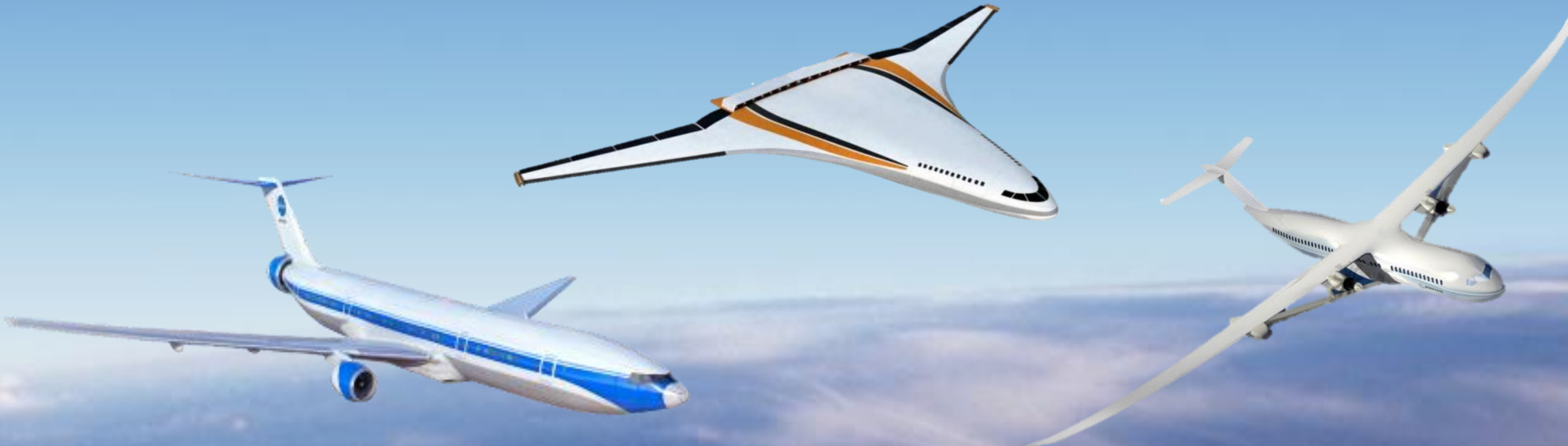

NASA Electric Aircraft Testbed Single-Aisle Transport Air Vehicle Hybrid Electric Tail-Cone Thruster Powertrain Configuration and Test Results

July 12, 2018

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Hybrid Gas Electric Propulsion Technical Lead
NASA Glenn Research Center

What is NASA Electric Aircraft Testbed (NEAT)?

