Impedance Measurements of Motor Drives and Supply in SPEED Testbed

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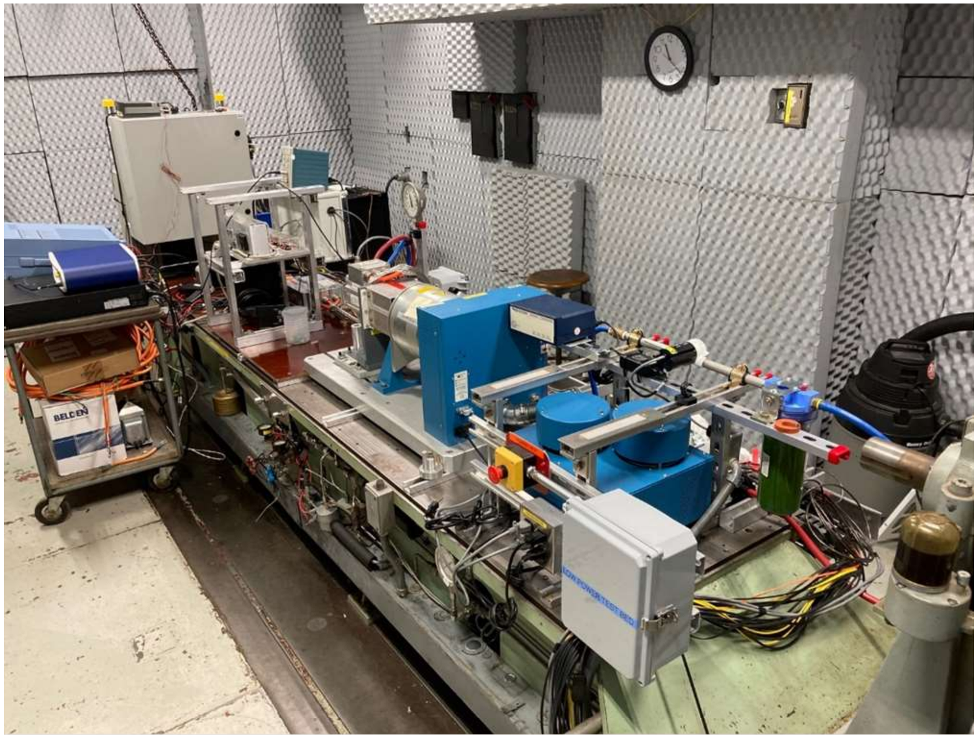
Presentation Overview

1. SPEED testbed overview
2. Impedance measurements
    1. Approach
    2. Test configuration
3. Load (machine/drive) impedance measurements
    1. Impact of load power
    2. Impact of drive controller tuning
    3. Impact of field weakening
4. Source (DC supply) measurement results
    1. Stability Analysis
    2. Bus current spectra
5. Conclusions and Future Work

SPEED Testbed

- DC supply
- Motor drive
- Electric machine (PMSM)
- Dynamometer
- Controllers
- Cooling system

