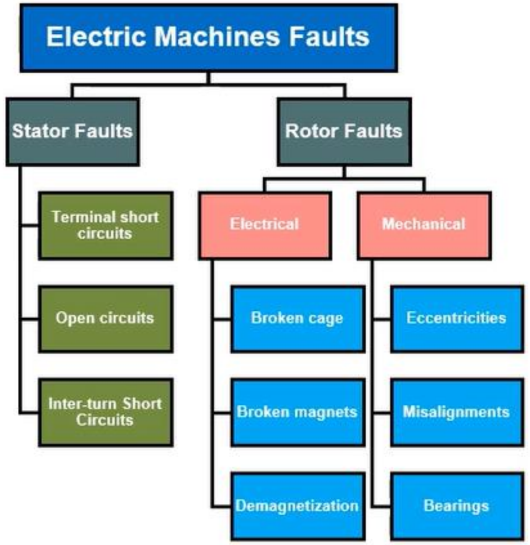
HBK Technology Days – Virtual Seminar Series

Tuesday, November 8, 2022



Understanding motor degradation and failure modes using electrical characteristics

Presented by Mr. Mitch Marks,
Electrification, HBK

Understanding motor degradation and failure modes using electrical characteristics

Abstract

Electric motors and powertrain present new challenges for durability testing and understanding the physics of failure. Traditional acceleration methods of running at an increased temperature are often not possible because the motor and inverter cannot survive them. Motors also introduce new failure modes like demagnetization, delamination, and turn to turn shorts amongst others. These failures will result in mechanical failure modes, but can be more easily monitored and understood through electrical measurements. This session will discuss the failure modes of electric motors, benefits of measuring electrical values for durability testing, and give real data from durability testing.

About the presenter, Mr. Mitch Marks, Electrification, HBK

Mitch has worked in electric motor developing and testing his entire career and specializes in test and measurement traction motors and drives. He has been with HBK since 2017 as a member of the electric power testing team. He has an undergraduate and a master’s degree in electrical engineering from the University of Wisconsin – Madison WEMPEC program.

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Understanding Motor Degradation and Failure Modes Using Electrical Characteristics

HBK TECH DAYS

Mitch Marks

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

Presenter

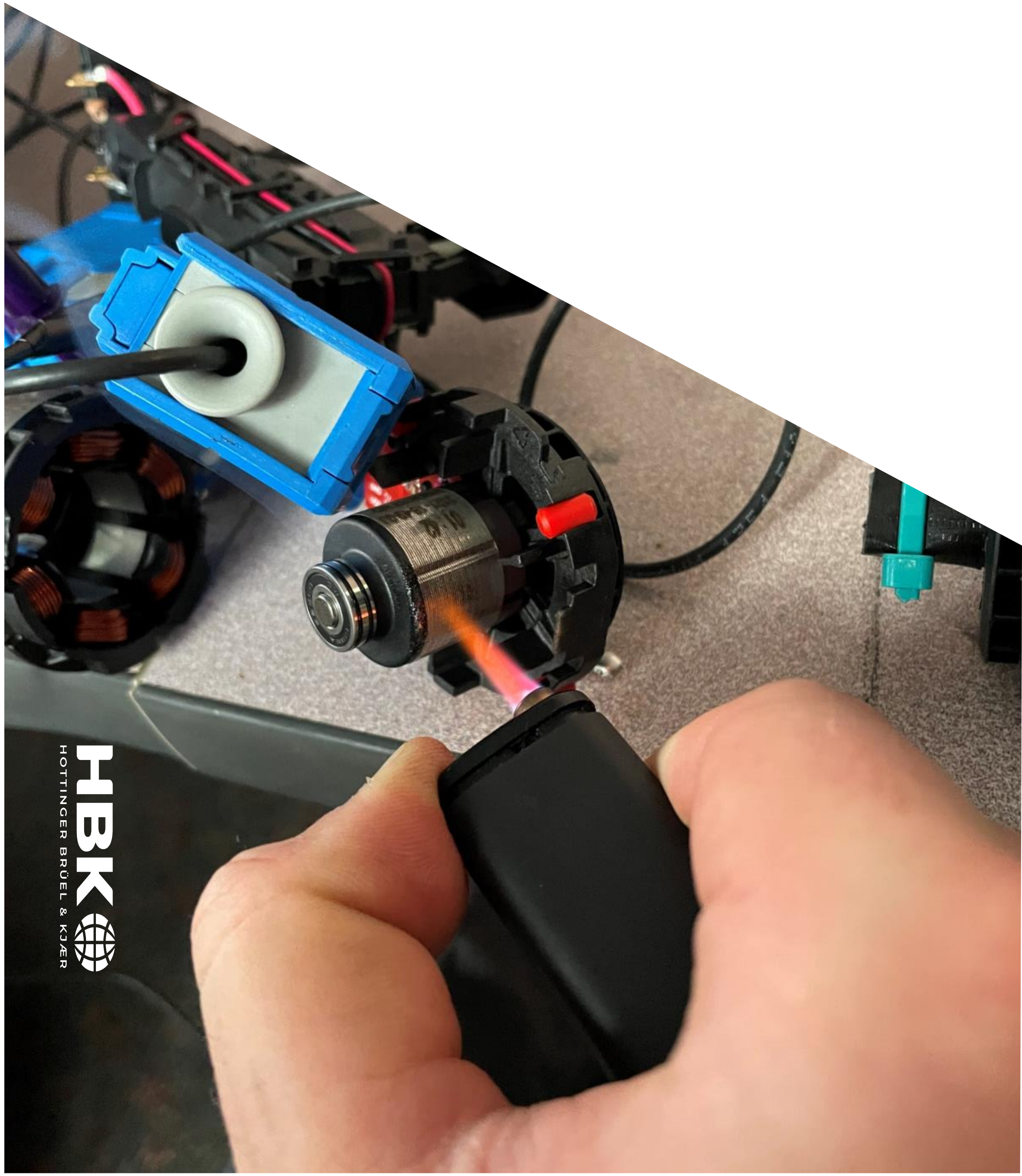
Mitch Marks

- **Business Development – Electrification**
- **NOT A DOCTOR 😂**
- BSEE, MSEE –University of Wisconsin – Madison WEMPEC
- Joined HBM in 2017
- Previous positions in motor manufacturing, controls, and testing
- E-Mail: Mitchell.Marks@hbkworld.com

Mitch Marks

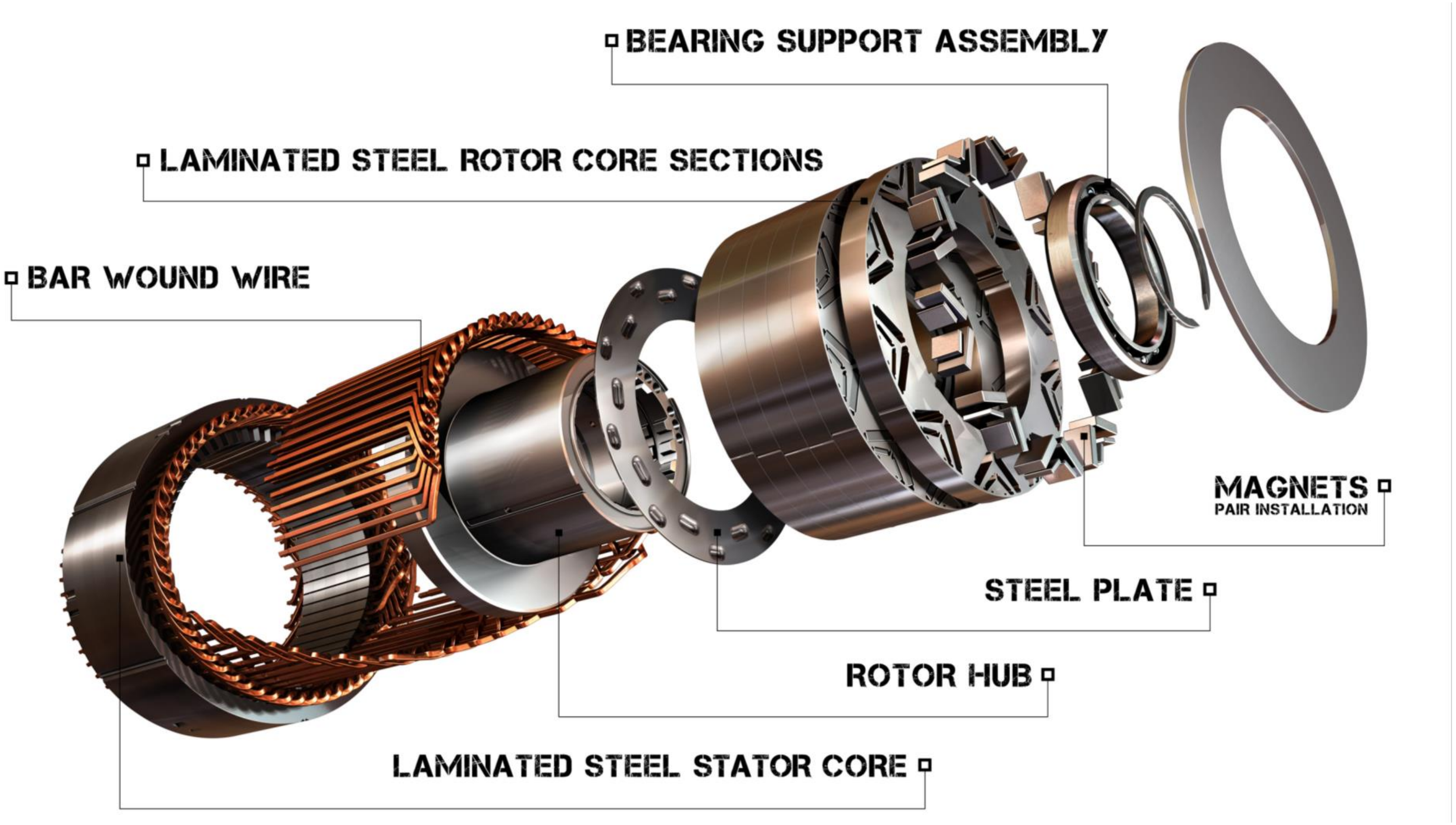
Agenda

1. Failure Modes for Electric Motors
2. Challenges in Measuring Failure Modes
3. Using Electrical Signals for Monitoring and Characterization
4. Example of Failure Measurements



