RVLT Experimental Capabilities and Power Quality Investigation

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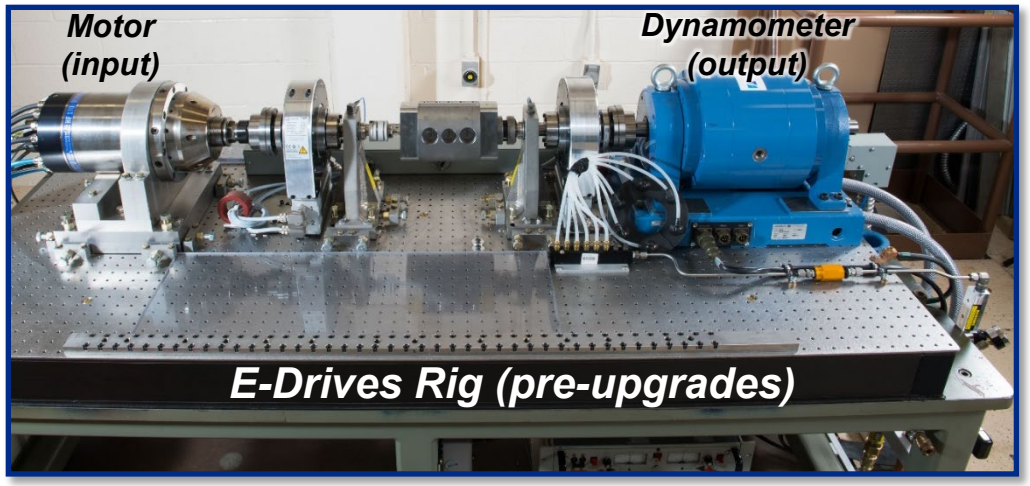
RVLT E-Drives Rig (POC: Justin Scheidler/GRC)

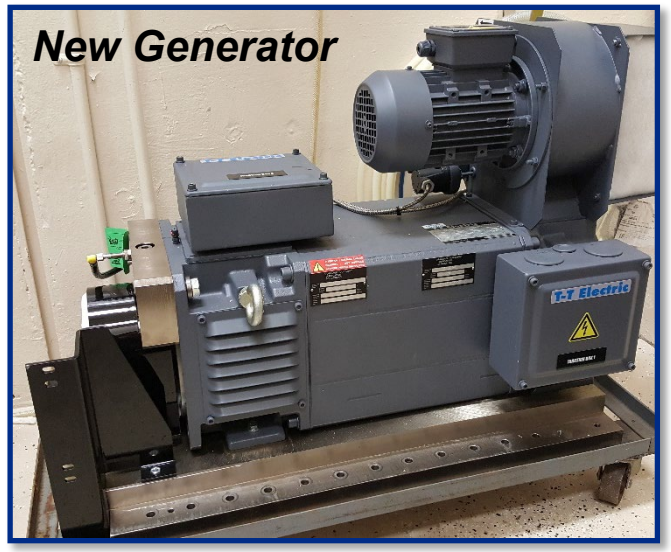
Scope

- Test motors, gearboxes, & power electronics
- Mechanical, electrical, vibration, & thermal measurements
- After upgrades completed, capable up to 21,500 rpm input & 7,400 rpm output



Key capabilities for this tech challenge

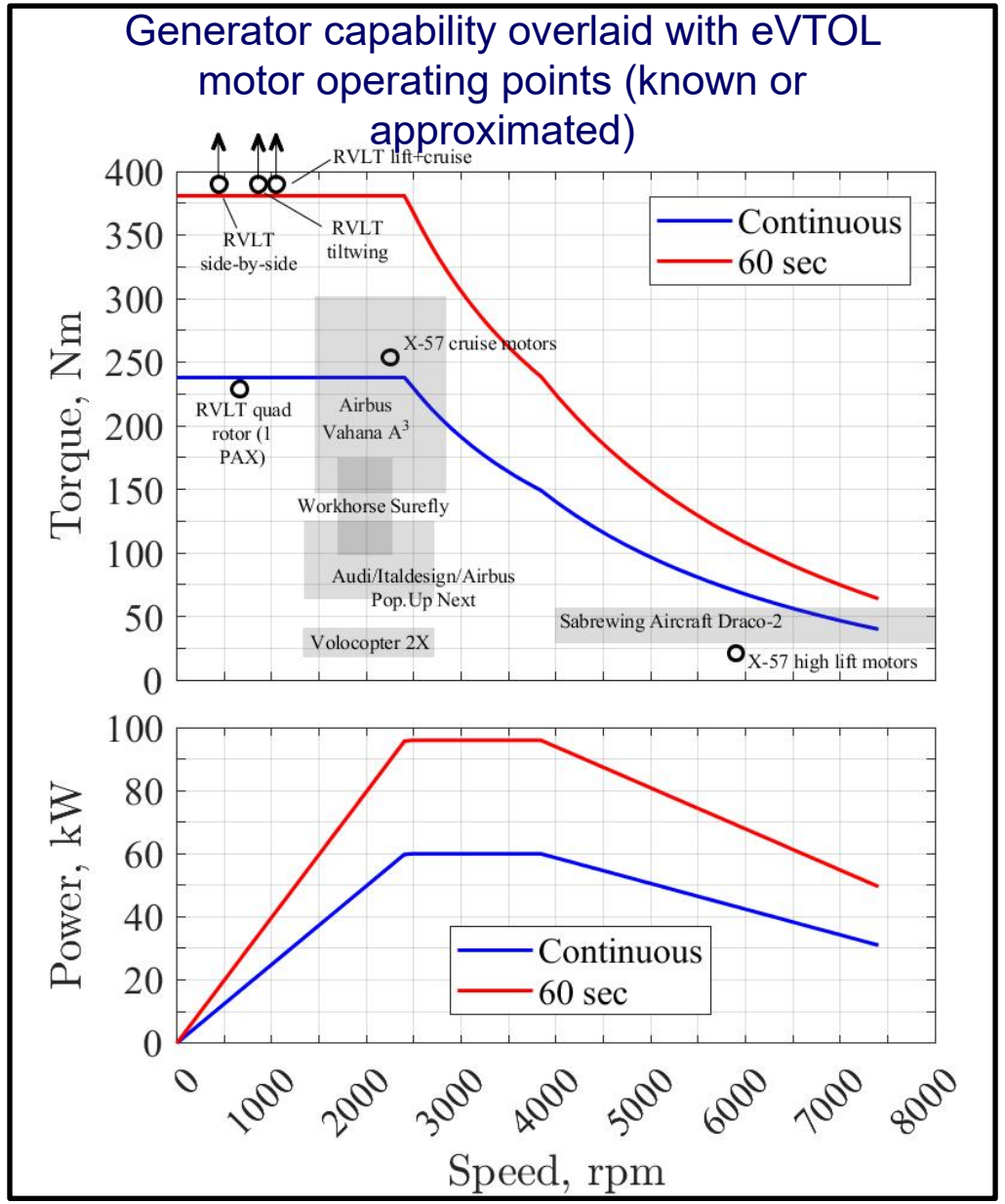
- Validation-quality data (very high precision – e.g., gearbox efficiency up to < ±0.2% with 95% confidence)
- Directly measure temperature of energized motor windings (up to 1000 V RMS continuous)
- Emulate rotor loads with new generator dynamometer
- Year-round operation (no reliance on cooling tower water)
- Provides platform for magnetic gear and motor evaluation



