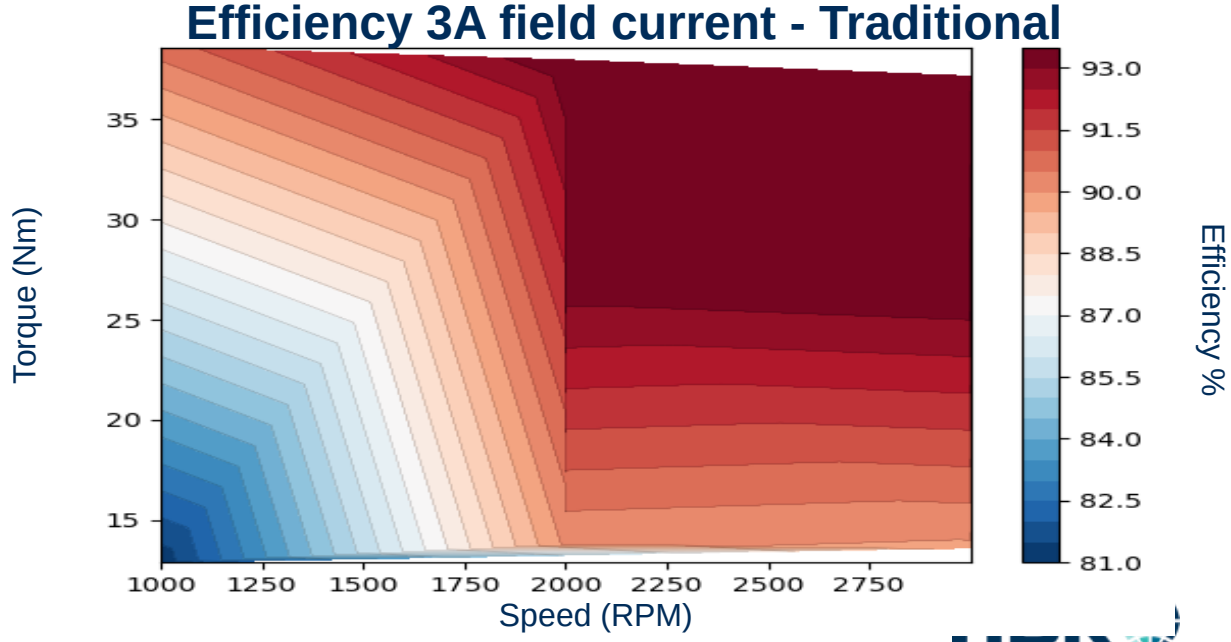
Efficiency from ramps

- Ramps efficiency can be used to plot efficiency
  - Requires dynamic power measurement
  - Requires high bandwidth torque
- Results can be used by NVH to gauge how their changes effect efficiency
- Close correlation to point by point map