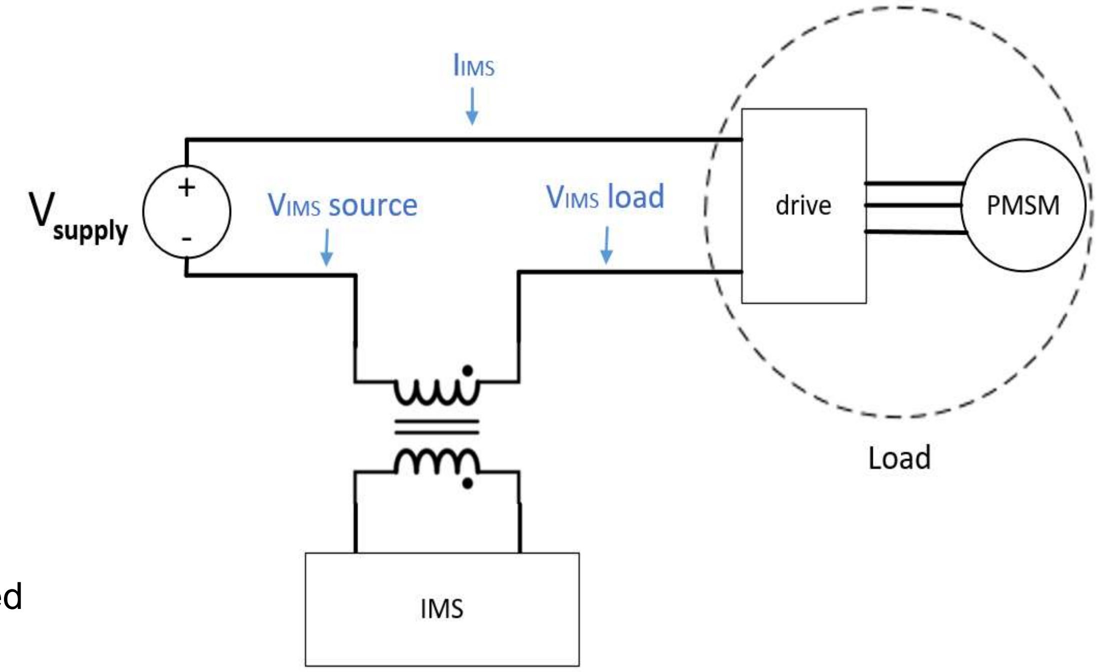
Component	Rating
Motor Rated Output power	14 kW
Inverter Peak output power	100 kVA
Dyno Power Rating	7 kW (5 minutes) 6 kW (continuous)



Impedance Measurement Approach

Components
- DC Supply: source
- Load: drive and PMSM
- IMS

Impedance Measurement System (IMS)
- Low level sinusoidal signal
- Power amplifier
- Transformer to inject signals
- Voltage and current measurements
- Load and source impedances calculated



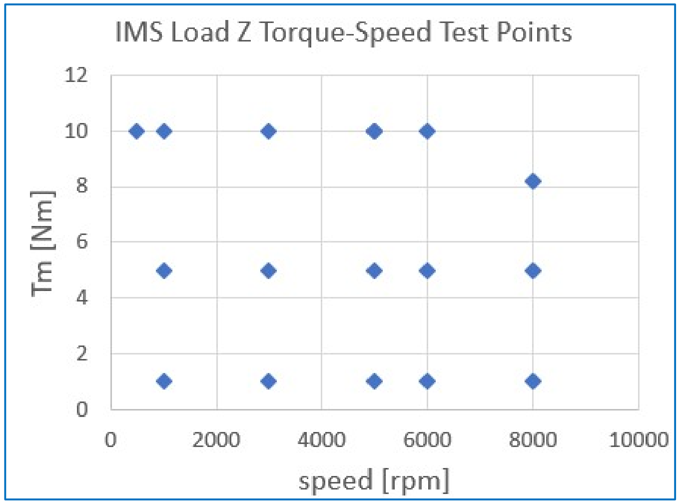
Impedance Measurement Configuration

Safe facility operation

- Dyno the pacing element
- Test points (ω, T) beneath dyno max
- Corner avoided

Safe IMS operation

- Frequency limits (30 Hz-100 kHz)
- Transformer temperature monitoring
- defining injected signal level:
  - Z not known in advance
  - Concern large variation with load impedance
  - Conservative experimental approach to guide selection
  - Approach warranted