Specific Experiments

- Motor efficiency, output torque, and temperatures under steady-state and transient conditions
- Performance mapping of magnetic gears (& possibly magnetically-geared motors) for motor design code validation & TRL advancement of new concepts

RVLT E-Drives Rig Capabilities



Generator capabilities:

- **Controlled via ~500 Hz control loop**
- **Continuous**
  - 0-2400 rpm 238 Nm
  - 2400-3840 rpm 60kW constant
  - 3840-7400 rpm decreasing power to 31kW at 7400 rpm
- **Short duration (60 seconds)**
  - 160% overload

RVLT Power / Powertrain Testbeds

- **Scaled Power Electrified Drivetrain (SPEED) -Low-Power Testbed**
  - Low power (up to 9 kW) motor & controls
  - Low voltage test platform for high power testbed hardware

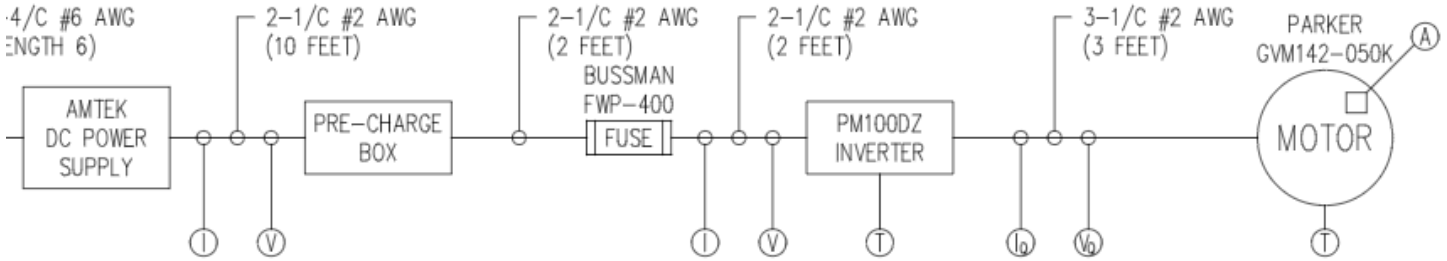
- **Advanced Reconfigurable Electrical Aircraft Lab (AREAL) - High Power Testbed**
  - Emulated, reconfigurable system (single-string, multi-string)
  - 1kVDC Peak, nominal 200kW source

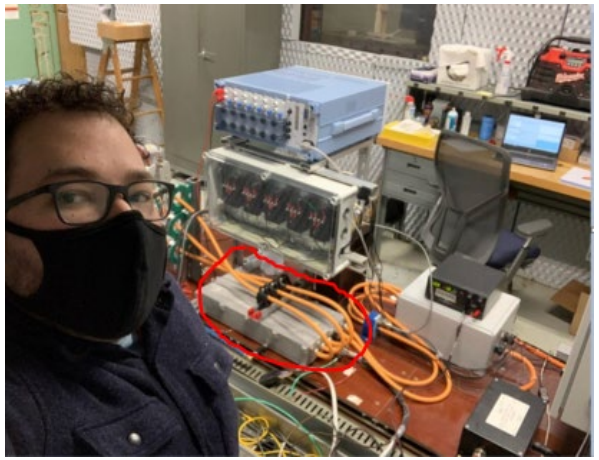
End goal to have all equipment/circuitry completed for AREAL lab integration – due for completion FY22

RVLT Low Power Testbed (*SPEED*) - Overview

Capabilities

- “Single String” of “scaled” components
- 400 VDC supply
- 6 kW cont. and 7 kW peak (5 min)
- 12,000 RPM max speed
- 28 Nm max torque
- Has been repurposed for RVLT RTOW





Status

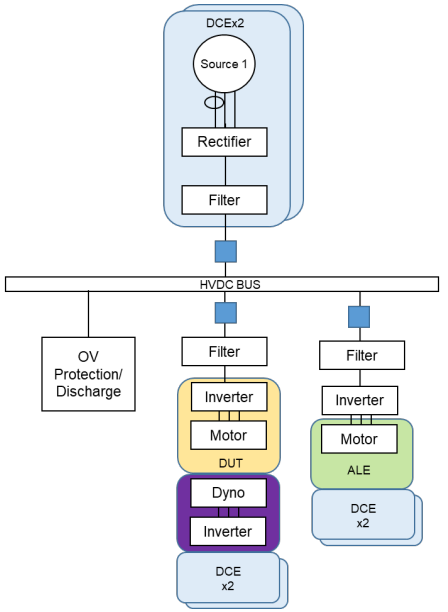
- Easy to accommodate various motors/inverters (at low power)
- Safety permit obtained
- Impedance measurements and equipment characterization initiated

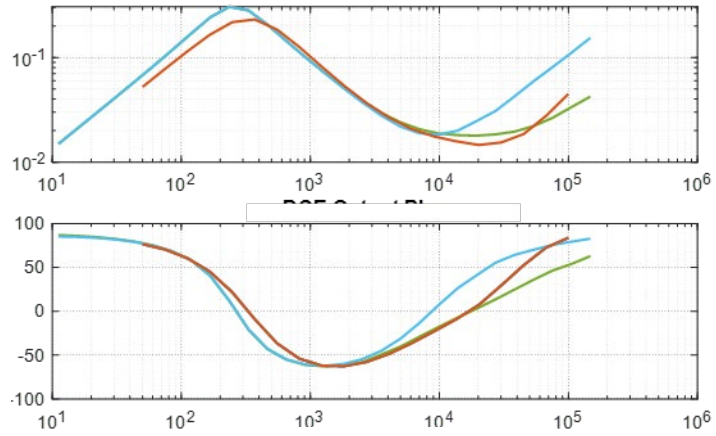
RVLT High Power Testbed (AREAL) - Overview