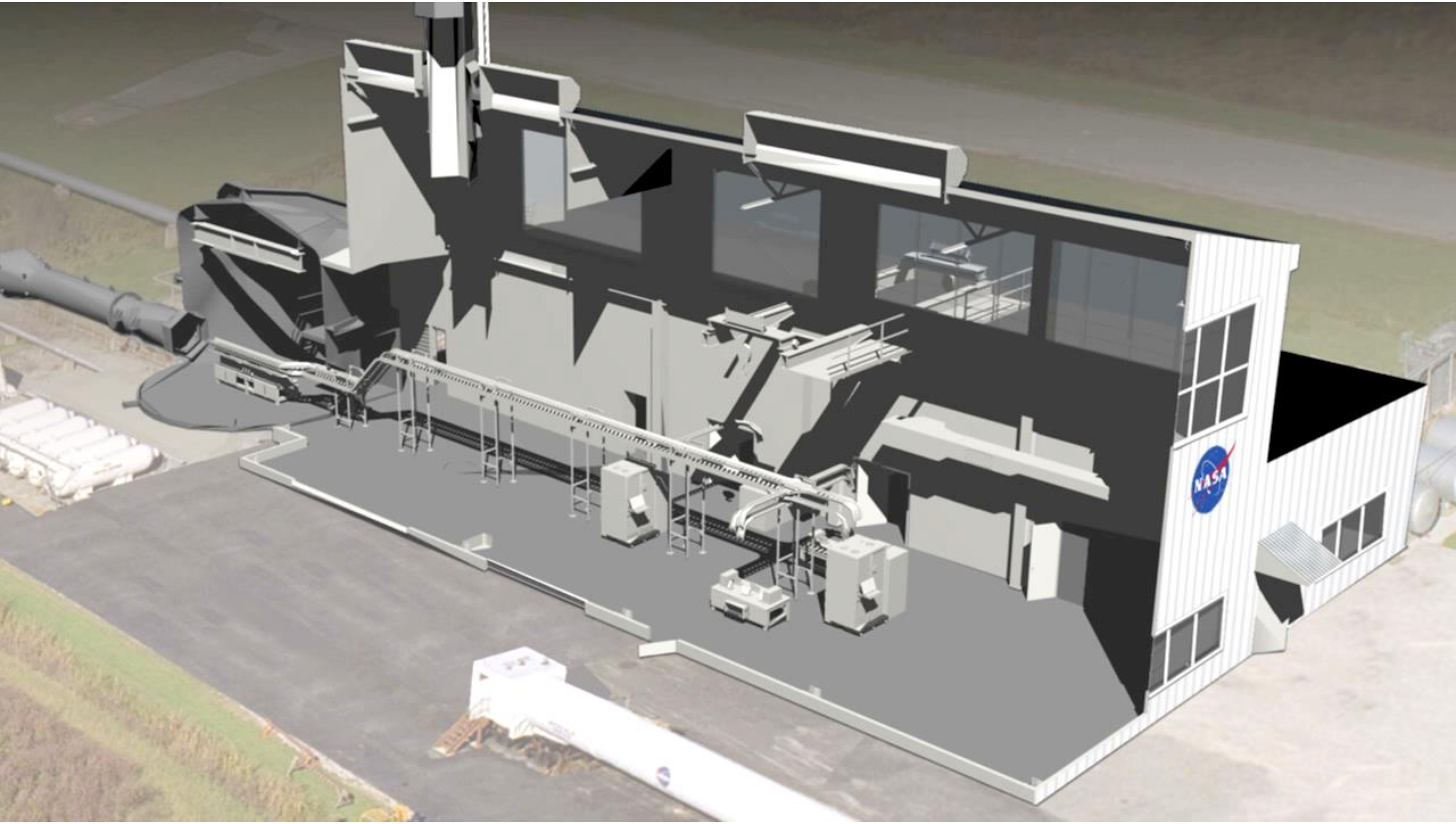
Reconfigurable Powertrain Testbed

- Located at NASA Glenn Plum Brook Station in the recently refurbished Hypersonic Tunnel Facility (HTF)
- Full-scale powertrain testing under actual flight scenarios
- Can support cryogenic fuel, high voltage, large wingspan, electromagnetic interference, and high power research h/ware