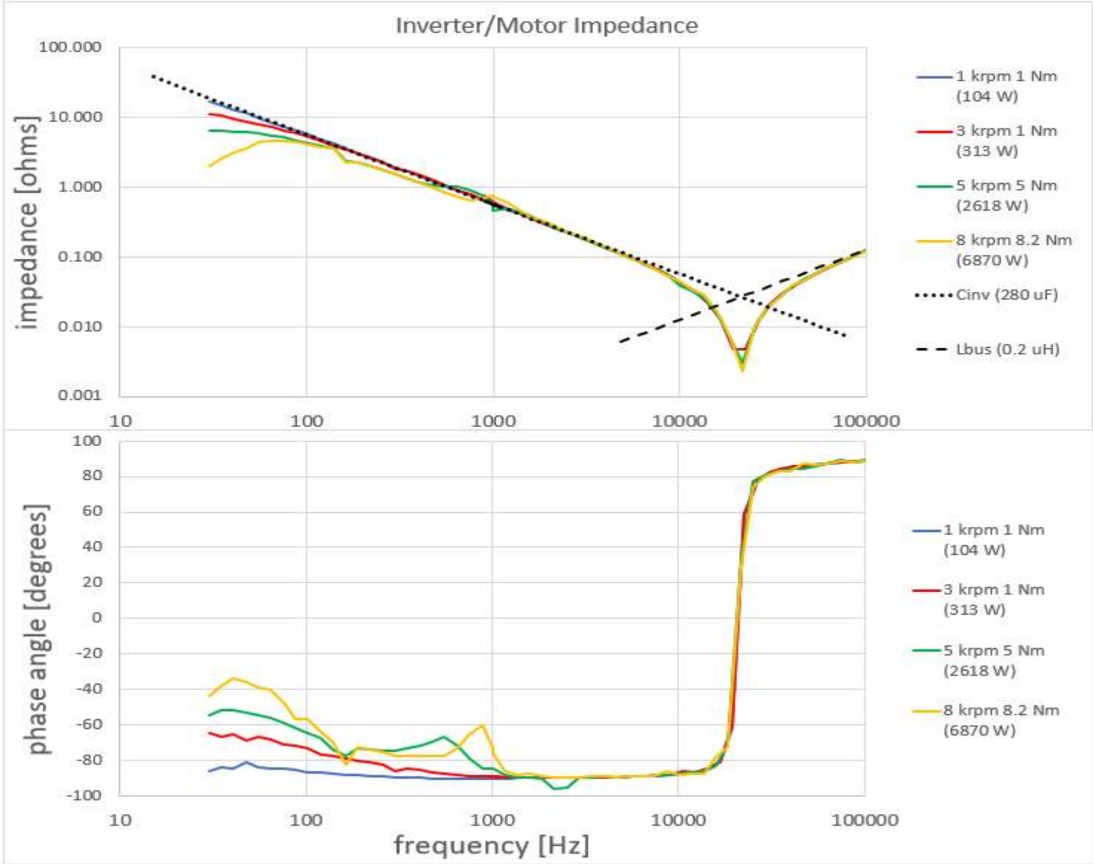


Load Sweep Definition			
sweep	**Fstart**	**Fend**	**signal**
LF	30	1100	1
HF	900	100k	0.05