- **Scope**
  - Investigate Power Quality & Integration Issues
  - Feed Standards (AS7499, AS8441)
- **Capabilities**
  - Emulated, Reconfigurable System
    - Single-string, Multi-String
  - 1kVdc Peak, 600-700Vdc Nominal
  - 200kW Nominal Source Capacity
  - Ability to test Faults
- **Experiments**
  - Nominal, Transient, Fault Operation
  - Characterization and Response

AREAL Hardware

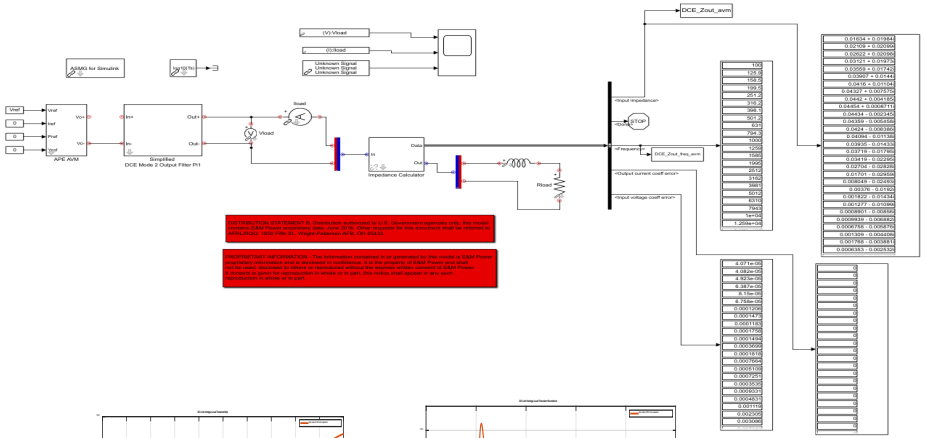
- **DC Emulators**
  - Reconfigurable to emulate most DC sources from a small-signal and transient level
- **Physical Motor Stand**
  - State-of-the-Art Inverter/Motor, Back-to-Back
  - Can replace as needed
- **Motor Emulator**
  - Ability to Emulate Physical Motor
  - Ability to Introduce Faults
- **Fault Protection**
  - Initially Contactors/Fuses
  - In the process of procuring advanced fault protection devices

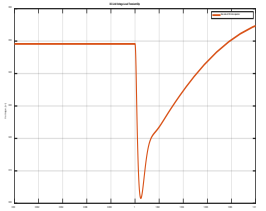


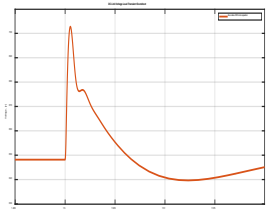


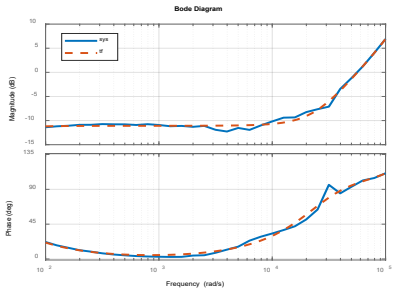
AREAL DC Emulator Capabilities

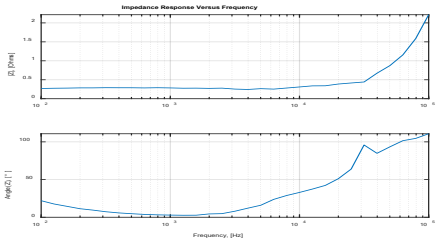
- **High Bandwidth DC Power Supply**
  - 20kHz Large Signal Bandwidth
  - 40kHz+ Small Signal Bandwidth
- **500V, 100kW Bidirectional (2Q) per unit**
- **Multiple Applications**
  - Source Emulator
  - Power Sink
  - Limited Capability as Amplifier for Impedance Sweeps
  - Constant Power Load with programmable bandwidth
- **Currently Developing Modifications**
  - Developed dynamic model of 650V Wound Field Generator
    under Phase III SBIR with PCKA for PQ Study
  - Generator Model meets Lift+Cruise Power System PQ Requirements in accordance with AS7499 HVDC Power Quality
  - Using DCE dynamic model from WPAFB to match transient and frequency response of generator with mods
  - Also investigating low cost/ quick turnaround emulation strategy w/ Speedgoat







