Common Mode Current Challenges and Opportunities in Electric Powertrain Testing

Michael Garrett

NASA Glenn Research Center

AIAA/IEEE Electric Aircraft Technologies Symposium (EATS) June 12, 2023

Abstract

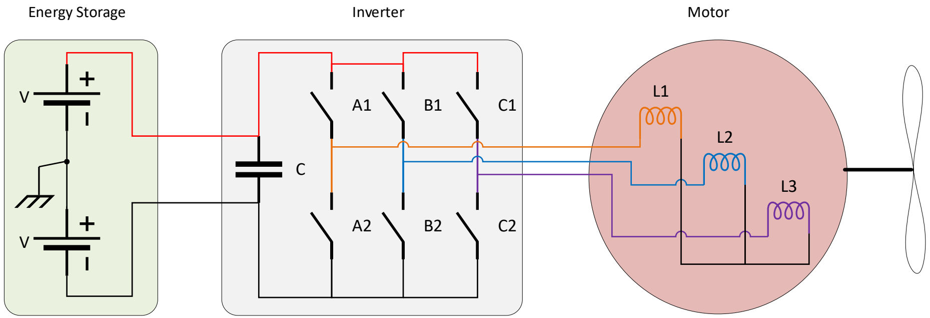
During the development of novel electric powertrain (EP) components key parameters may be evaluated by test before a fully integrated EMI design is implemented. However, insufficiently mitigated EMI could impact the test equipment and test measurements. This risk is particularly valid with high voltage wide bandgap switching converters which enable high efficiency but can increase the EMI source function producing high levels of common mode (CM) current. Test facility equipment may be susceptible to the CM current from these converters causing test delays or measurement errors. Characterization of the common mode EMI of a powertrain component by analysis and/or measurement and assessment of the test facility EMC design can reduce this risk to yield efficient tests and successful measurements.

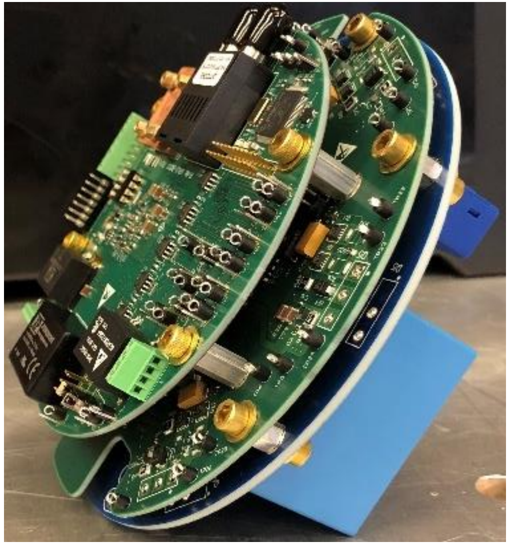
Overview

- Discussion of X-57 High Lift Motor Controller Common Mode Challenges
- System Level Challenges of Common Mode Current Encountered
- Opportunities to use Common Mode Current measurements to improve hardware development.