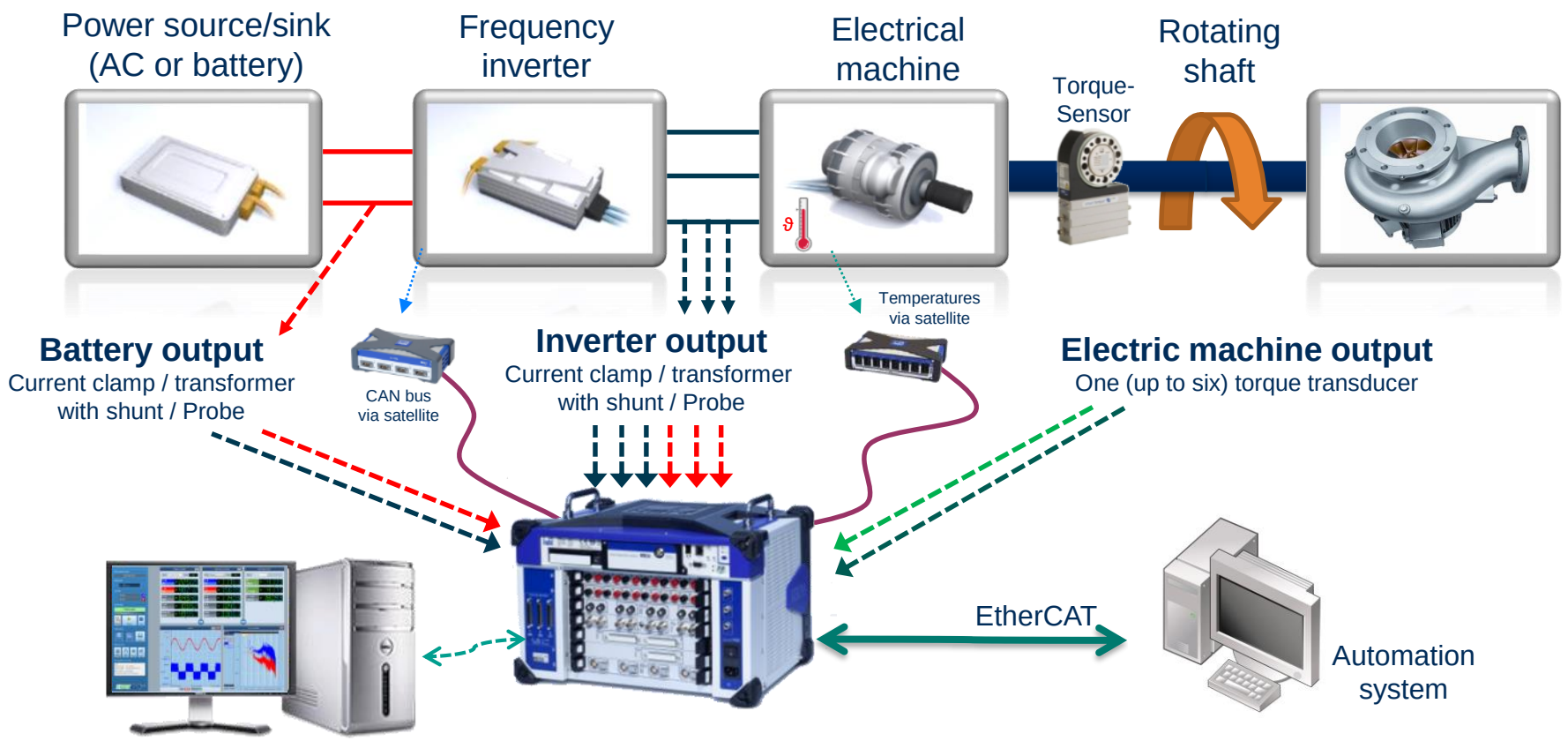
Efficiency heat maps for DUT

eDrive Solution

Simple Measurement Chain - Electric & Mechanical Measurements

Measurements taken with one system

- Voltages
- Currents
- Accelerometers
- Microphones
- Torque
- Speed
- Temperatures
- CAN
- Pressure
- Flow
- Force
- **Calculations for Power & Efficiency**



eDrive: The HBM components for advanced power analysis

- GEN DAQ configurable, expandable mainframes
  - Up to **51 channels for power measurements (102 U&I)**
  - Continuous streaming or **storage per set point in real time**
  - Support for up to **6 torque transducers** (12 as special)
- 6 channel input card (= 3 power channels)
  - Voltage up to +/- 1000 V, current via CT´s or clamps
  - Sample rate 2 MS/s @ 18 bit, typ. power accuracy 0.02%
  - Option: 5 kV_{rms} differential probe, 0.1% accurate
  - Plug-in artificial star adapter, cascadable
  - Burden resistors for CT usage
  - On board DSP with **user programmable math**
- High accuracy HBM torque transducer (with speed)
  - Accuracy 0.02%
- Options
  - EtherCAT interface for **real time data transfer** to automation
  - **Temperature** satellite, 1 kV isolated, 8 channels
  - **CAN** input
  - Various inputs for **strain, vibration, temp**.....
    …and also “scope cards” up to 250 MS/s

eDrive testing – Mission statement

Like other power analyzers, the HBM eDrive computes power values and efficiency and displays these in real time.

Unlike other power analyzers, the HBM eDrive can store a variety of signals & raw data - like a high end DAQ - for review, verification and advanced analysis such as efficiency mapping or dq0 transformation.

Thus it does not only give you "efficiency" ,
but it also helps you to improve the efficiency.

It also offers a complete solution acquiring more than 3 phases, complex setups, temperatures, CAN and vibration as well.

For system integration, it offers modern integration tools including real time result transfer and accelerated motor mapping capabilities to save test time.

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Questions?

Mitch Marks
Business Development at HBK - Hottinger, Brüel & Kjær

eDrive Information