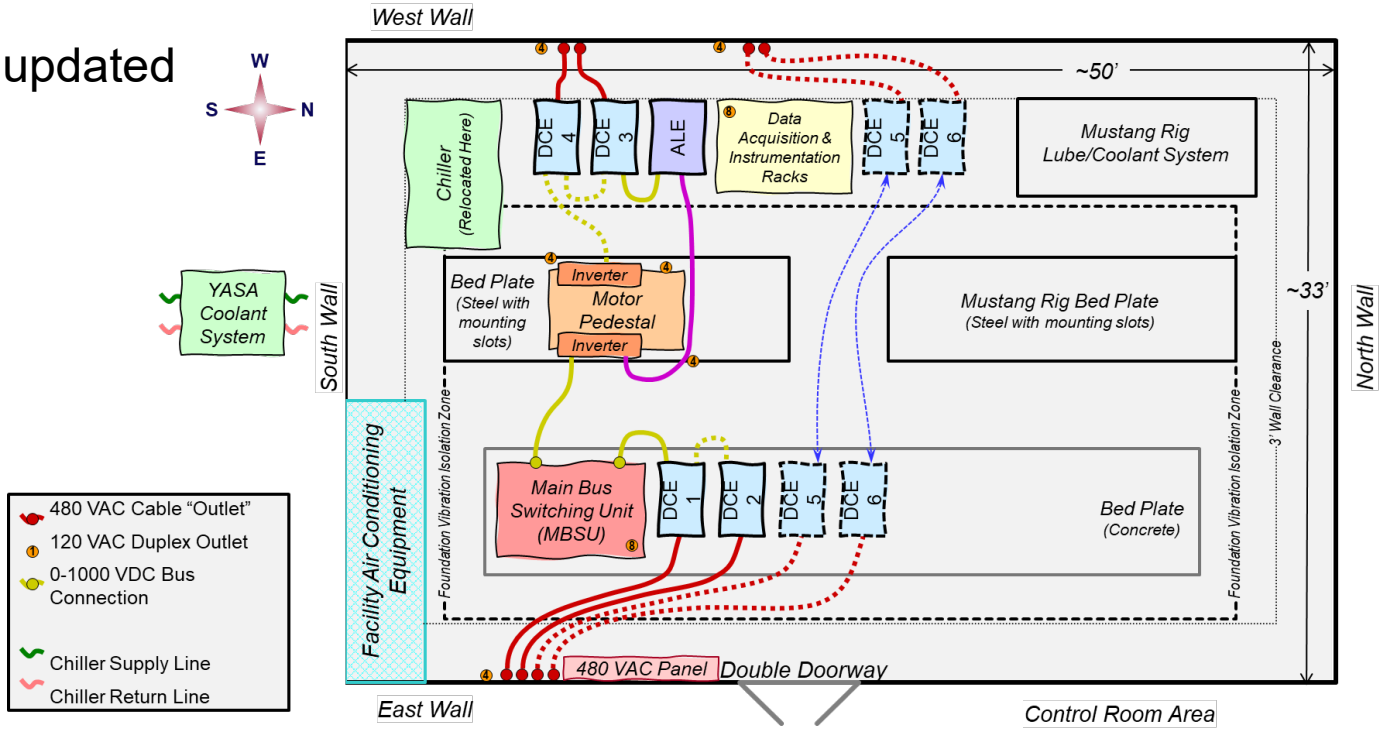




AREAL Status

AREAL Testbed

- Lab layout being finalized
- Facility 480V Power Complete
- Cooling System being upgraded
- Arc Flash Study Completed for Single String
- Safety Permit being updated



Tools, Standards, & Working Group Related Efforts

Data from testbeds will be used to inform tools and standards efforts

- **Developing Analysis Tools:**
  - **NPSS**
    - **Developed high level electrical power system models & electrical/thermal ports for architecture trades**
    - **Demonstrated electrified propulsion system models**
    - **Accepted into next release of NPSS**
  - **EPS-SAT**
    - **Electrical power system sizing**
    - **Utilized for trade studies and sensitivity analyses**
  - **Toolset for Motor Reliability**
    - **Reliability Modeling of Electric Motor**

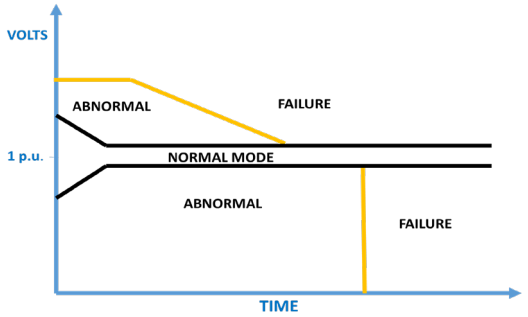
Outreach/Interest-
Govt: FAA, AFRL, Navy
Industry: Colins Aerospace, Boeing, GE, Airbus, Astronics, Lillium, IEEE, Crane Aerospace, Safran, Solar Electronics, Rolls Royce, Eaton, and many more

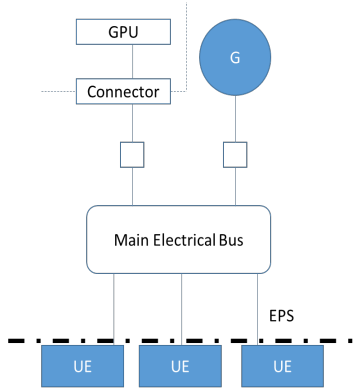
- **Leading two SAE standards**
  - AS7499 - *Aircraft High Voltage Power Quality Standard (D. Sadey)*
  - AS8441 – *Minimum Performance Standard for Permanent Magnet Propulsion Motors and Associated Drives (P. Hanlon)*
- **Participate in AAM (UAM) Aircraft Design & Development Working Group**
- **PPSA- WPAFB**

AAM Working Groups (internal to government)
To collaborate and coordinate research findings across the NASA research portfolio with the relevant FAA Lines of Business to efficiently address gaps in technology, policy, and regulations to operationalize AAM in a timeframe consistent with Congressional and FAA guidelines through:
- **Prioritizing needs and gaps**
- **Centralizing AAM collaboration and coordination**
- **Jointly developing use cases, concepts, requirements, and research findings**
- **Transitioning and implementing appropriate research findings**

DC Power Quality

- **What is Power Quality and why does it matter?**
  - Physical description of power, namely voltage (DC)
    - Applicable during any operational period (Normal, Abnormal, Emergency)
    - Voltage: Steady-state, transient, ripple
    - Stability, fault conditions, & much more
  - Improves reliability
    - Reduces component failures by defining operational boundaries
    - Ensures stable operation
    - Defines/drives proper fault recovery
  - Drives one towards ‘plug and play’ approach to design and integration
    - Not completely obtainable, but moves one closer
    - Helps guide lower level standards (e.g. components, connectors, etc.)





RVLT Example Study – Model Overview

- Work done via contract with PCKA
- Lift-Plus-Cruise Vehicle Model (Conceptual NASA Design)

- 650V, <1MW Simulink® Power System Model for PQ Studies
  - Generator, one cruise motor, four lift motors, and a power distribution unit (PDU) for each bus, with two busses total.
  - Each generator and motor has an integral rectifier and inverter and are scaled based on validated models
  - Utilizes directional overcurrent protection scheme