Failure Modes in Electric Motors

Permanent Magnet Motor Construction



[1]

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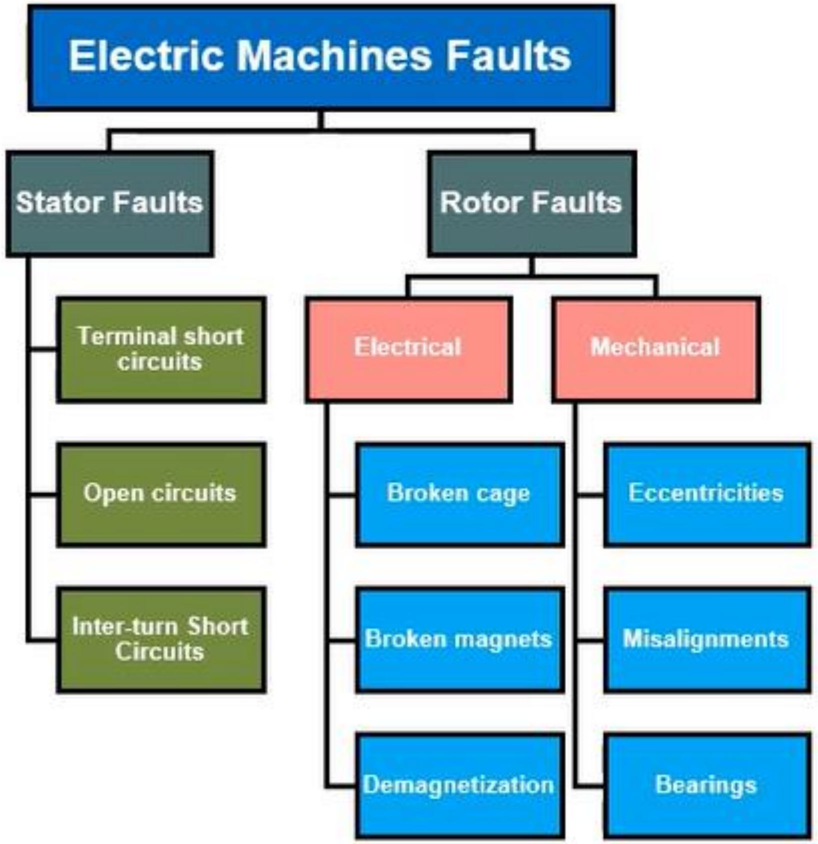
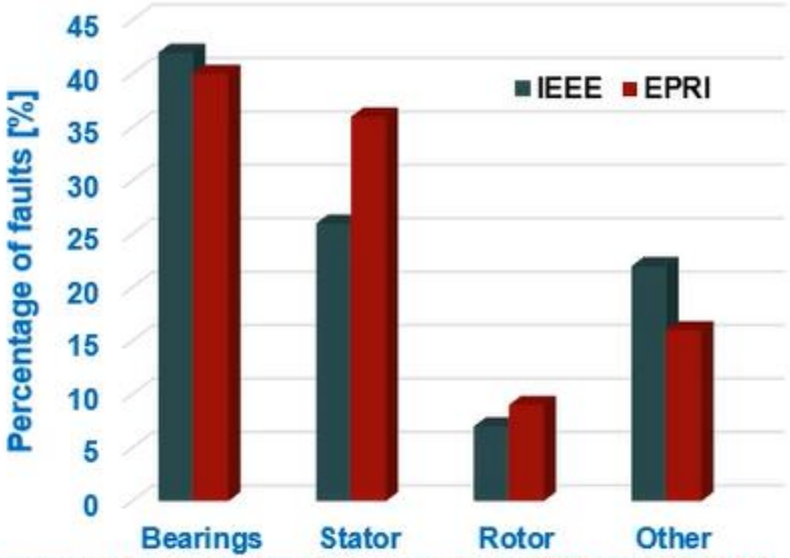
Faults in Electric Machines





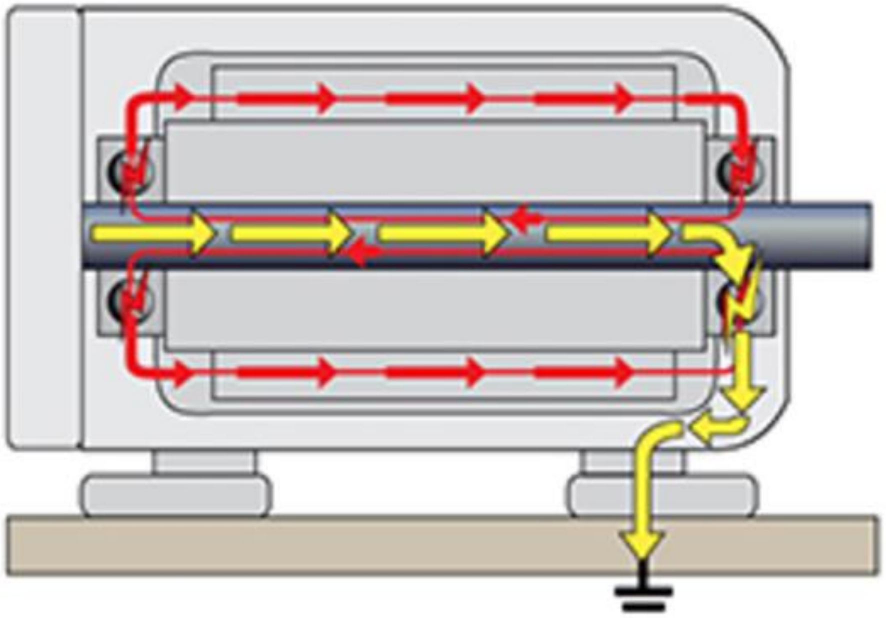
Survey on faults in electric motors from IEEE and EPRI [1]

- Bearing faults are the most common faults in electric machines.
- Stator faults are the second most common faults. However, stator faults can develop into a catastrophic fault very fast.
- It can take less than 2 seconds for an inter-turn short circuit to permanently damage a 15kW motor. [2]

[2]

Bearing Currents

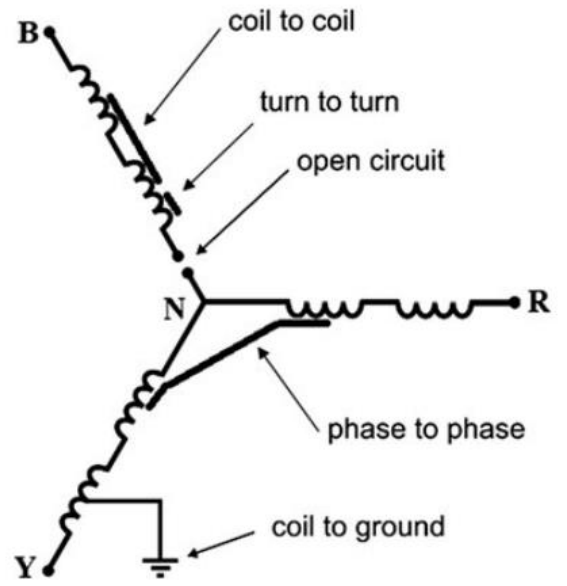
- Fault
  - Voltage on rotor discharging through bearing to stator
  - Currents through bearing
- Cause
  - Common mode currents
  - Grounding currents
  - Rotor eccentricity
- Effect
  - Race fluting
  - Fluid insulation breakdown
  - Bearing pitting
  - Bearing failure

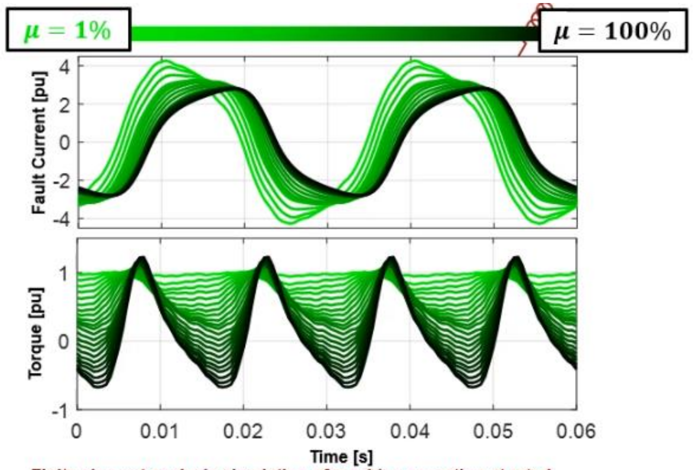


[3],[4]