Planned Testing at NEAT

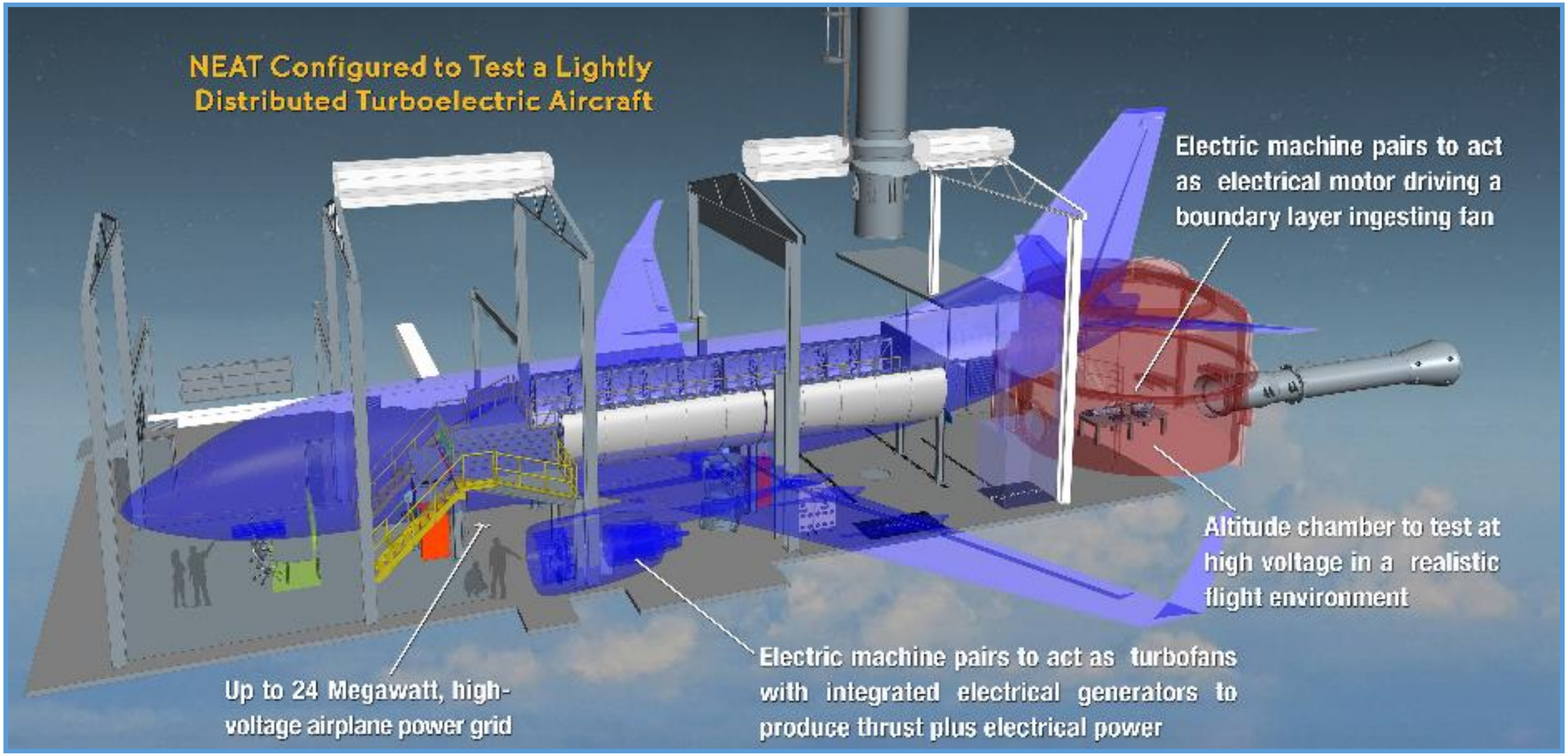
- Phased approach with ~1 aircraft configuration per year (goal)
- **Initially COTS, ambient**
  - **TRL maturation of:**
    - **High voltage bus architecture** – Insulation, geometry, 600V up to 4500V
    - **High power MW Inverters, Rectifiers**- Commercial, In-House, NRAs
    - **High power MW Motors, Generators**- Commercial, In-house, NRAs
    - **System Communication** – Aircraft CAN, Ethernet, Fiber-optics
    - **System EMI Mitigation and Standards** – Shielding, DOD-160, MIL-STD-461
    - **System Fault Protection** – Fuse, Circuit Breaker, Current Limiter
    - **System Thermal Management** – Active/Passive, Ambient/Cryo, Distributed/Mixed

NASA Electric Aircraft Testbed (NEAT)