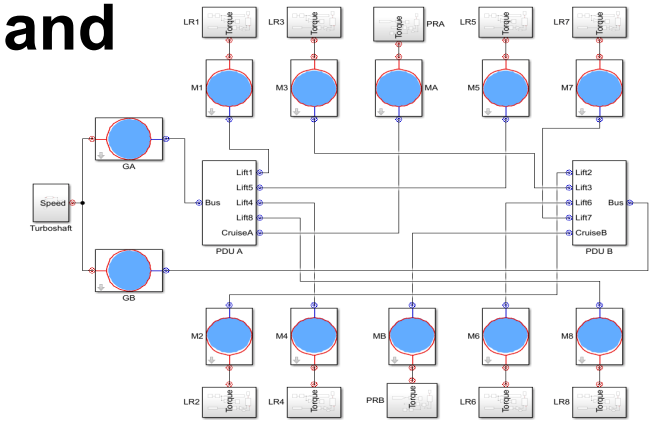
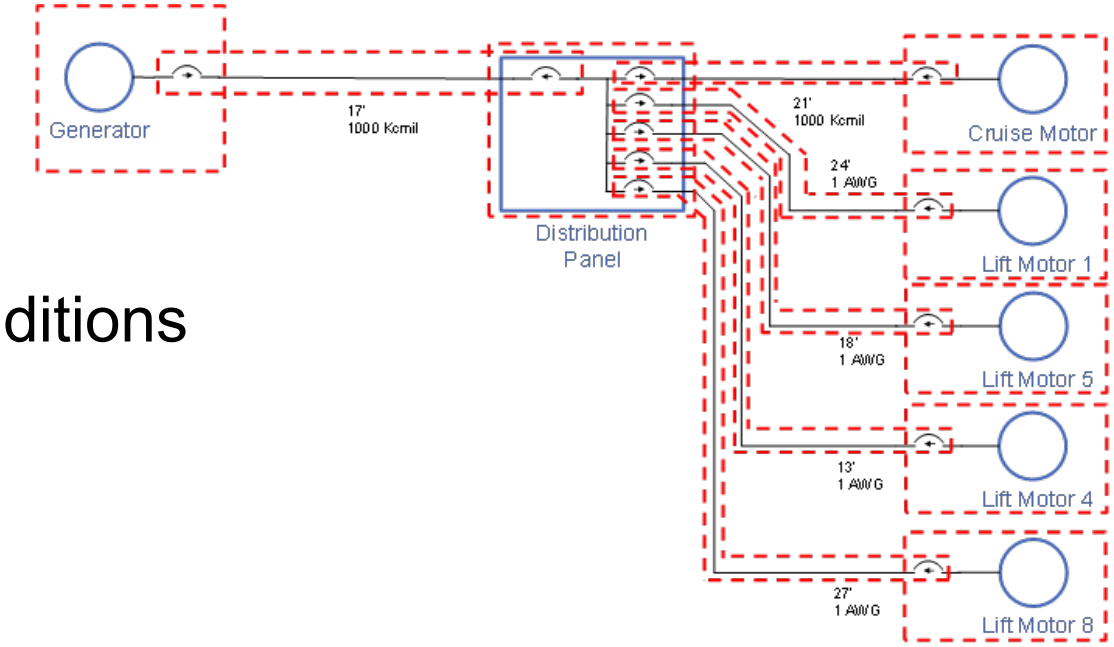


Table 1: Machine and associated Power Converter Parameters

	Generator	Lift Motor	Cruise Motor
Count on Aircraft	2	8	2
Machine Type	Wound-Rotor Synchronous	Permanent Magnet Synchronous	Permanent Magnet Synchronous
Rate Power (HP)	1000	98.6	423
Rated Torque (N m)	1978	668	2366
DC Voltage (V)	650	650	650
Rated DC Current (A)	1147	113	485
Speed (RPM)	3600	1050	1273
Control Objective	DC Voltage	Speed	Speed

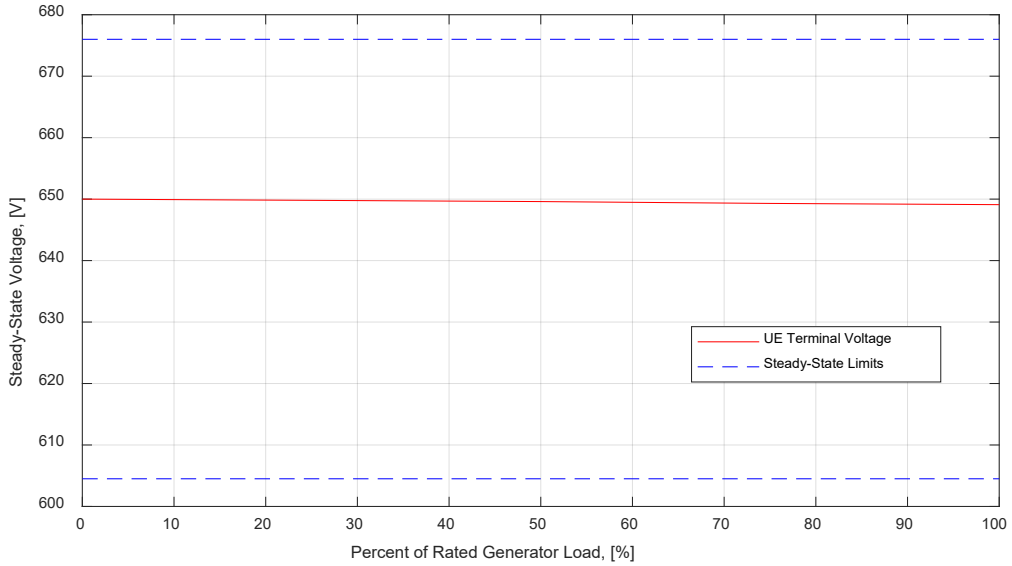
Power Quality Analysis Overview

- **System iteratively designed and tuned to meet an internal PQS specification**
- **Normal Operation**
  - Steady-State, Transient Voltage
  - Stability
- **Abnormal Operation**
  - Voltage response under short circuit conditions