Inter-Turn Shorts / Terminal Short Circuits

- Fault
  - Windings short together, or to ground
  - Breakdown of winding enamel
  - Short of an inverter switch
- Cause
  - Mechanical stress
  - Electrical stresses – Inverter Voltage Gradient
  - Thermal stresses
- Effect
  - Inefficiency
  - Demagnetization
  - Smoke & fire





Finite element analysis simulation of machine operating at rated conditions varying the number of shorted turns

[5],[6]

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De-magnetization

- Fault
  - Magnets lose strength
  - Magnet "shape" changes
  - Symmetrical / unsymmetrical
- Cause
  - Overheating - Curie temperature
    - 100-220C for NdFeB
  - Conflicting magnetic fields
  - Stator Faults
- Effect
  - Torque Ripple
  - Reduced power
  - Unbalanced line currents

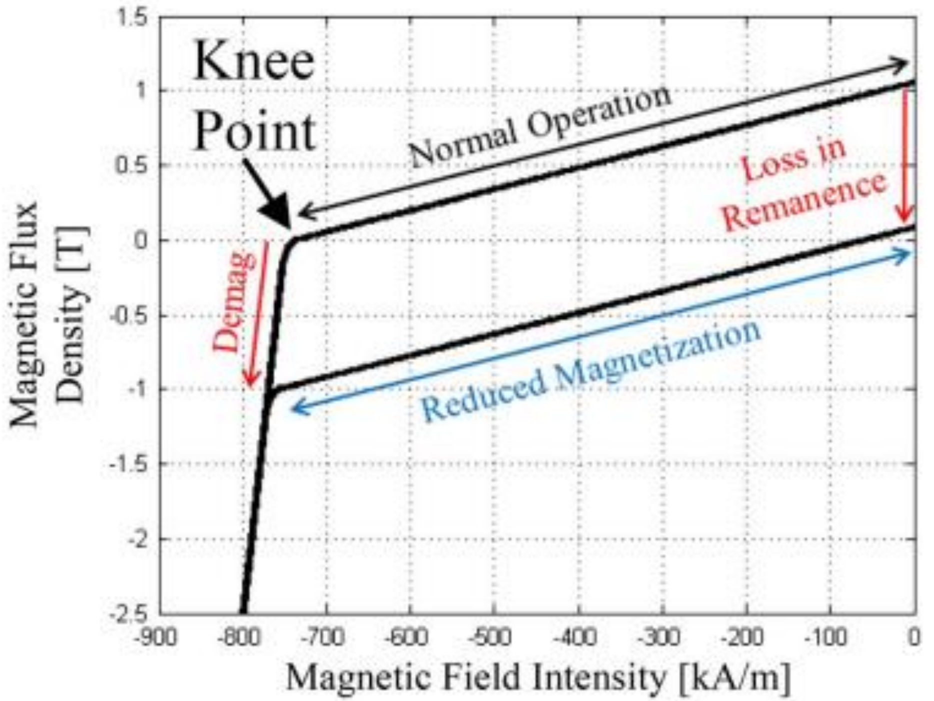


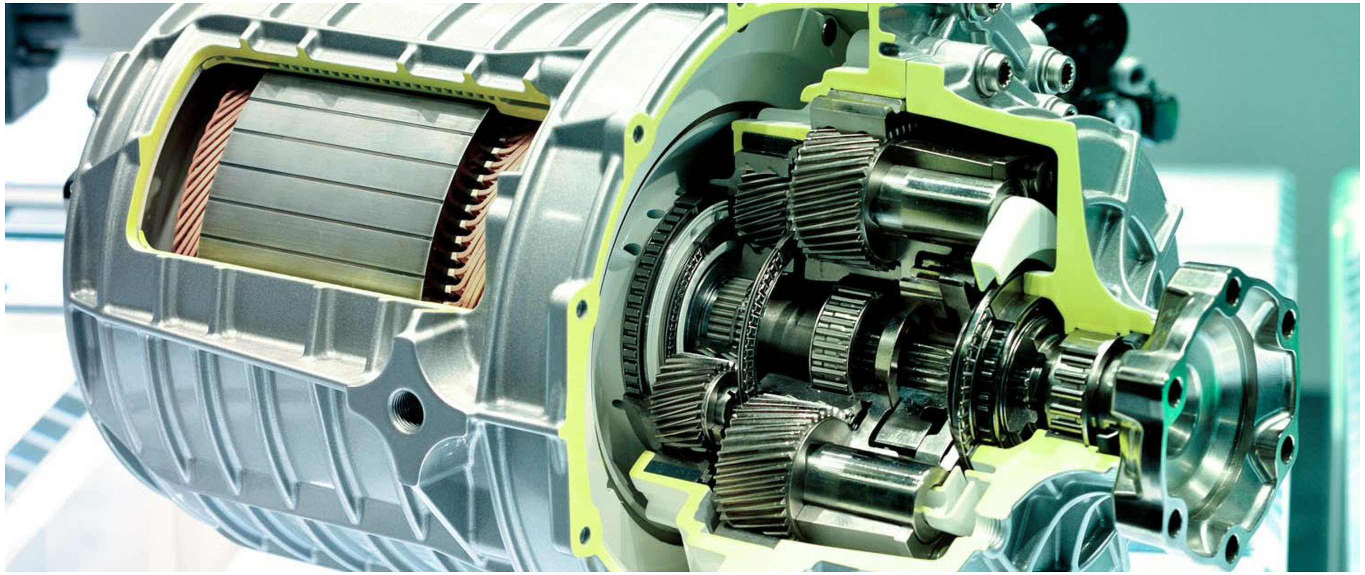
Fig. 5. B–H curve for Camry magnet material at 180 °C, showing an example of irreversible demagnetization.

[7]

Challenges in Durability Testing for Electric Motors

Challenges in Durability Testing for Motors

- Hard to accelerate
  - High temperatures cause demagnetization
  - High temps drastically alter performance
- Every motor’s failure modes are unique
  - Different magnet patterns
  - Different winding patterns
- Difficult to measure rotor temperature
- Electromechanical
  - Electrical influences mechanical
  - Mechanical influences electrical
- Looking for a high speed event on long time scales
- Long test durations - data



Using Electric Signals for Electric Motor Durability

Measuring Bearing Currents

- Measure common mode current
  - Current measurement around all 3 motor leads
- Bearing Currents i_b
  - Insulate bearings
  - Run conductor from stator to bearing
  - Measure current
- Measure V_b
  - Voltage between bearing and stator
  - Brushes/slip rings
- Measure Temperature
- Increased frequency or amplitude of voltages/currents will indicate degradation

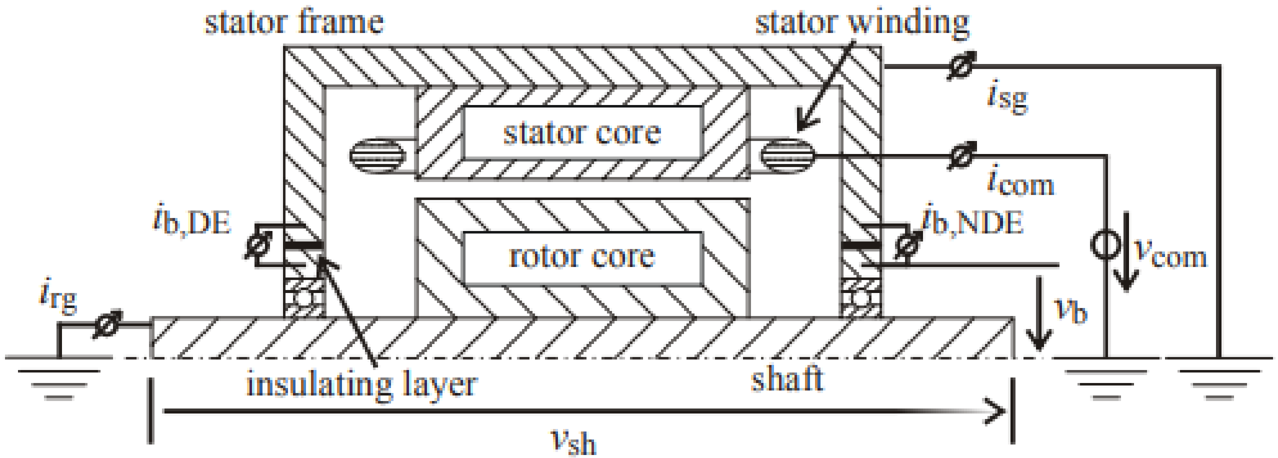


Fig. 6. Sketch of selected measured electrical quantities

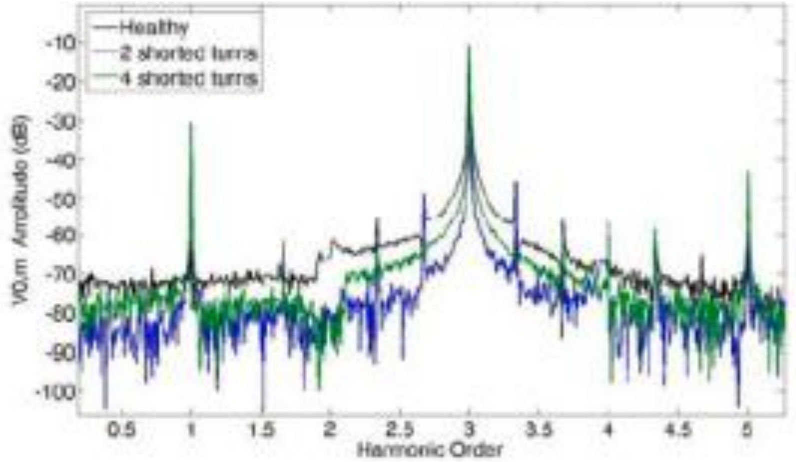
[8]