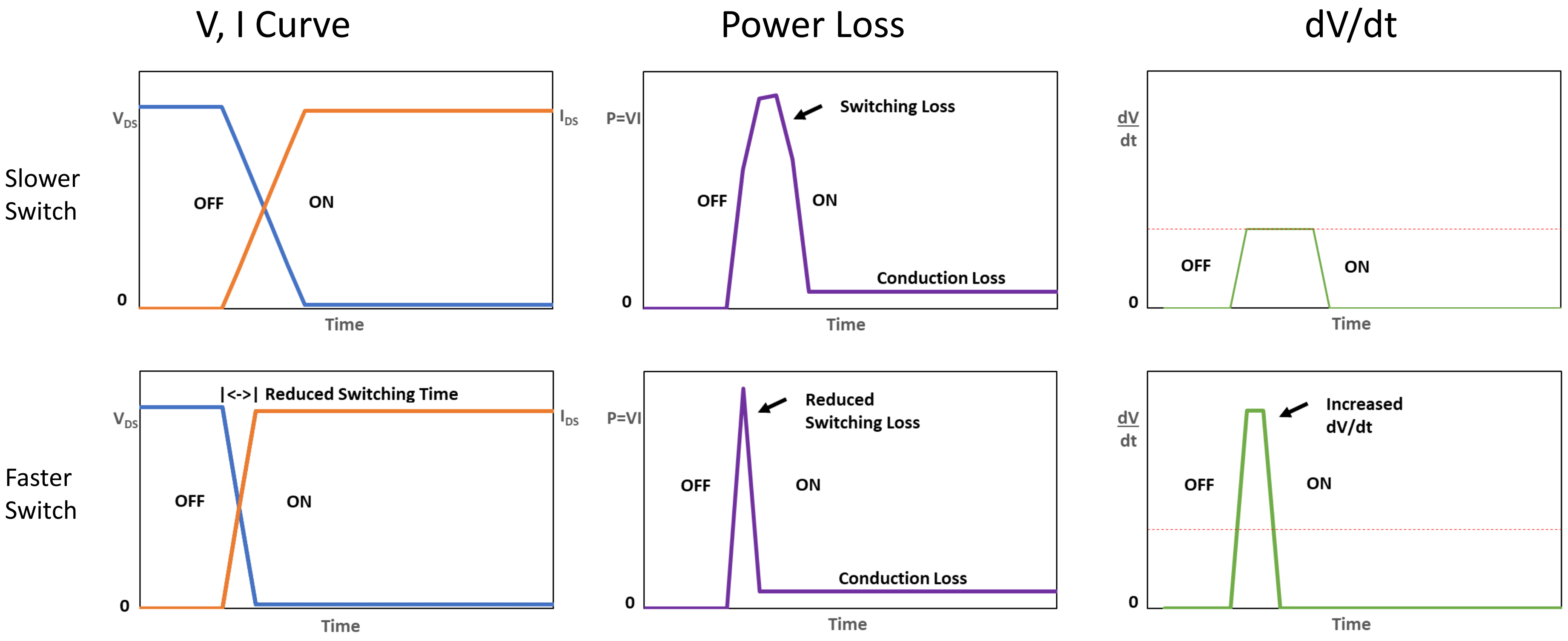
X-57 High Lift Motor Controller

- Designed for Mod IV Distributed Propulsion
- Inverter & Controller
- Qualified in 2018 to 11kW Output
- Upgraded to 14 kW
- 97% efficiency
- Passive thermal cooling
- Mass ≤ 2.2 lbs





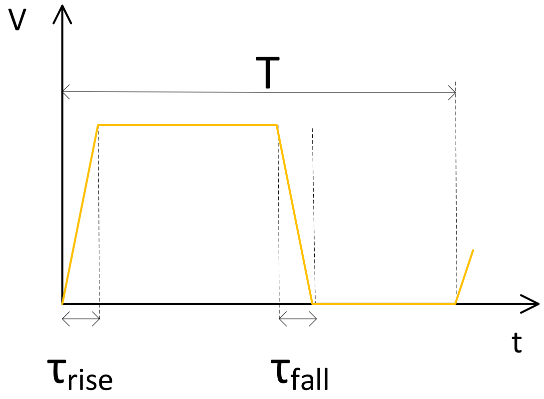
Switch Efficiency & EMI Relationship

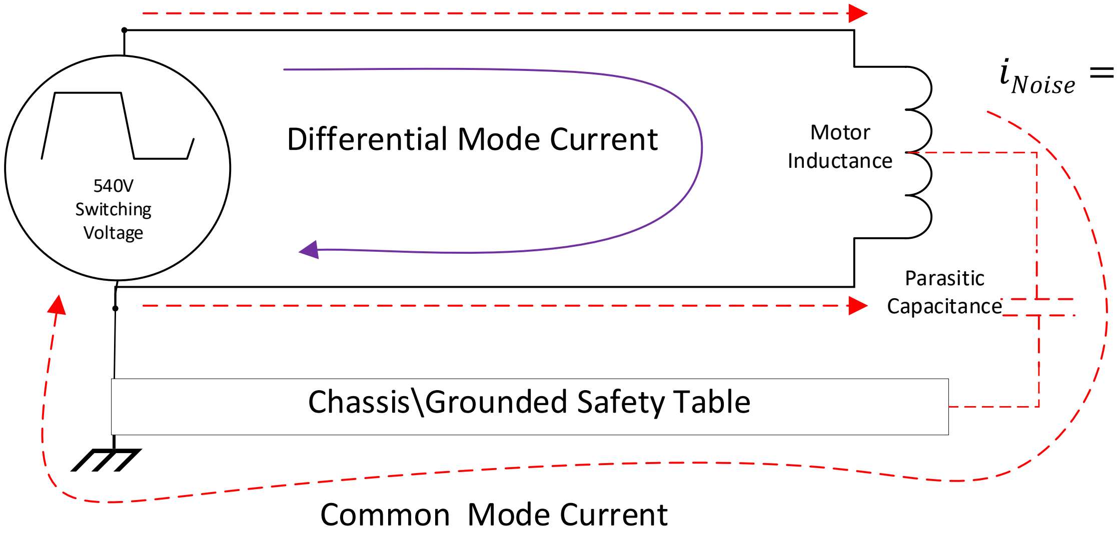


Fast Switching reduces power loss & thermal load in switch, but increases dV/dt

Differential & Common Mode Currents

High frequency harmonics conduct through stray capacitances creating a circuit that returns current to the inverter through lowest impedance path(s).