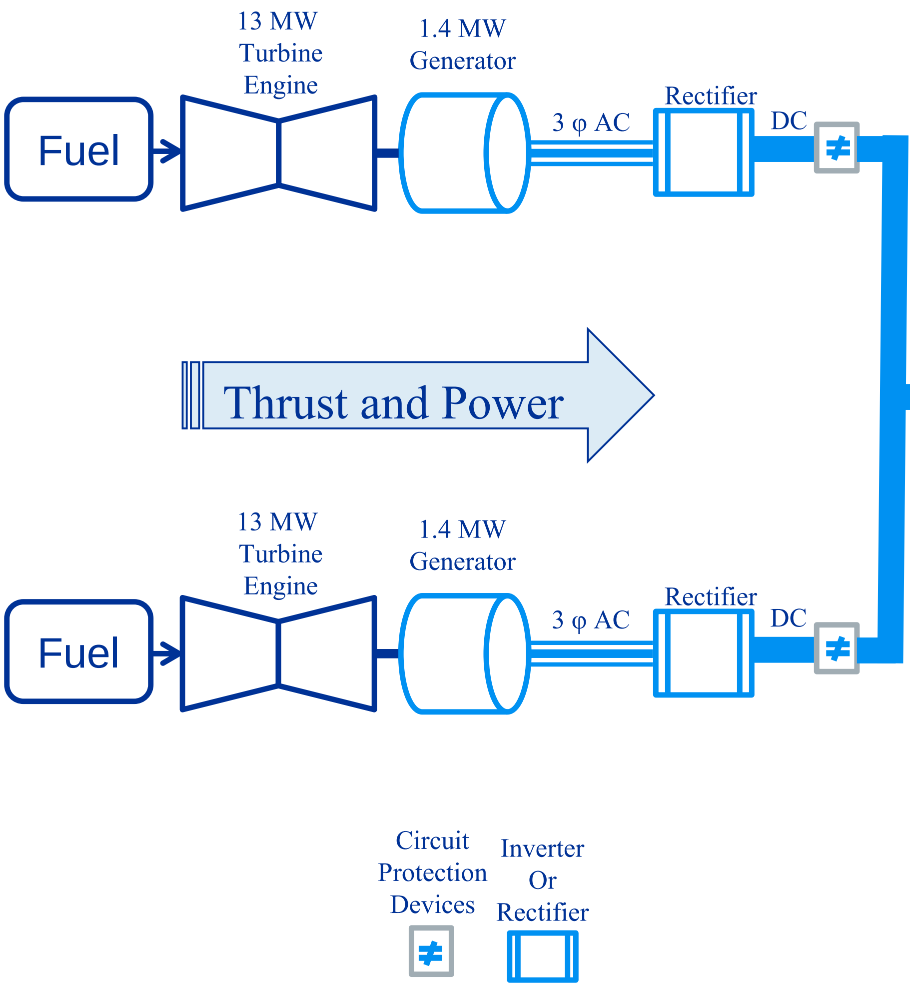


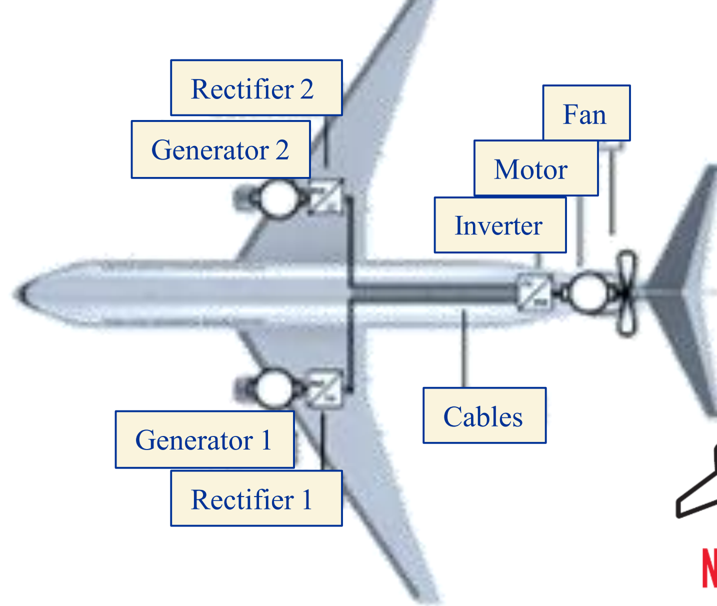
NASA Electric Aircraft Testbed (NEAT)