Measuring Inter-Turn Shorts

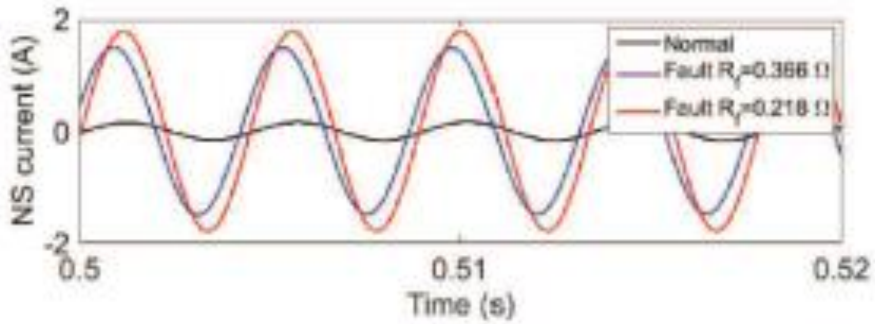
- Current Disturbances
  - Zero sequence voltage/current
  - Phase imbalance

- Increases in harmonic amplitude
  - Zero sequence voltage
  - Phase currents

- Other Measurements (on and offline)
  - Data driven
  - High- freq injection
  - Model-based
  - Vibration analysis



Zero Sequence Voltage spectrum for 0, 2, and 4 turns at 5500 RPM



Negative sequency components for motor operating at fixed voltage and torque

[9],[10]

Measuring De-Magnetization

- Monitoring de-mag causes
  - (-)D axis current
  - Flux Linkage
  - Stator Temperature

- Monitoring de-mag effects
  - Unbalanced/increased line currents
  - Torque ripple
  - Increased losses
  - Reduced average torque
  - Harmonics in back EMF
  - Reduced back EMF / rotor flux

TABLE II: SUMMARY OF POST-DEMAGNETIZATION PERFORMANCES FOR THE THREE BASELINE PM MACHINES AT RATED CONDITION

Machine Type	48s/8p DW-IPM			12s/10p FSCW-IPM			12s/10p FSCW-SPM		
Condition	**No Demag**	**Demag (SSC)**	**Demag (ASC)**	**No Demag**	**Demag (SSC)**	**Demag (ASC)**	**No Demag**	**Demag (SSC)**	**Demag (ASC)**
Demag Rate (%)	-	98.1	97.1	-	97.9	97.4	-	79.9	77.4
I_{rms} (A)	100	108.9 (+8.9%)	105.6 (+5.6%)	100	127.3 (+27.3%)	115.9 (+15.9%)	100	129.4 (+29.4%)	120.2 (+20.2%)
Copper Loss (W)	494.7	569.4 (+15.1%)	535.1 (+8.2%)	299.9	471.2 (+57.1%)	385.1 (+28.4%)	384.2	662.5 (+72.5%)	563.4 (+46.7%)
Stator Core Loss (W)	468.3	506.6 (+8.2%)	491.6 (+5%)	509.1	569.9 (+11.9%)	513.6 (+0.9%)	402.6	393.1 (-2.4%)	392.3 (-2.6%)
Rotor Core Loss (W)	32.6	34.8 (+6.8%)	33.7 (+3.4%)	107.5	158.3 (+47.2%)	135.2 (+25.8%)	3.6	7.3 (+102%)	6.1 (+69.3%)
Magnet Loss (W)	8.9	17 (+91.8%)	11.7 (+31.8%)	106.4	189.6 (+78.1%)	149.1 (+40%)	303.9	611.2 (+101%)	509.9 (+67.8%)
T_{avg} (Nm)	101.9	102.8	102.4	102.6	102.7	102.6	101.9	101.7	102
T_{ripple} (%)	16.9	15.1 (-10.6%)	14.7 (-13.3%)	13.2	28.7 (+117%)	22.5 (+70.5%)	4.8	11.4 (+140%)	8.6 (+81.7%)
Efficiency (%)	97.6	97.3 (-0.3%)	97.4 (-0.2%)	97.6	96.7 (-0.9%)	97.1 (-0.4%)	97.4	96 (-1.4%)	96.5 (-0.9%)

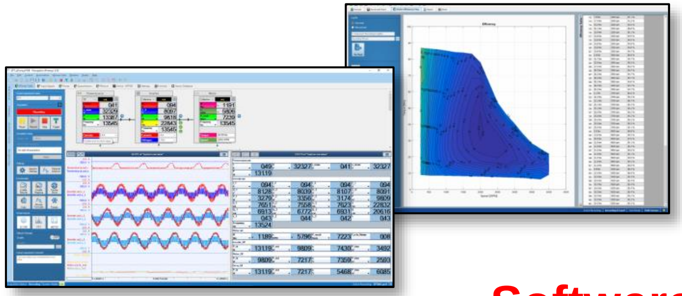
[11]

HBK Solutions for Motor Durability

eDrive Value

- Continuous collection of electro-mechanical signals
- Lowest measurement uncertainty
- Live view of calculated vales
- Data Reduction & Triggering
- Local Support & Training