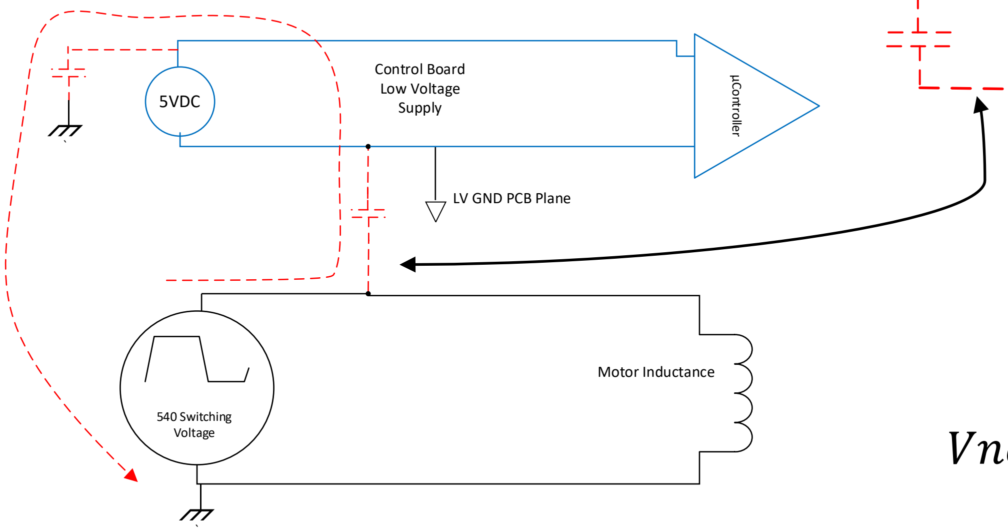


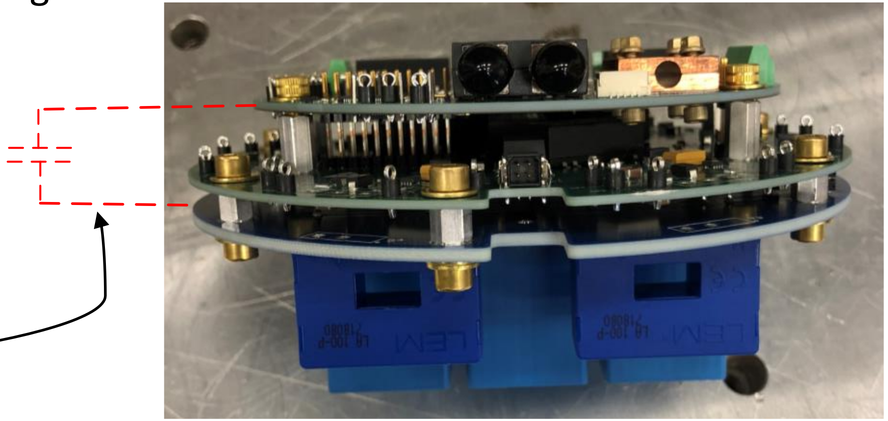
$$i_{Noise} = C\frac{dV}{dt}$$

$$For\ \tau = 10\ ns,\ CM\ Noise\ Bandwidth = \frac{1}{\pi \cdot (10^{-8} s)} \approx 32\text{ MHz}$$

X-57 HLMC Self Compatibility Challenges

- 540 Volt Switching Yielded High dV/dt
- Challenged low voltages of Motor Controller through stray capacitive coupling.