- Reconfigurable testbed to support full-scale large aircraft powertrain testing
- Plans to demonstrate high fidelity turbo-generation and ducted fan transient emulation and to test MW-class research motors, inverters, and powertrains



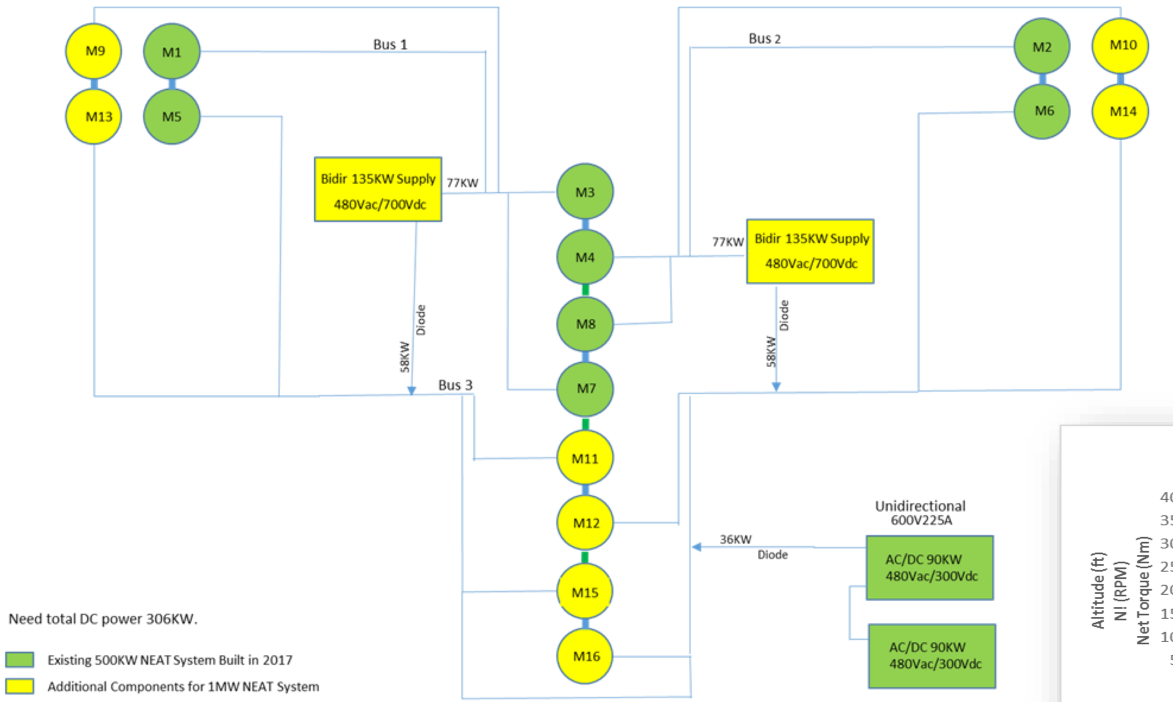
STARC-ABL Configuration

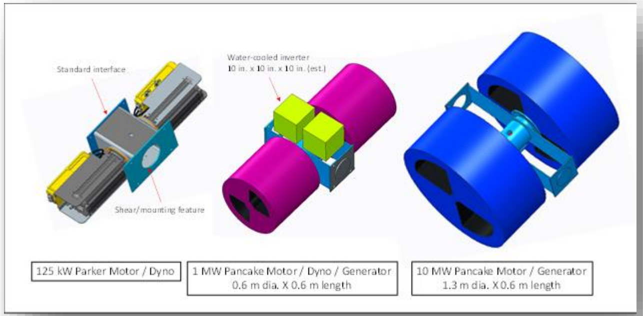


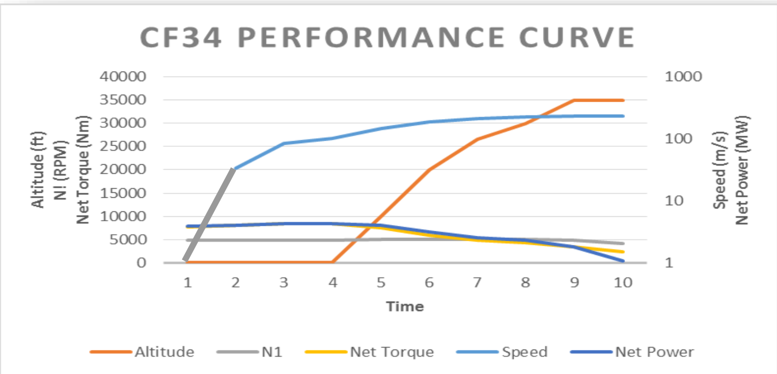


STARC-ABL Motor Pairing

1MW NEAT System With 2-Channel 135KW DC Supplies and an 135KW Unidirectional Supply at 600V