Acquisition

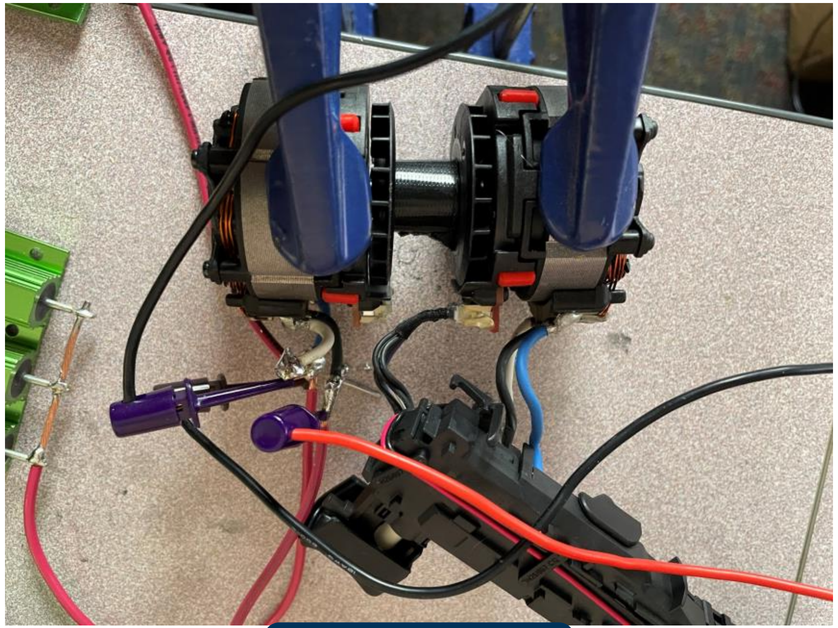


Software

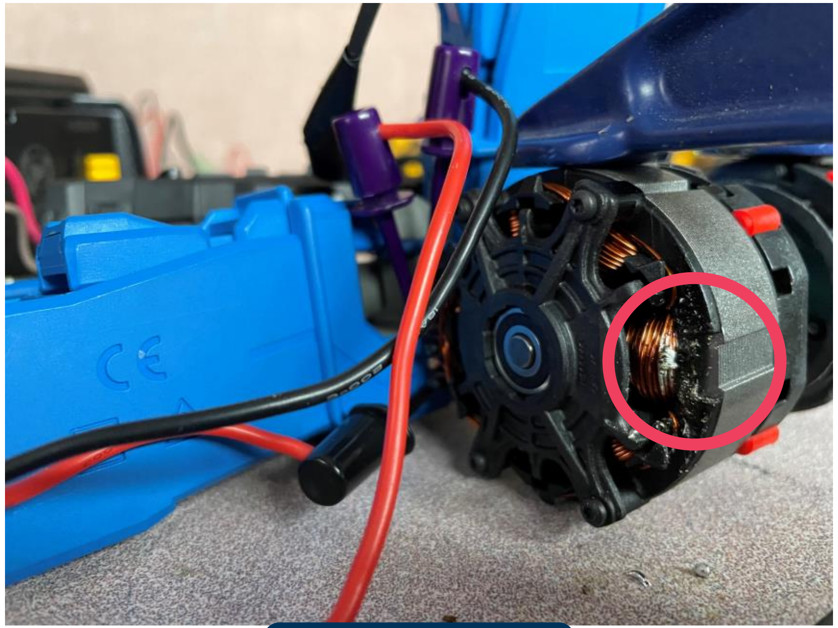
Sensors

Example

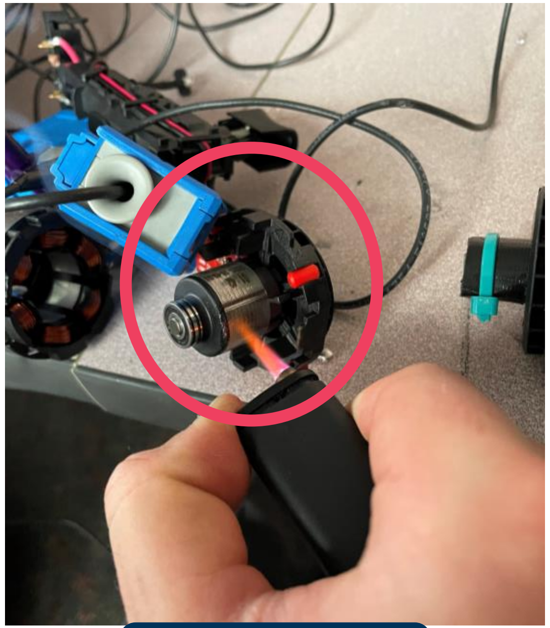
Induced Faults in Small Motors



Dyno



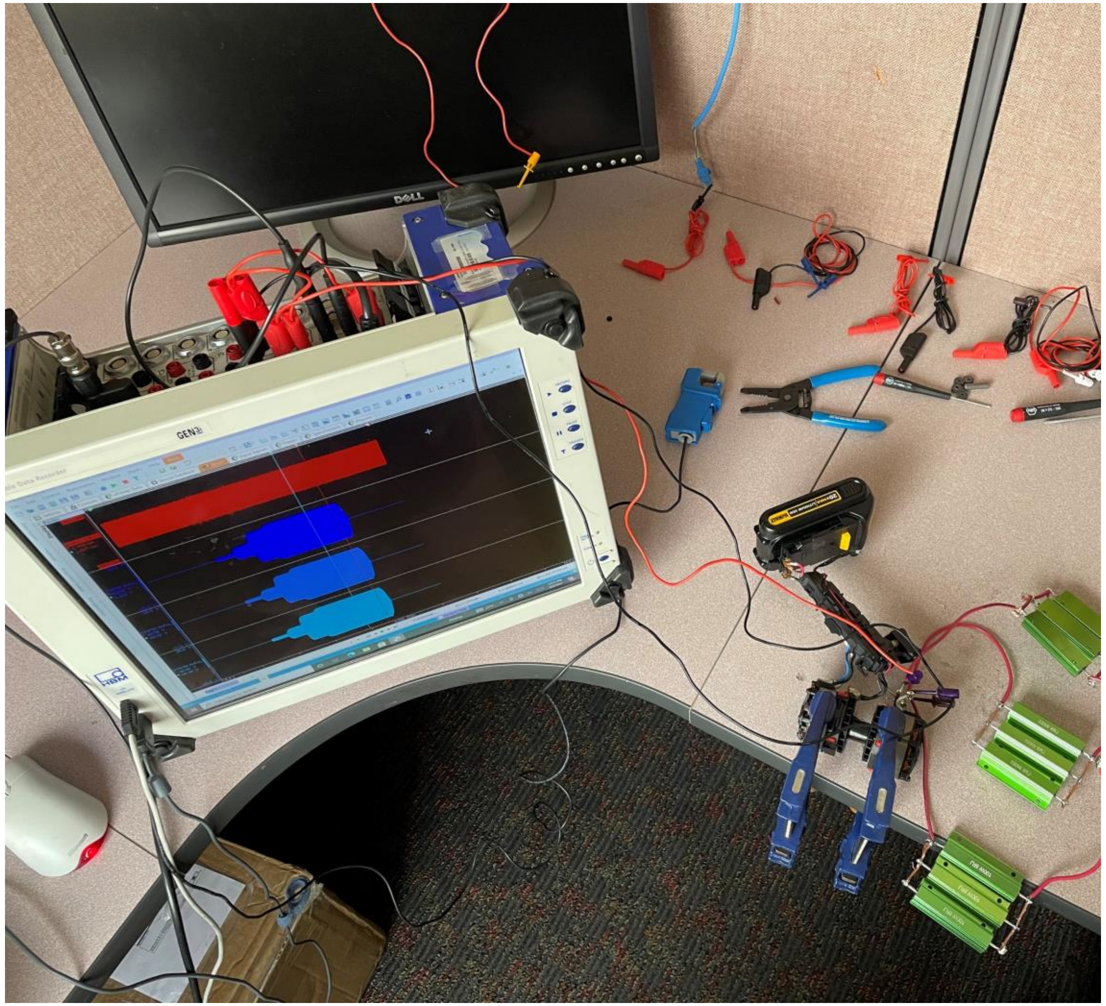
Short Circuit



Demag

Test Procedure

- Characterize healthy state
- Characterize short circuit
- Characterize Demag



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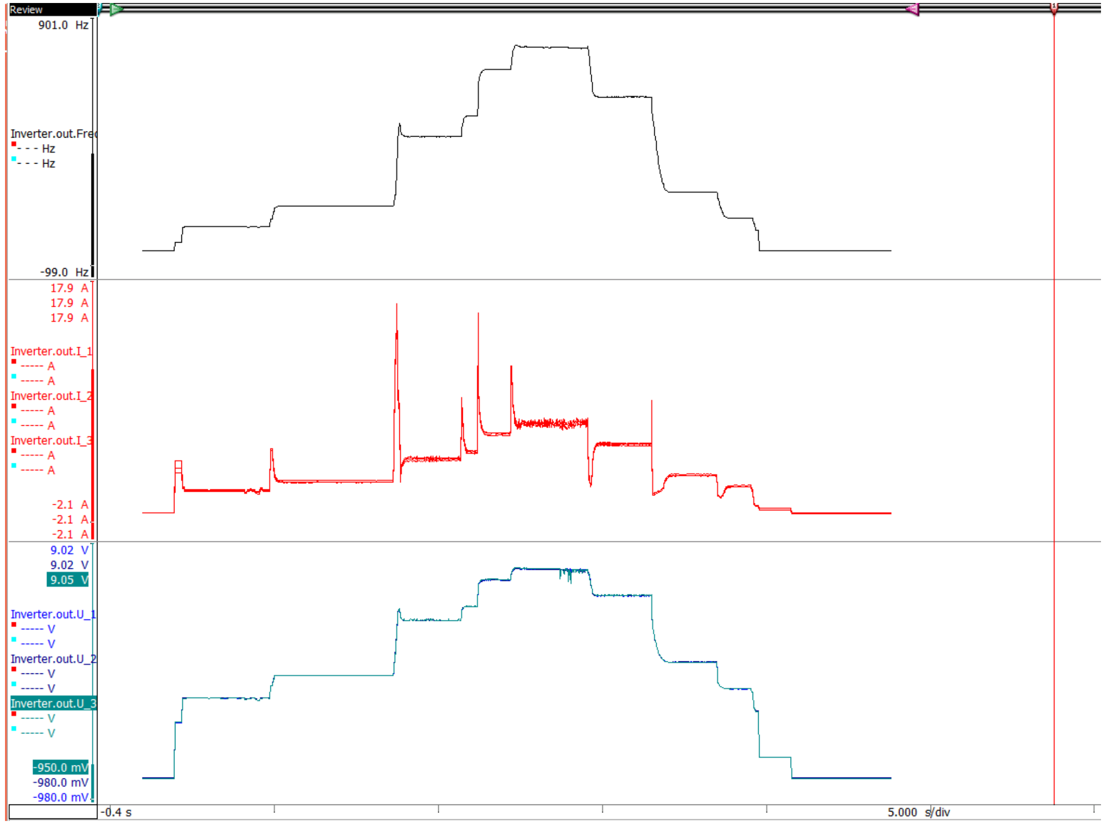
Test Data Example

- Measure & Record
  - 3 phase voltage
  - 3 phase current
- Calculate
  - RMS
  - Power & reactive power
  - THD
  - Zero sequence voltage