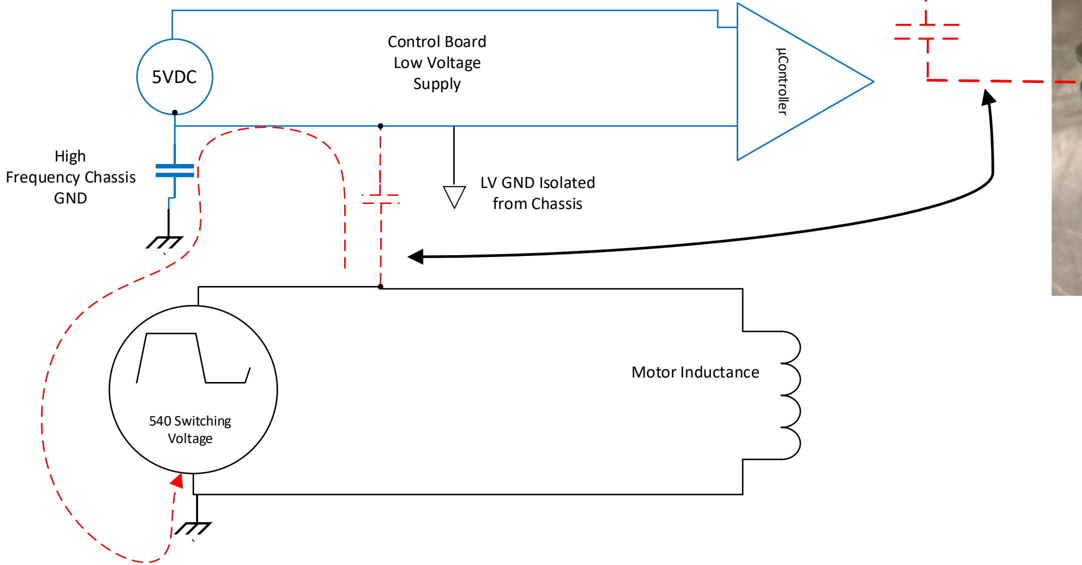


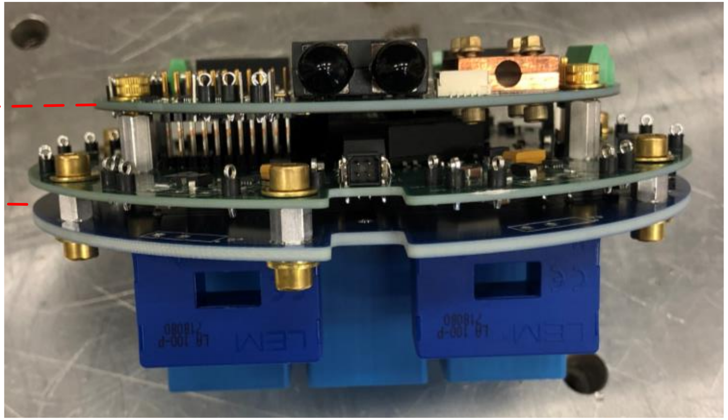


$$Vnoise = (j2\pi f C\ \Delta V)R_{eq}$$

X-57 HLMC Self Compatibility Challenges

- 540 V switching yielded high dV/dt
- High frequency path from LV GND through Controller circuits shorted by
- “hybrid” ground with capacitors.