Load Z Measurement: Impact of Load Power

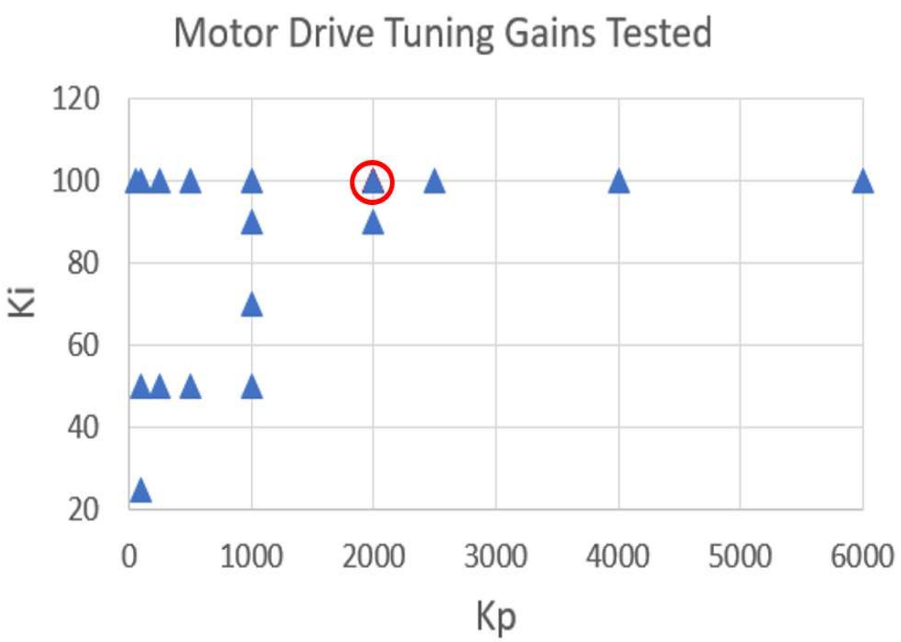
Load Z measured at all test points

- Data similarity
  - Representative data selected
  - Magnitude variation: 3 orders of magnitude
  - Low f: looks capacitive (input cap 280 uF)
  - High f: looks inductive (~0.2 uH)
  - Resonance point ~22 kHz
- Load Z as a function of delivered power
  - magnitude decrease with increased P
  - phase angle increase with increased P

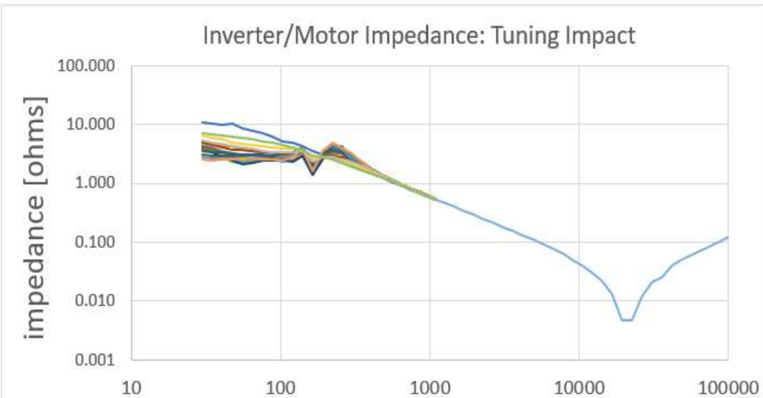


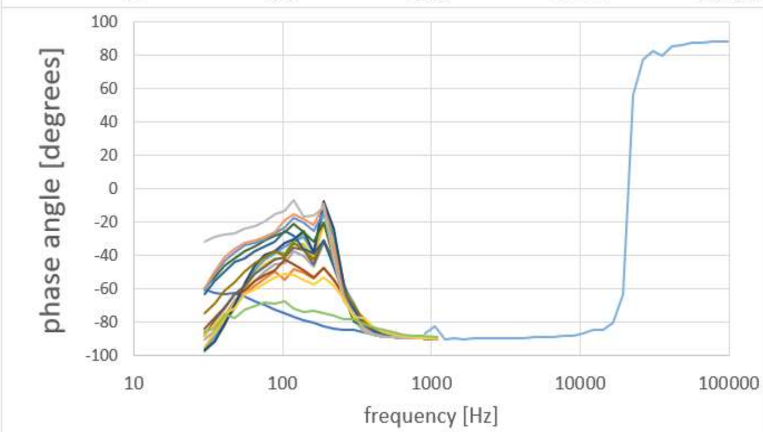
Load Z Measurement: Drive Tuning Setup

- Gains selected: current loop Kp and Ki
- Nominal tuning: Kp = 2000, Ki = 100
- Varied over a large range
- Motor operating point: 1000 rpm, 5 Nm
- Load Z measured at all points