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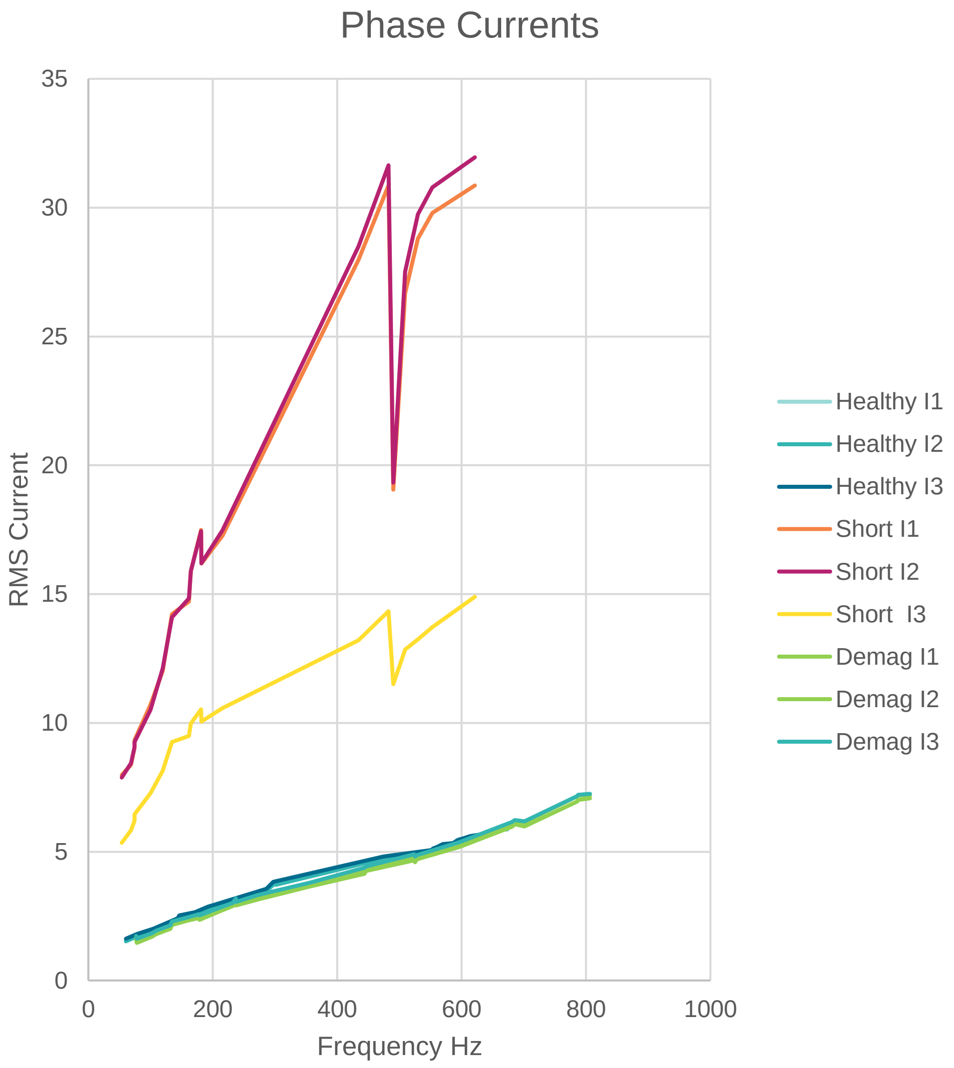
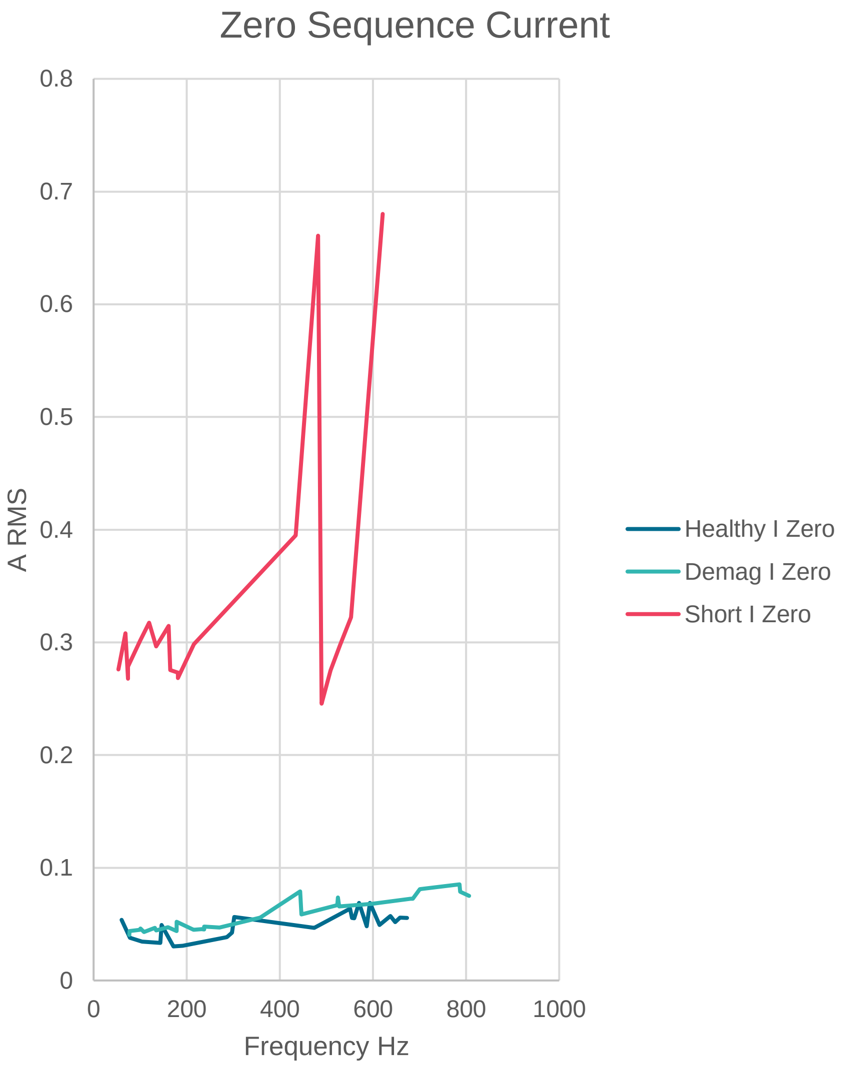
Short Circuit