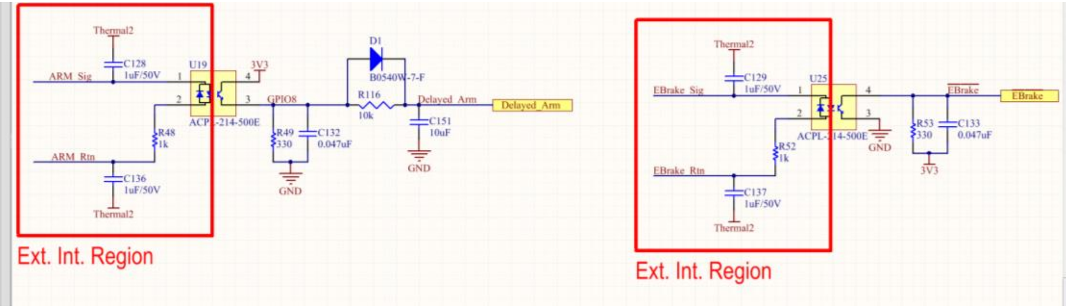


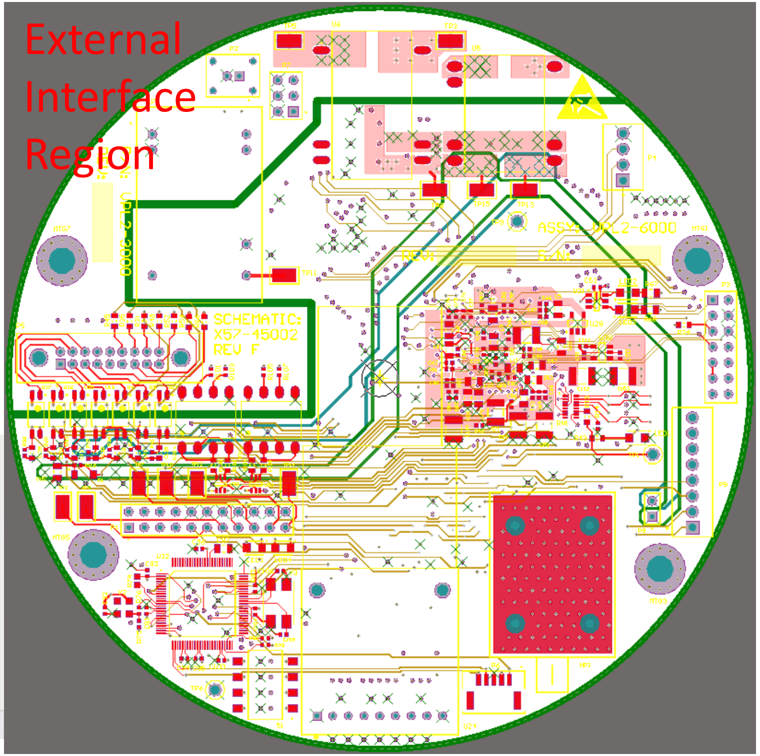
Common Mode Current Challenges

- high *dV/dt* produces CM current at RF frequencies
- Exploits parasitic capacitances
- Fast rise/fall times yield greater bandwidth
- Unintentional circuits will exist driven by switching source
- Current returns by path of least impedance at frequencies in the noise bandwidth

X-57 Controller Board CM EMI Mitigations

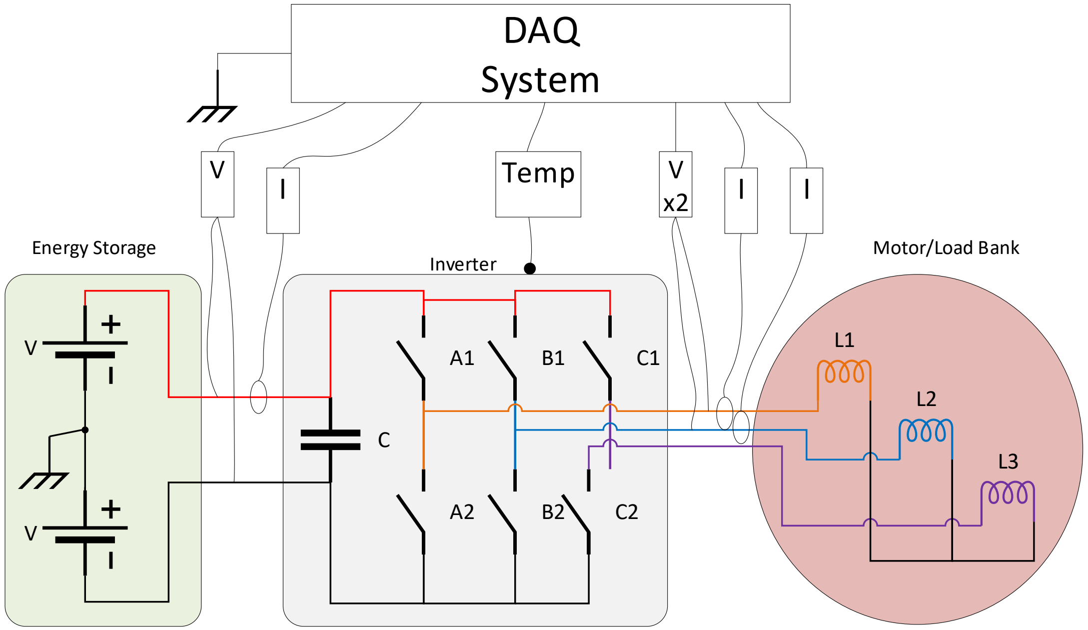
- Fiber Optic Ethernet
- Opto Isolated Discretes
- Isolation regions improve EMI immunity
- Hybrid (High Frequency) GND to Chassis