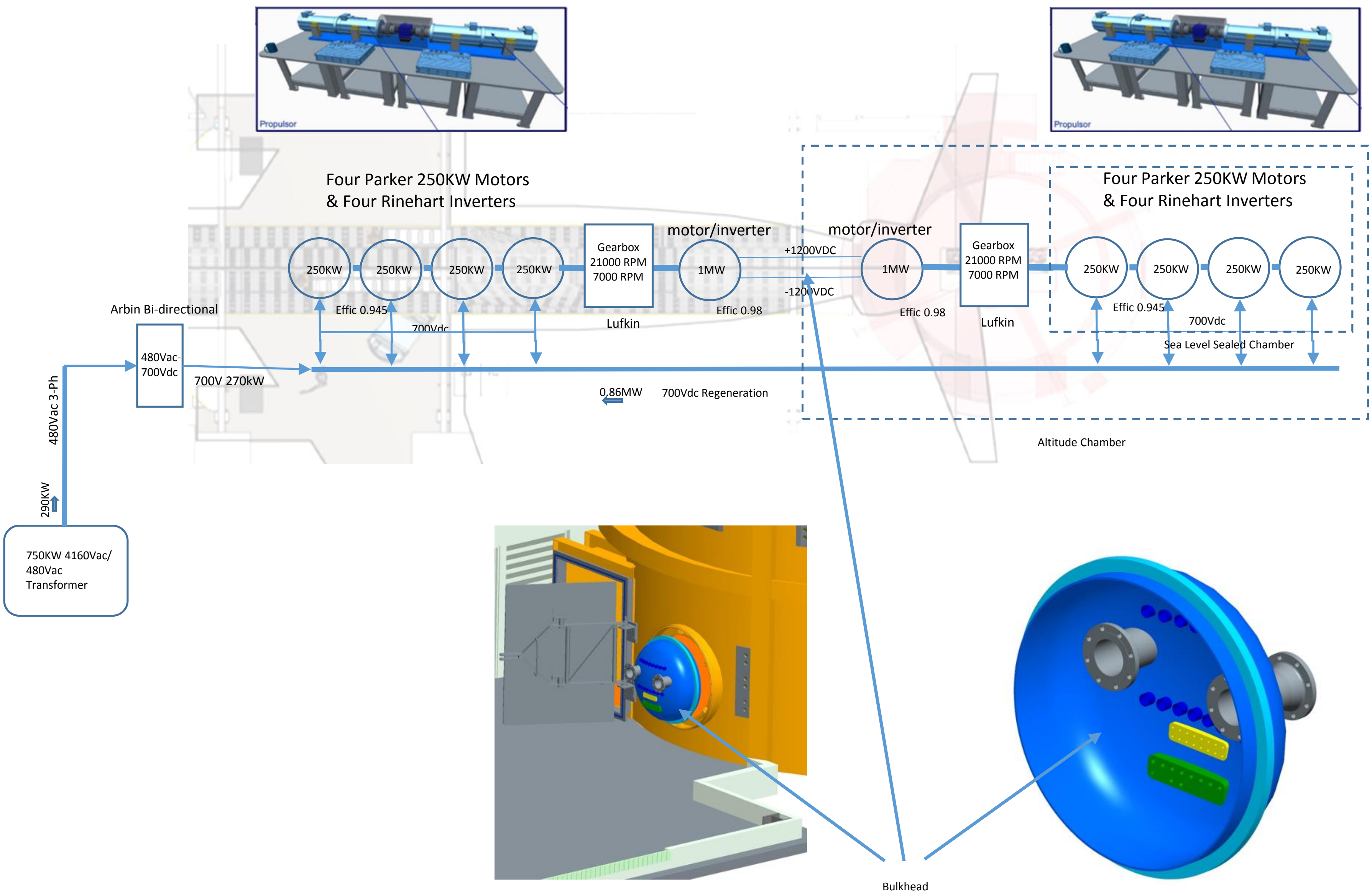




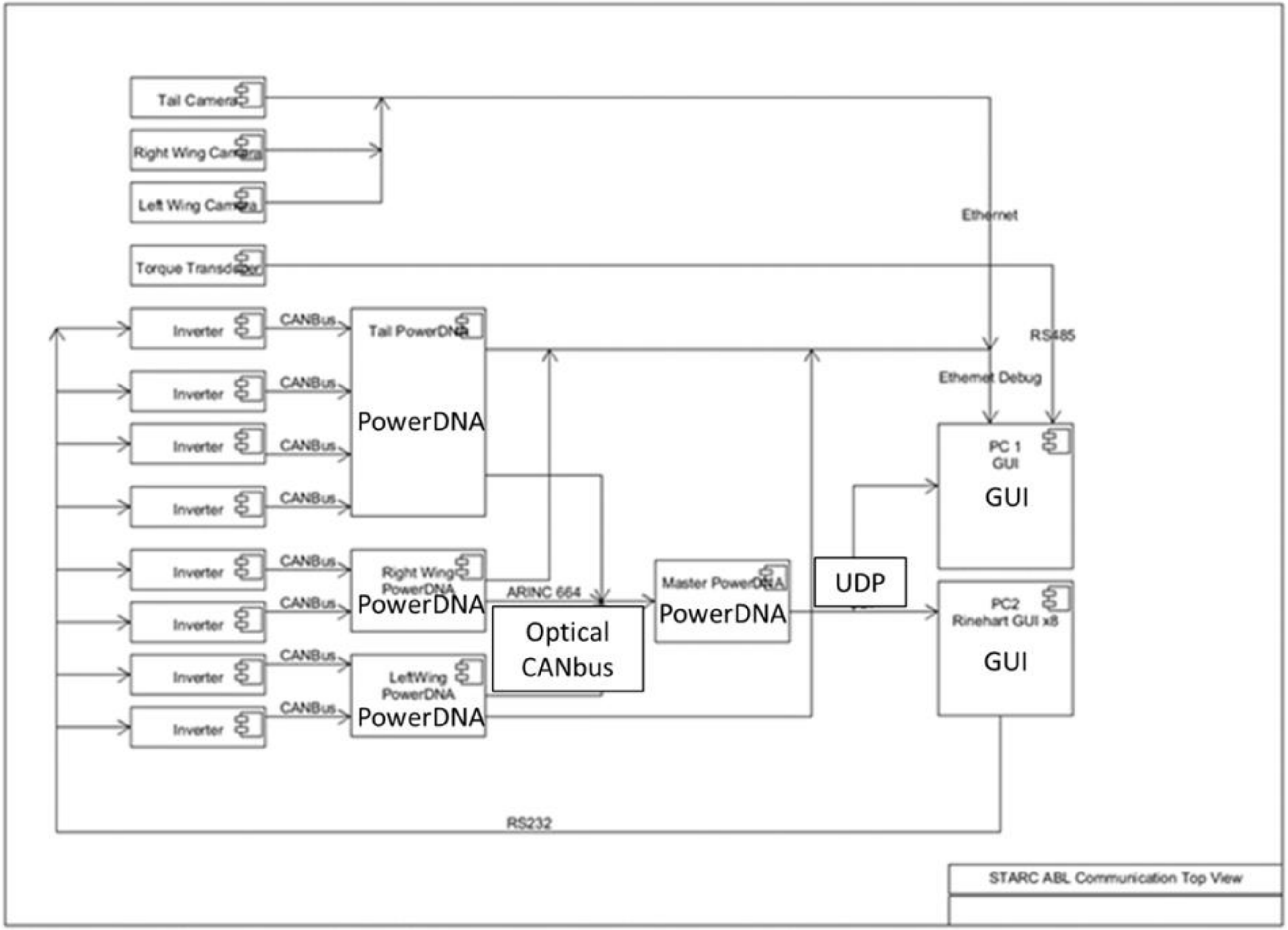