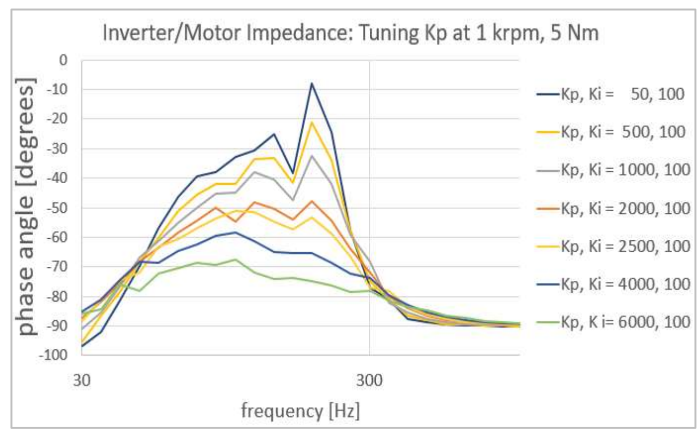


Load Z Measurement: Impact of Drive Tuning





- All 17 data points shown (left)
  - Significant tuning impact at lower frequencies
  - Increased Kp & Ki drive load Z toward capacitive behavior
  - Example Kp on phase angle, while Ki, w, T constant (below)
- Not exhaustive tuning study
  - Limited f range
  - One operating point
  - Additional gains available (speed loop gains, field weakening gains)
  - Measurements indicate low f Z shaping via drive controller tuning possible



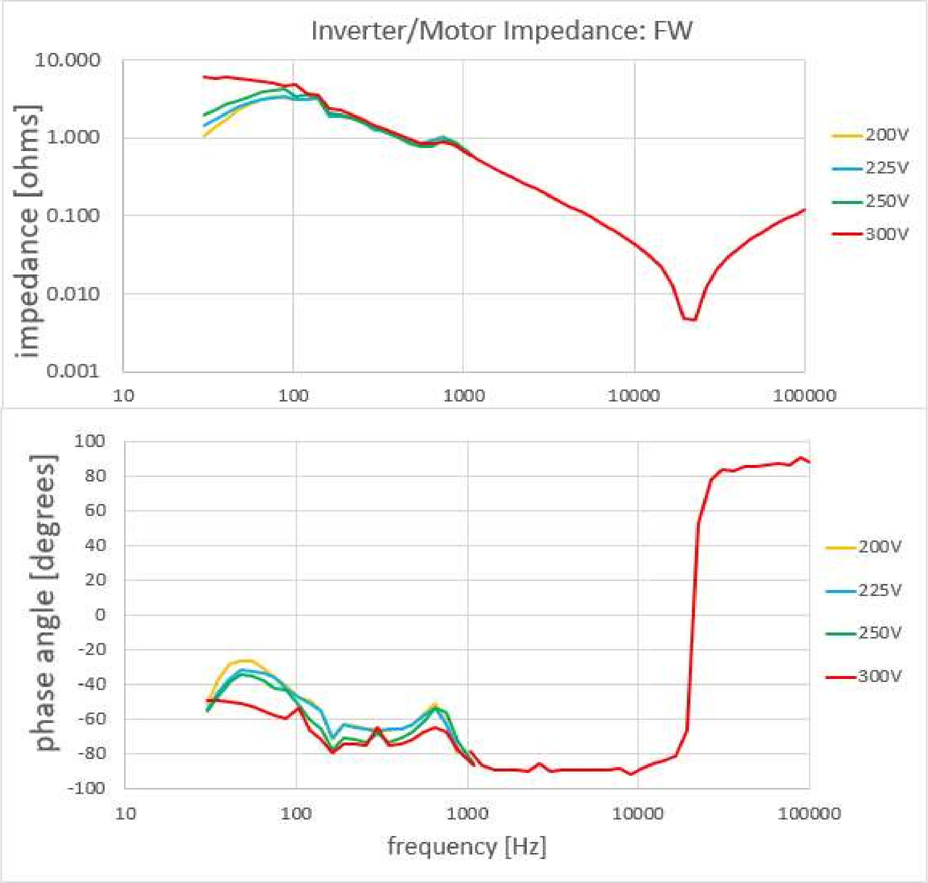
Load Z Measurement: Impact of Field-Weakening