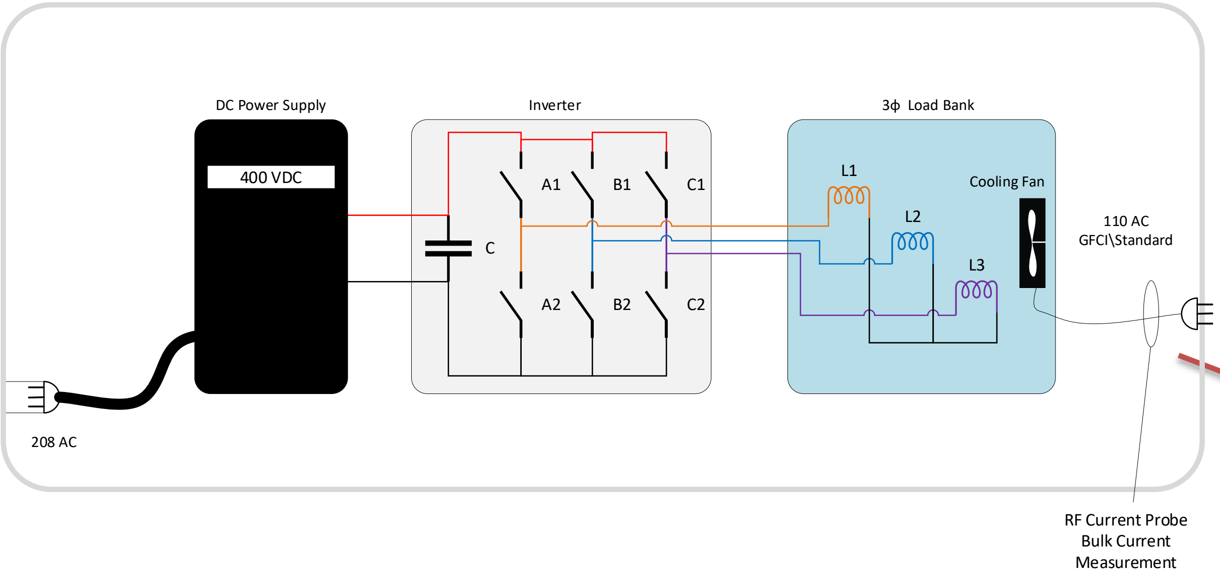


Facility Instrumentation Mitigations

- Instrumentation CM EMC
  - DAQ & Sensors can become a common mode current circuit
  - High Common Mode Rejection >60 dB at relevant frequencies is required
  - EUT and facility electrical grounding and cable layout should promote HV and isolation.



CM Current Laboratory Measurement



- GSE Load Bank
  - Load simulator for inverter
  - Not identical to motor load
  - Not optimized wrt CM
  - Measured 110VAC cord during functional test.

FCC F-65 Current Probe on 110 VAC

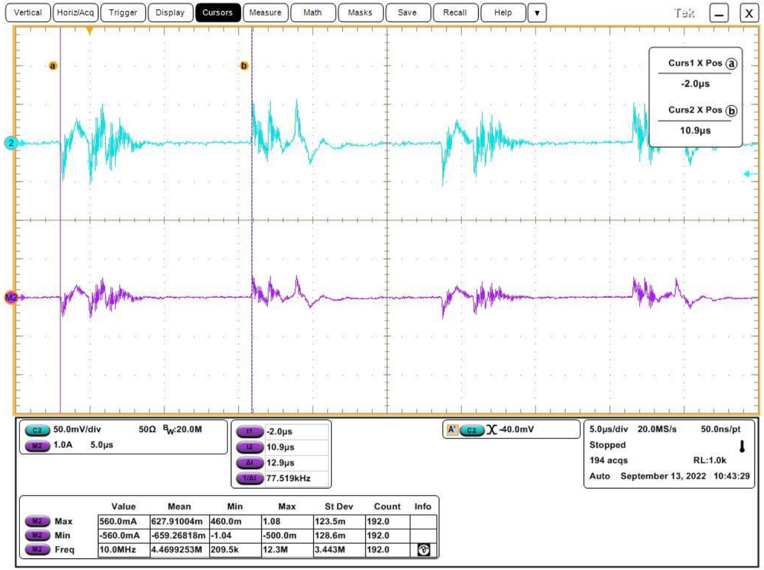
CM Current Laboratory Measurement

Spectrum Analyzer, Digital Oscilloscope
Measuring EMI Lab F-65 Current Probe Output

- GSE Load Bank
  - Load simulator for inverter
  - Not identical to motor load
  - Not optimized wrt CM
  - Measured 110VAC cord during functional test.