- Increase in
  - Voltage
  - Current
  - Input power
  - Zero sequence

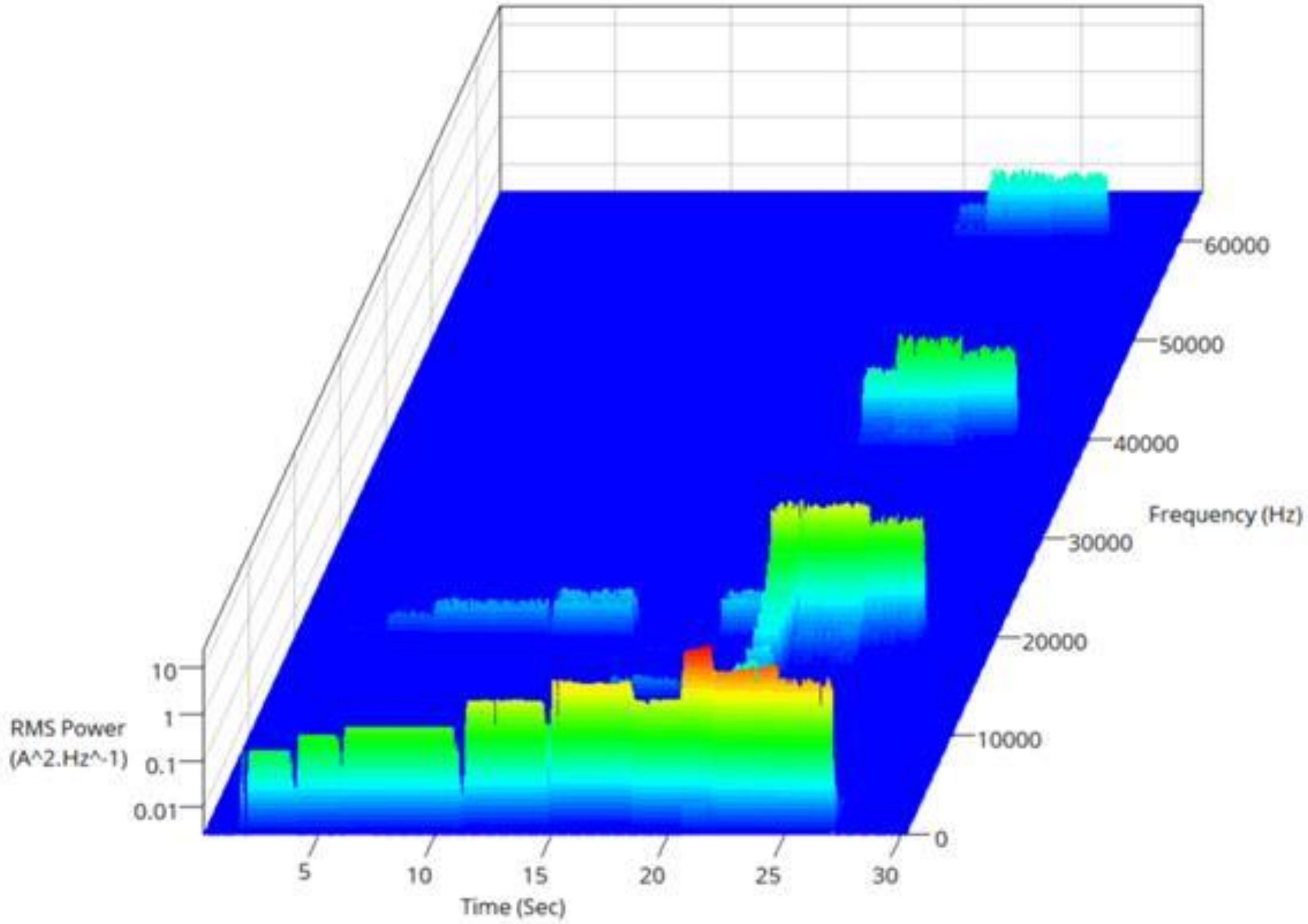
- Crazy power factor





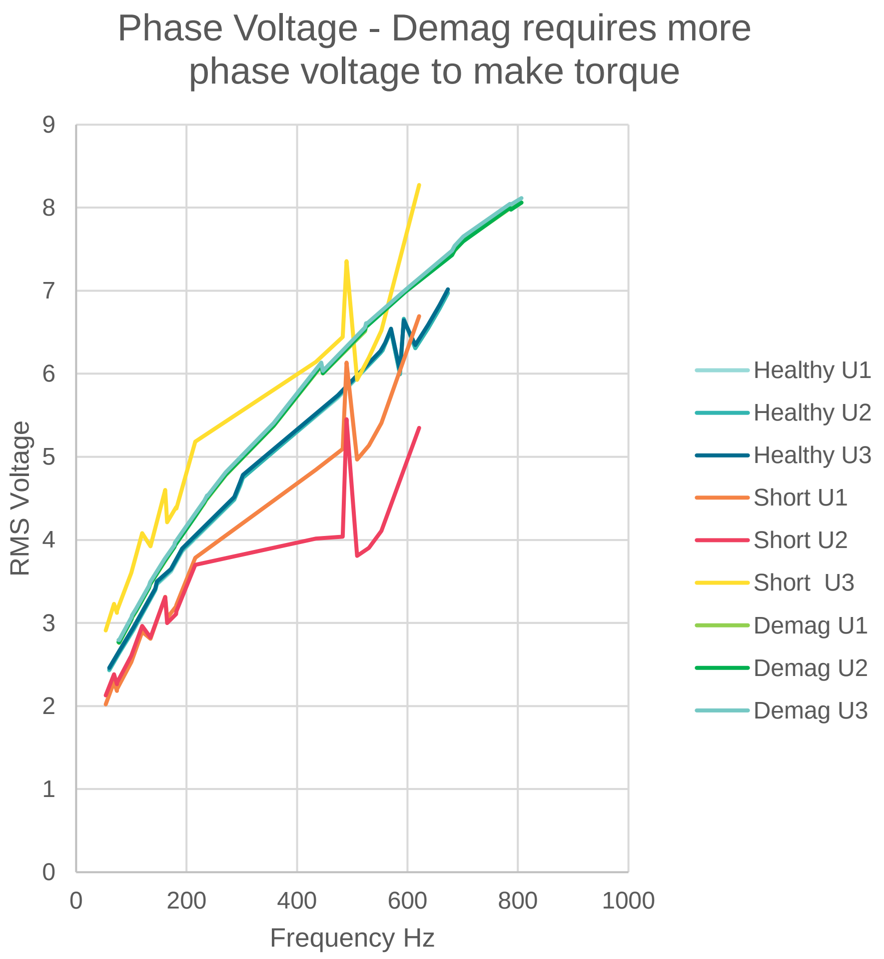
Short Circuit Test

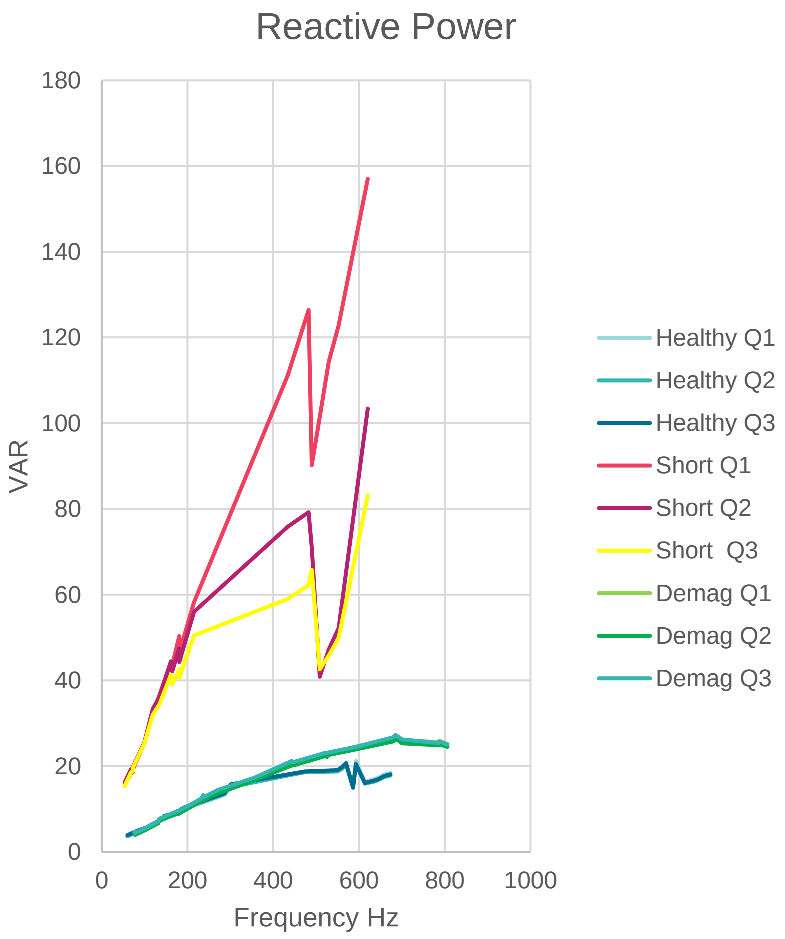
- Harmonics have a strong presence after the fault
- There are many ways to analyze data
- Can be used to predict failures



Demag

- Increase in
  - Voltage
  - Current
  - Input power
  - Zero sequence





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How Motor Durability Ties into Production

Can this tie into Production?
→ Get ready for DR. Holger

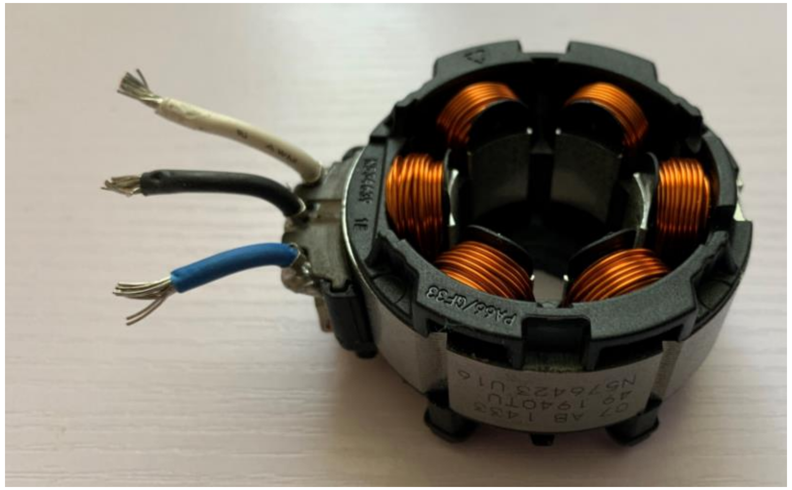
Motor Construction

Stator

- Laminations pressed together
- Wound with N turns
- Solder connections
- Sensors inserted

Rotor

- Laminations pressed together
- Sensors inserted
- Permanent magnets pressed into rotor
  - Pre magnetized or
  - Need to be magnetized



Magnet Failure **Sensor Function** **Incorrect Winding**

Sensor Mis-Alignment **Incorrect Wiring Harness**

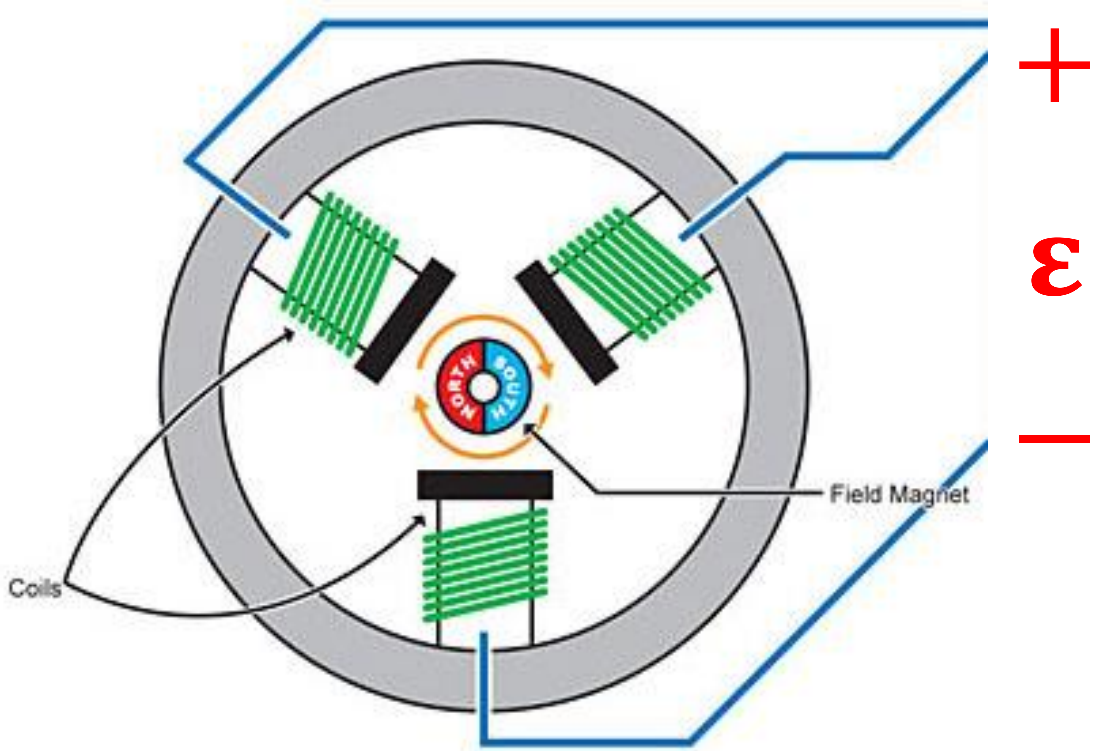
Rotational Back EMF Test

Definition of Back EMF (ε) & Back EMF Constant (Ke)