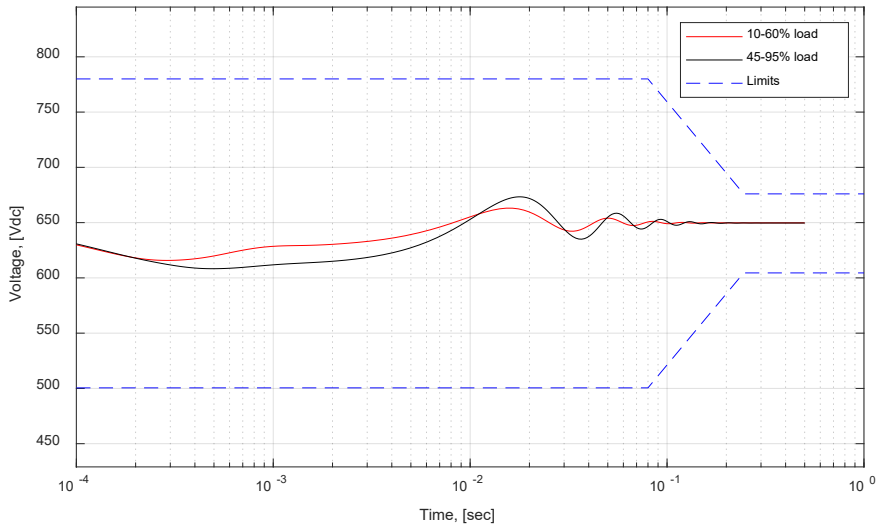
Steady State Voltage

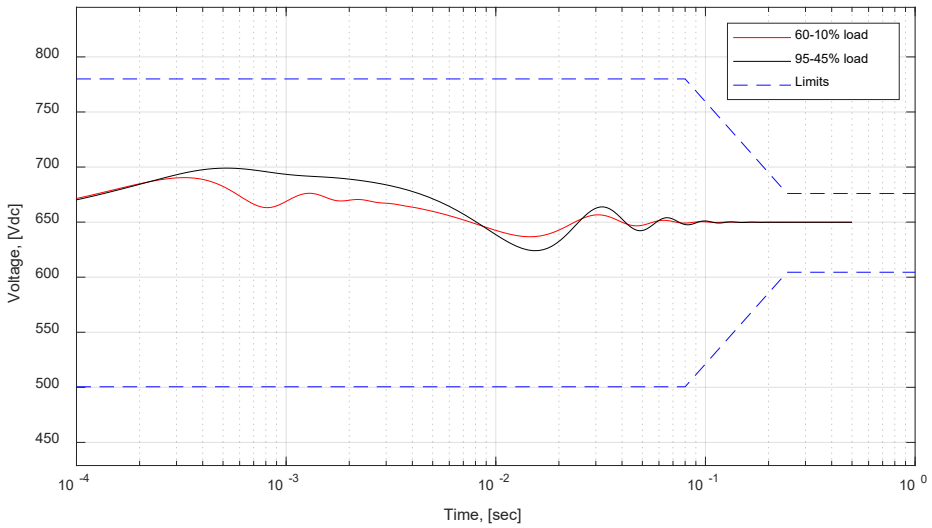
- **Requirement: Steady-State Voltage must remain between 0.93-1.04 p.u.**
- **at UE Terminals**
  - Covers No-Load to Full-Load
  - 604.5 to 676 Vdc at UE Terminals
- **No Load Voltage of 650Vdc**
- **Full Load Voltage 649.1Vdc**



Load Step Transient Voltage

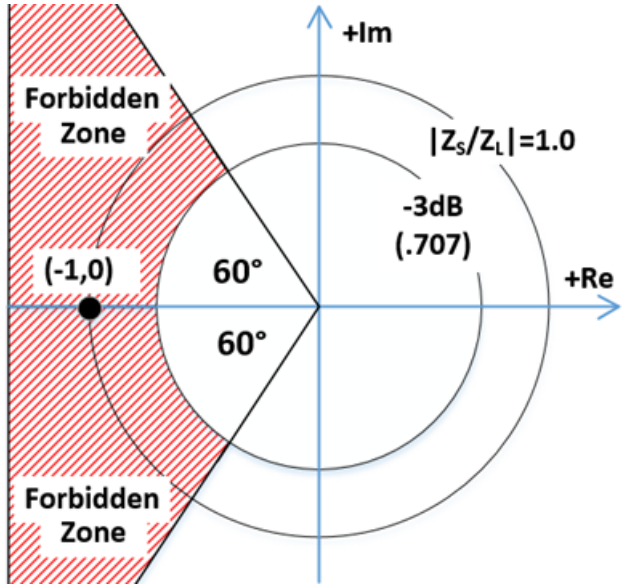
- **Requirement: EPS Transient Voltage must remain within the defined window limits under 50% load steps**
  - **Resistive Loads stepped 10 to 60%, 60 to 10%, 45 to 95%, and 95 to 45% at UE Terminal Locations**
  - **Worst-case voltage response was at Cruise Motor Terminals**
  - **Spikes <10usec ignored**

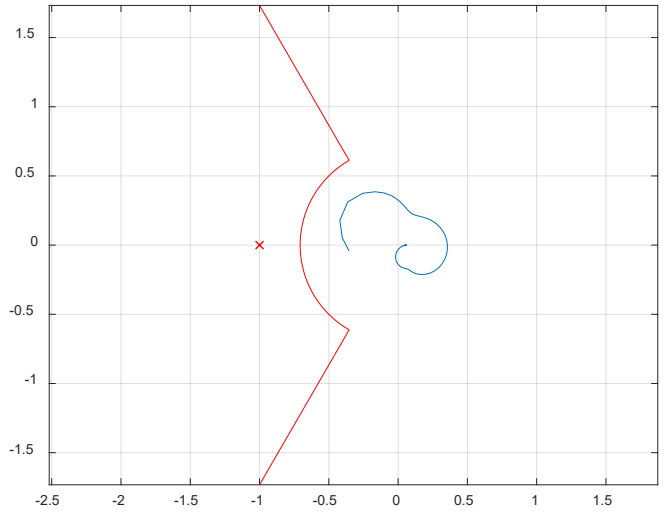




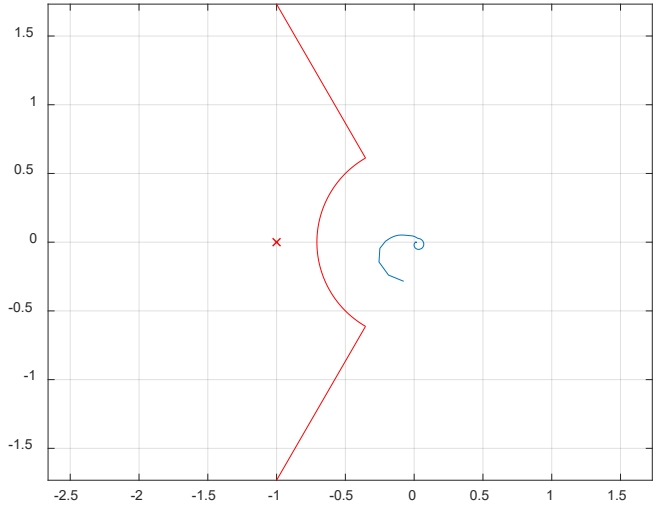
Small Signal Stability

- **Requirement: Ratio of Source to Load Impedance from 30Hz to 100kHz shall remain within the 60 degree, 3dB bounds shown**
  - Required modifying controller gains & input/output filters
  - Stayed within the required bounds for all loads & at main bus