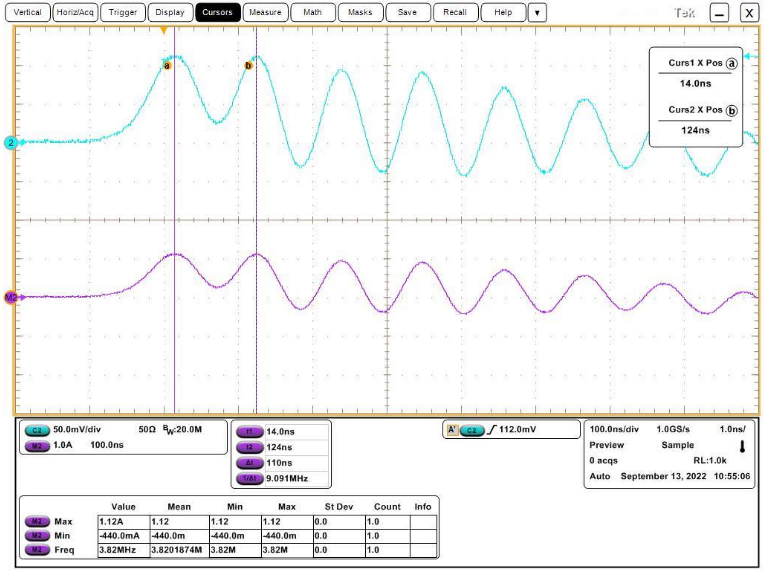
FCC F-65 Current Probe on 110 VAC

110 VAC CM Current Measurements



Ch2: Raw Probe Output
50 mV/div

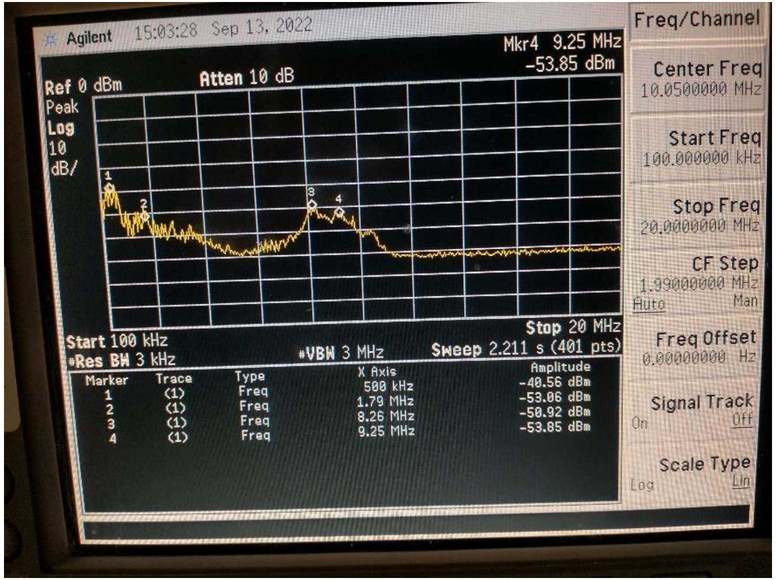
M2 Probe Corrected Output
Amps, 1 A/div



50 us/div
Effective fundamental frequency ~ 80 kHz
Bulk current pk-pk amplitude ~ 1.5 Amp