- $\varepsilon = -N\frac{d\Phi}{dt}$
  - N – number of turns of wire
  - Φ – magnetic flux

- $K_e = \frac{-N\frac{d\Phi}{dt}}{\omega_{no-load}} = \frac{V_{peak}}{\omega_{no-load}}$
  - V - peak voltage
  - ω - no load RPM

- **If a magnet is moved by a coil it will create a given voltage proportional to speed**



Pass with Lower Speed and Amplitude

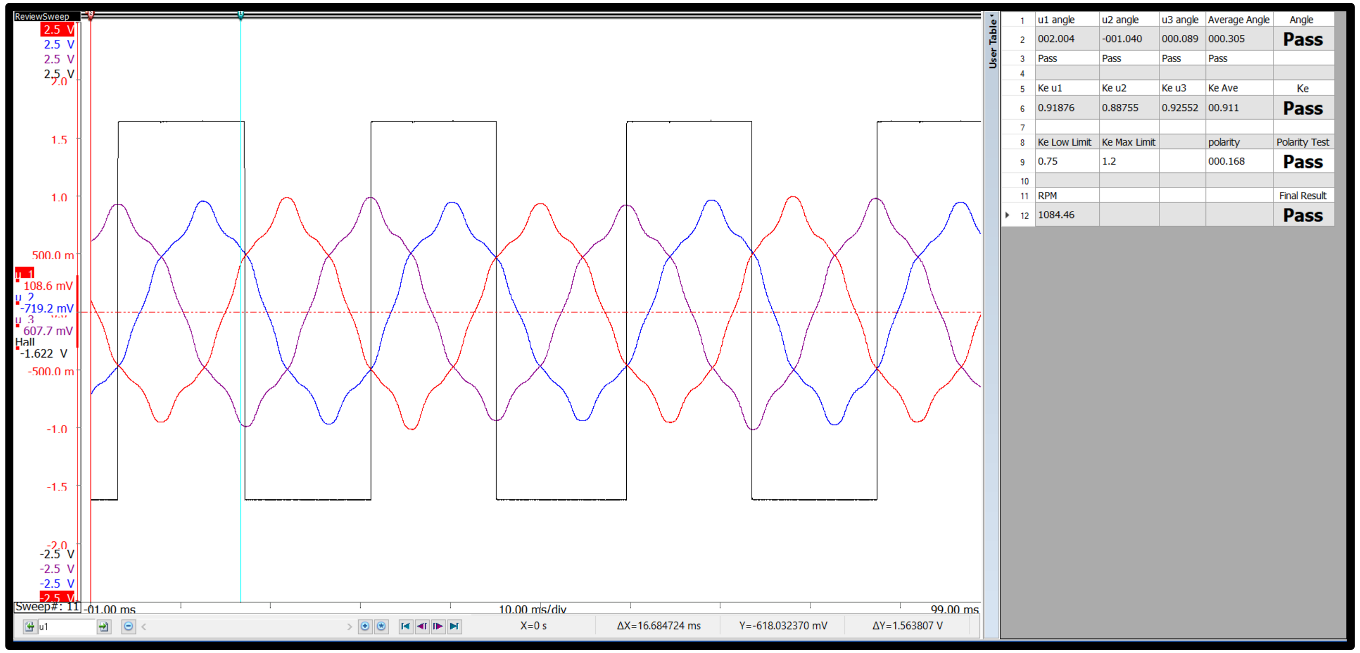
U1 –
U2 –
U3 –
Position –

- Voltage shape can indicate failure modes

- Monitor for
  - Amplitude
  - Harmonics
  - Averages

- **Same things we are watching for in durability testing**

- **Magnetization issues can also be seen in Torque**



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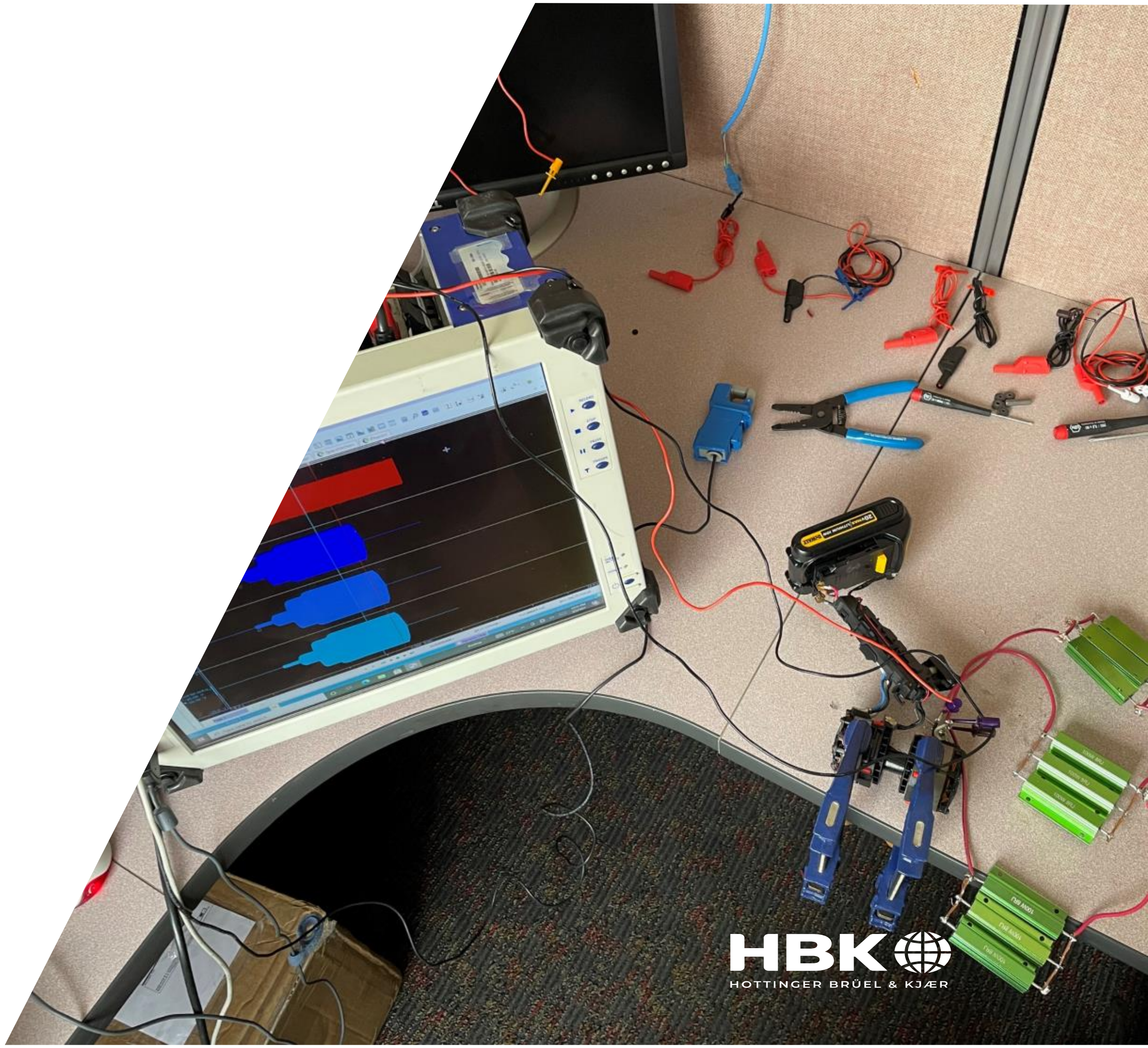
Conclusion

- Motors have electrical and magnetic failure modes and degradation
- Motor durability can be characterized with electric measurements
- HBK offers measurement tools and software for durability and fault analysis



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Thank You

Questions?

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Mitch Marks

Business Development at HBK - Hottinger, Brüel & Kjær

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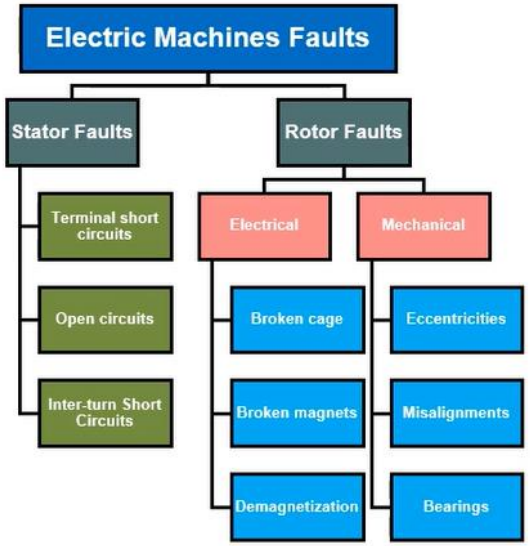

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