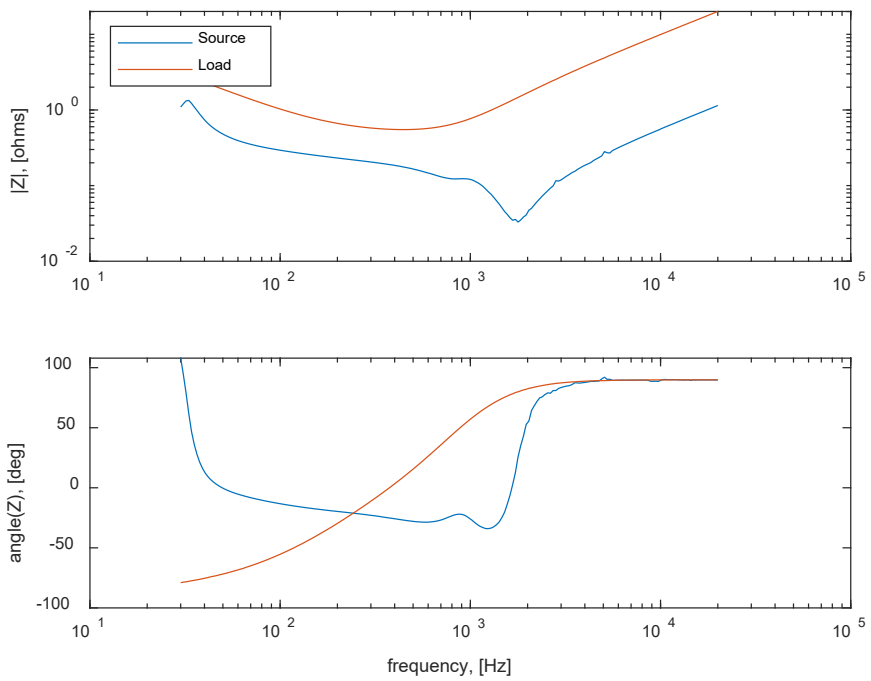
|Zs/Zl| at Cruise Motor Terminals



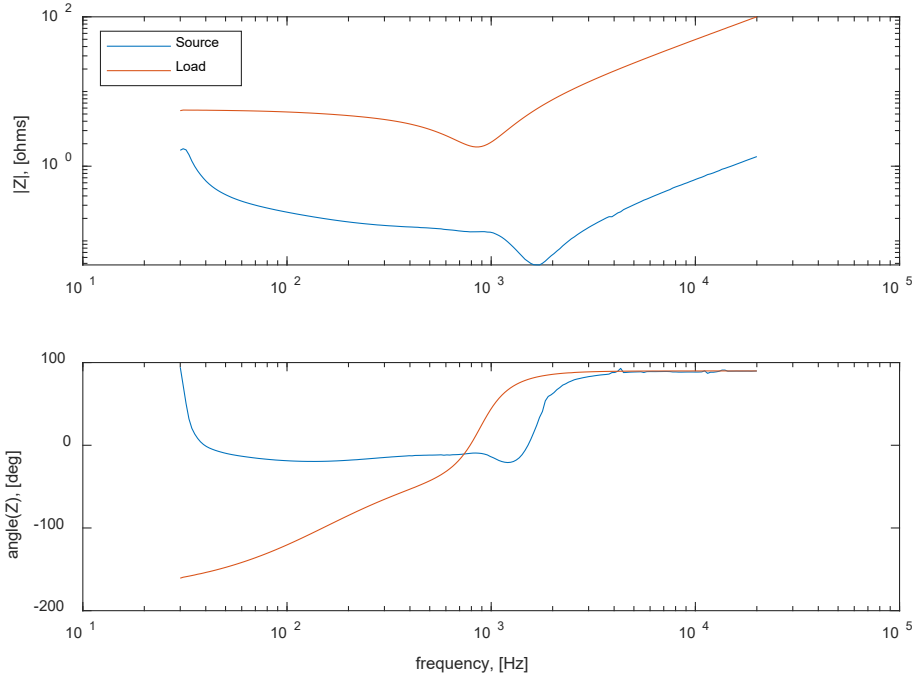
|Zs/Zl| at Lift Motor 8 Terminals

Small Signal Stability (cont.)