100 ns/div
Resonant frequency ~ 9 MHz
Bulk current pk-pk amplitude ~ 1.5 Amp

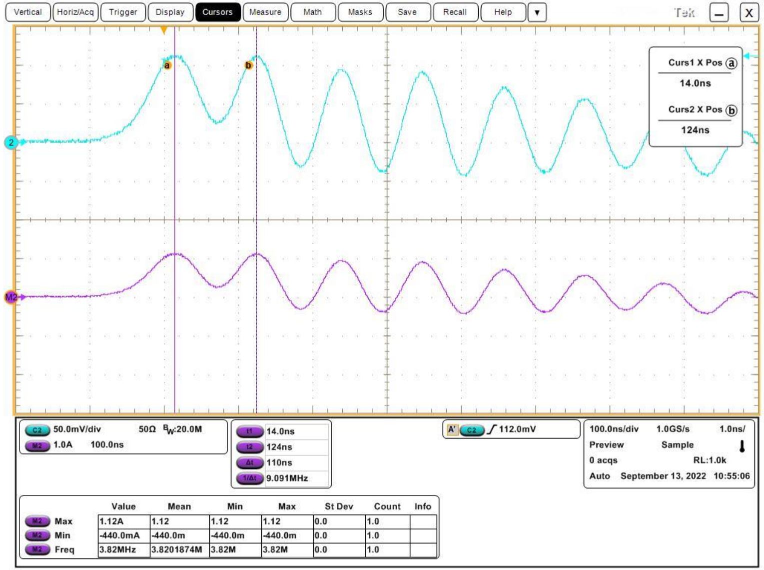
110 VAC CM Current Measurements



Reference Measurement (Non-Calibrated IMTE)
Bandwidth ~11 MHz

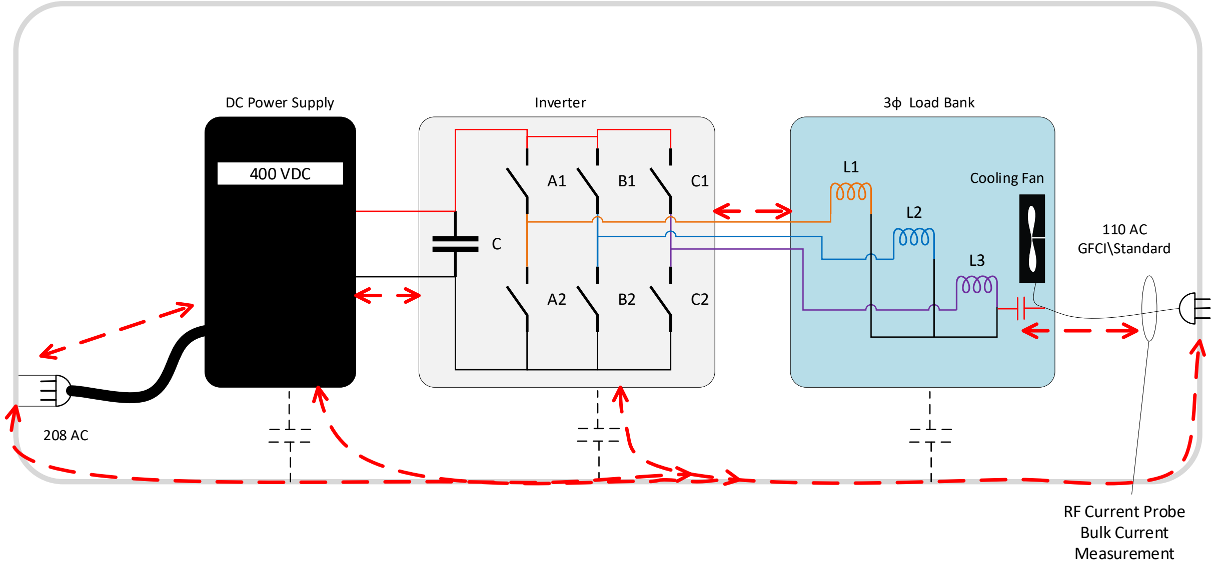
Ch2: Raw Probe Output
50 mV/div

M2: Probe Corrected
Output, 1 A/div



100 ns us/div
Resonant frequency ~ 9 MHz
Bulk current pk-pk amplitude ~ 1.5 Amp

CM Current Laboratory Path



- Common mode current generated by switching in Inverter/Converter
- Path through AC cables to load
- Current returned to the Inverter through path of least impedance, possibly through facility ground to thermal chamber to inverter.

CM noise could affect performance measurement data.
Ground support filtering may be necessary to protect facility.

CM Current & Radiated Emissions Prediction

- CM current on cables is the primary source of RE and qualification/certification failures.
- Simulation tools can be used to predict radiated emissions from common mode current on cables
- Models exist to predict radiated emissions levels from CM current measurements.
  - C. R. Paul and D. R. Bush, "Radiated emissions from common-code currents", *IEEE International Symposium on Electromagnetic Compatibility*, pp. 1-7, April 1987
  - W. Padungtin and V. Tarateeraseth, "Comparison of Radiated EMI Prediction Methods from Measured Common-Mode Currents," 2022 25th International Conference on Electrical Machines and Systems (ICEMS), Chiang Mai, Thailand, 2022, pp. 1-4, doi: 10.1109/ICEMS56177.2022.9982973.
- RE prediction from CM current measurement can inform overall system EMC design

Summary

- Measuring common mode current is recommended to characterize the EMI from development high voltage switching converters & inverters.
- Unmitigated emissions may impact the test facility. Ground support EMI filters may be needed during early stages of development to ensure measurement integrity.
- Consult with supporting test facilities on levels of EMI and work to mitigate against EMI impacts to planned tests.