Constant torque region & several points in field-weakening (constant power) region

- Consistent motor operating point (6 krpm, 5 Nm)
- Bus voltage decreased in steps
- Drive/machine impedance measured
- Watch modulation index and d-axis current

Increased field weakening impact: < 1 kHz

- Impedance magnitude decreased
- Phase angle moves away from pure capacitive
- Effect on Z load similar to
  - increased machine loading
  - decreased current loop Kp and Ki



Source Z Measurement: Impedance

Two level injection scheme selected by experiment

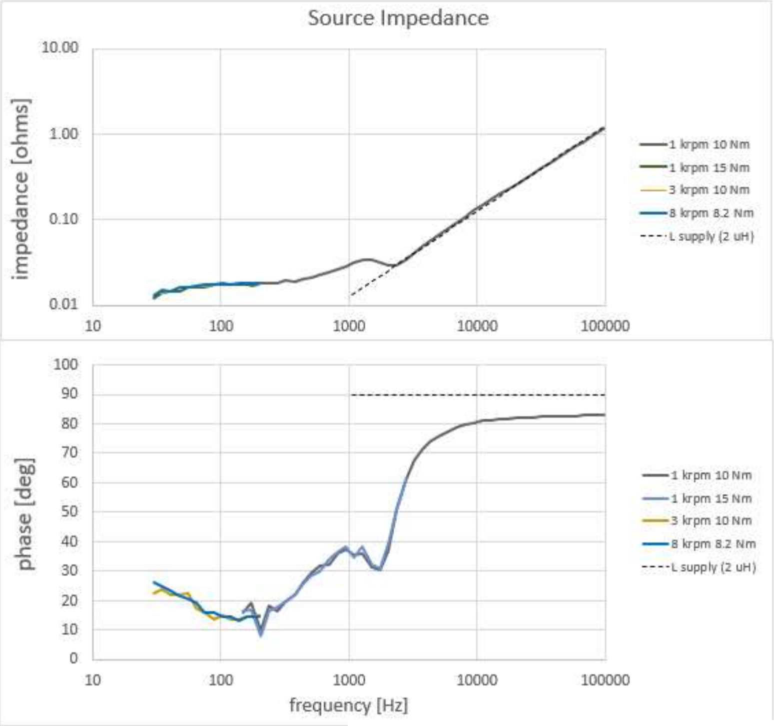
- breakpoint lower (1 kHz → 175 Hz)
- avoided load low Z region (~22 kHz)
- commonality in the source Z measurement

High frequency source Z behavior compared to load

- Similar: inductive behavior >5 kHz
- Differences
  - L 10x higher (0.2 → 2 uH)
  - f_{res} lower

Low frequency source Z behavior compared to load

- More resistive than capacitive
  - flat impedance magnitude
  - phase angle closer to zero than to -90°



Source Sweep Definition			
sweep	**Fstart**	**Fend**	**signal**
LF	30	200	1
HF	150	100k	0.05