- **Source and Load Complex Impedance Plots**



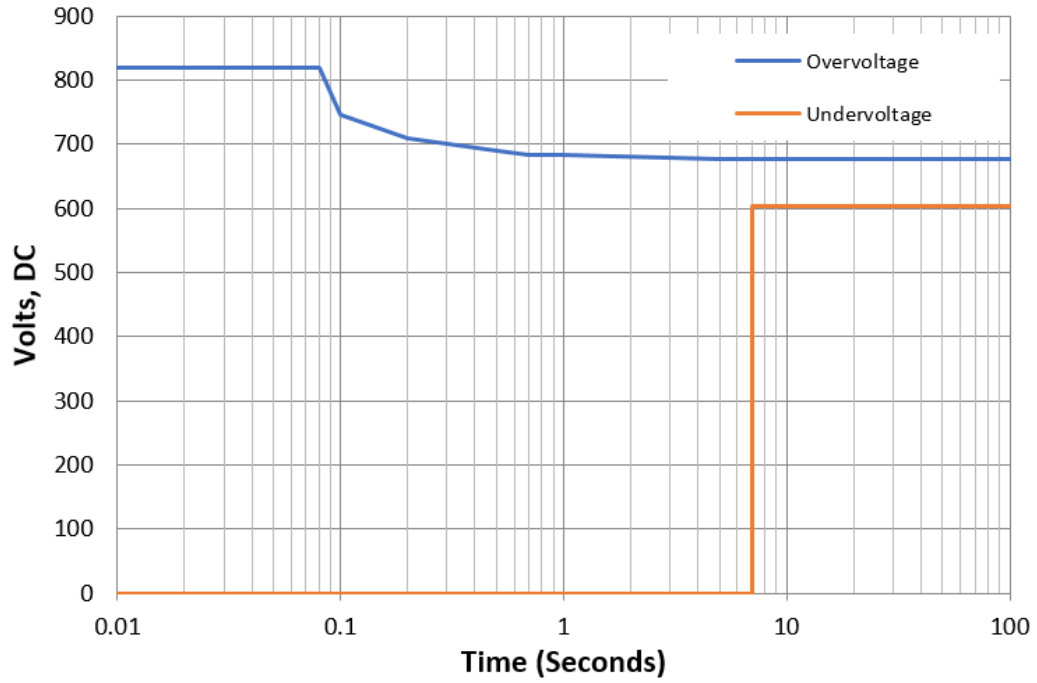
Cruise Motor



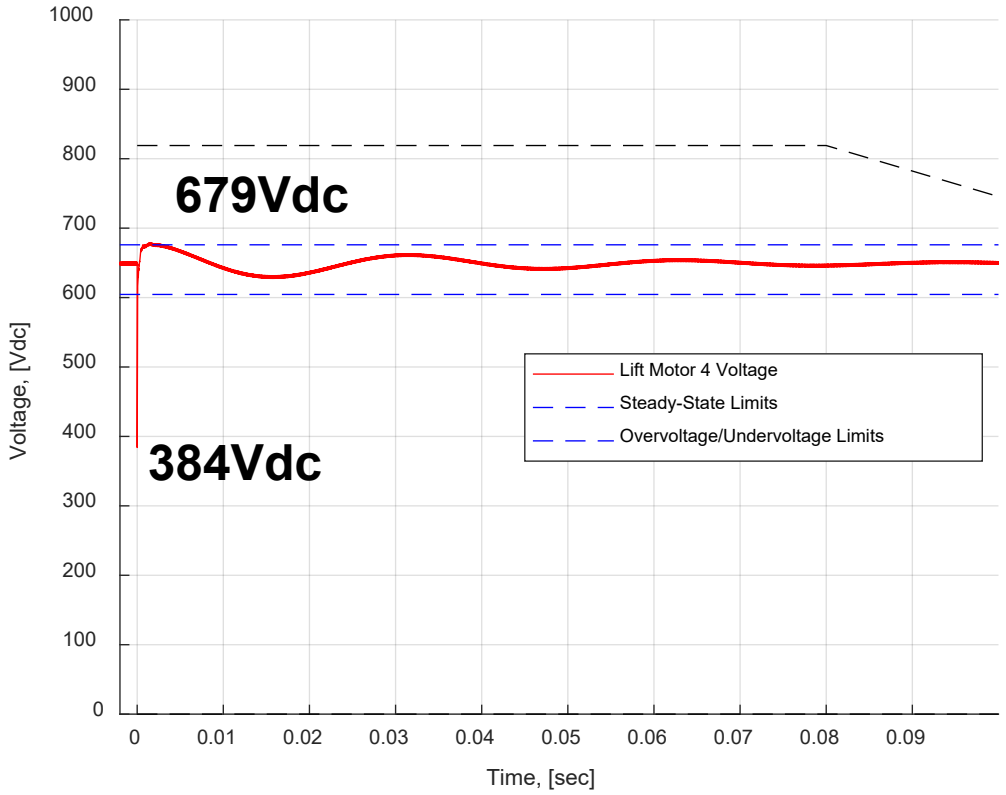
Lift Motor 8

Abnormal Voltage Response

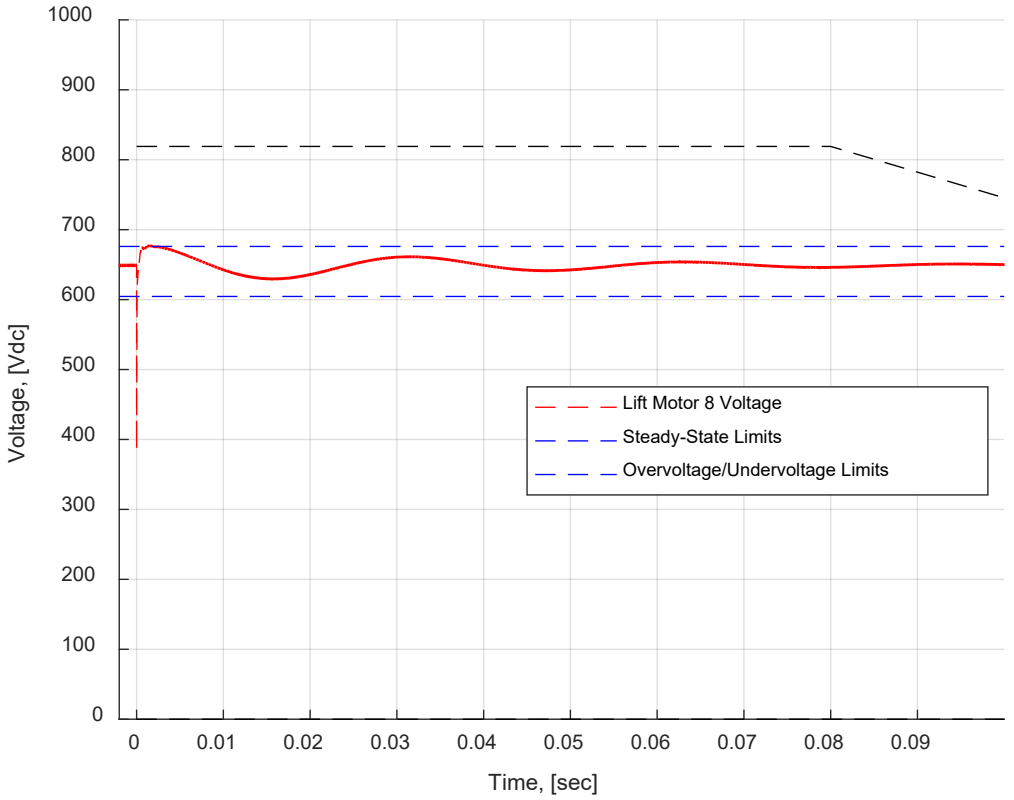
- **Requirement: EPS Transient Voltage must stay within the over- and under-voltage limits shown in event of a fault**
  - **Introduced short circuit faults onto Lift Motor branch circuits**
  - **Observed lift motor terminal voltages on unfaulted branch circuits**
  - **Spikes <10usec ignored**



Abnormal Voltage Response (cont.)



Lift Motor 4 UE Terminal Voltage
Fault Initiated/Cleared on Branch Circuit 8



Lift Motor 8 UE Terminal Voltage
Fault Initiated/Cleared on Branch Circuit 4

Conclusion and Future Work

- **Designed and Tuned 650Vdc, <1MW UAM Power System**
- **Met Internal PQS Requirements**
- **Normal and Abnormal Response Data to provide point design for standards development**
- **Future Work**
  - Currently analyzing soft faults (may require updates and re-evaluation)
  - De-tuning filters to analyze marginal stability
  - Analyze different fault strategies / responses
  - Introduce cross-tie and analyze bus recovery & other PQ metrics