Stability Assessment

Analysis: stability performance not an original design requirement

Bode plot Z_S and Z_L

- top dashed: $|Z_S/Z_L|$
- bottom dashed: Z angle difference

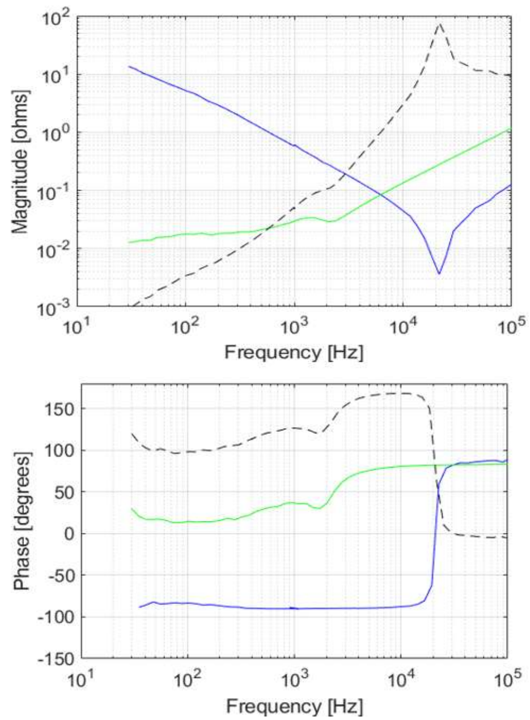
Nyquist plot of Z_S/Z_L

- Arbitrary stability margins defined
- 6 dB and 45° selected

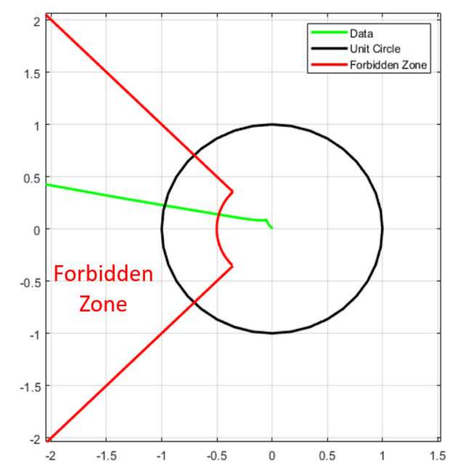
Small phase margin: Nyquist plot shows criteria not met, as expected

SPEED Lab very successful

- Small stability margin did not impact performance
- Identified potential improvement areas (e.g. adding filtering) in future work



Measured Z_S (green) & Z_L (blue); Dashed: top, $|Z_S/Z_L|$; bottom, phase angle difference



Z_S/Z_L Nyquist plot

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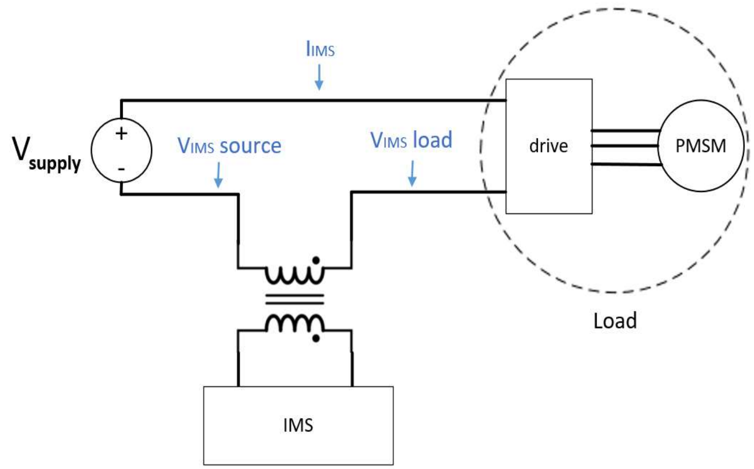
Bus Current Spectra

Bus current spectra

- Goal: understanding potential forcing frequencies injected by power supply
- Four machine speeds (1, 3, 6, and 8 krpm) and three torque levels (0, 5, and 10 Nm)
- Captured DC current on high speed scope & post-processing
- Results at low frequency, and higher frequency (centered around f_{SW})



Bus Current Spectra

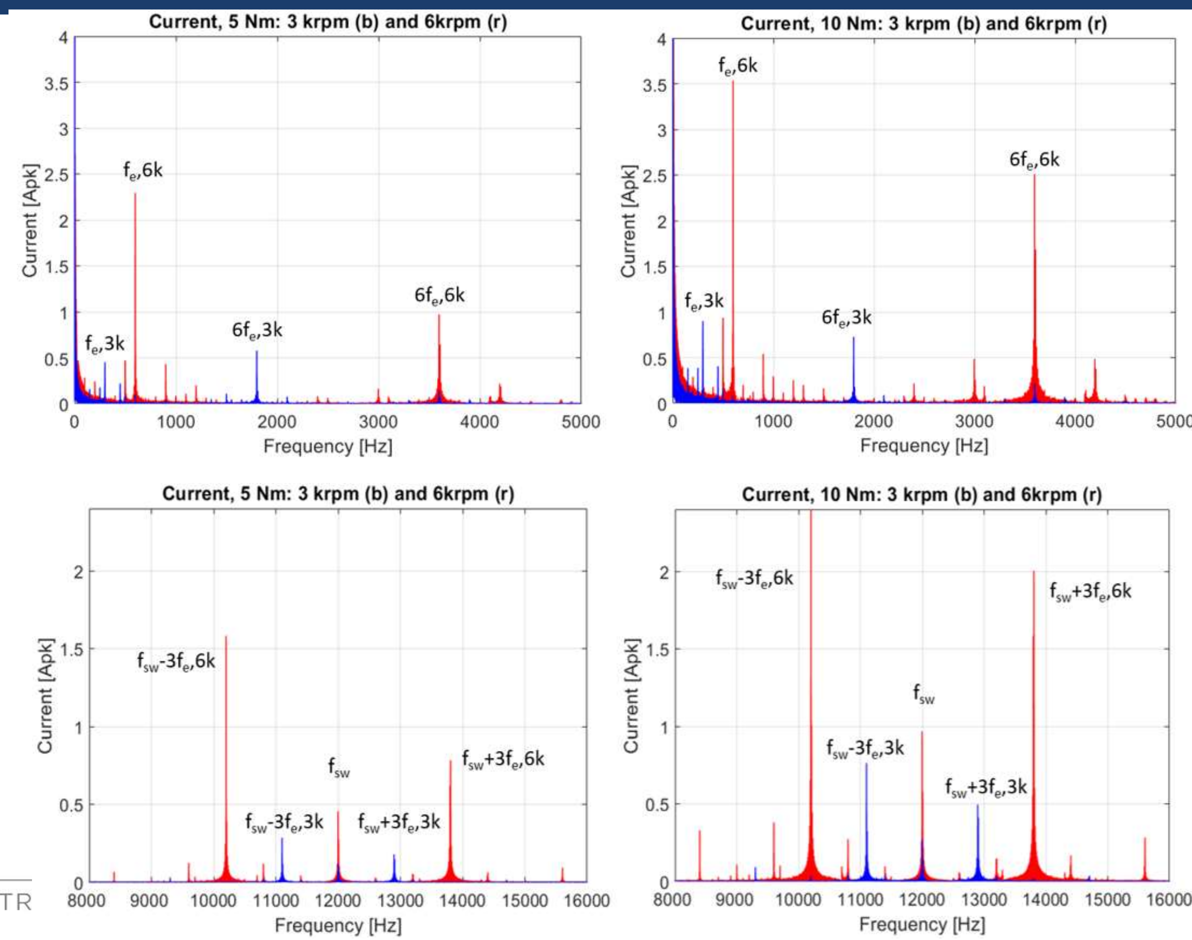
Conditions: 2 speeds and 2 loads (T)

<u>Low frequency data</u>

- Dominant peaks fe & $6f_e$ (= f_m)
- Increase with increased ω & T

<u>High frequency data</u>

- Centered at the motor drive switching frequency f_{SW}
- f_{SW} matches specs (12 kHz)
- Also at $f_{SW} \pm 3fe$
- Increase with increased ω & T



Conclusions and Future Work

1. Source and load impedance measurements in the NASA GRC SPEED Lab
2. DC supply, motor drive, PMSM, dynamometer
3. Load Z impacts from ω, T, drive controller tuning, field weakening
4. Source Z results
5. Stability analysis
6. DC bus current spectra under various loading conditions
7. Future work:
    1. Testing at lower frequency, higher power
    2. Further tuning; field-weakening impacts to system stability
    3. Load susceptibility to bus ripple, input filter impacts

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