Utilize Speed & Torque Maps under Takeoff, Landing, and Cruise Conditions

Flexible MW-Scale Aircraft Powertrain Altitude Testing

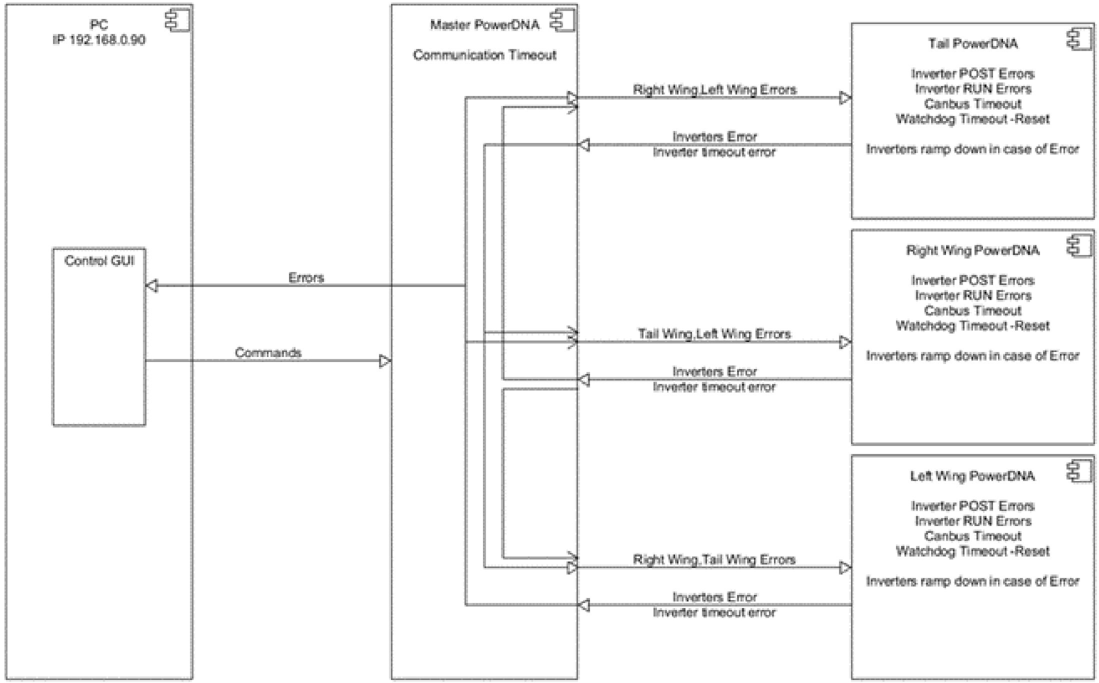


STARC-ABL Communication and Control

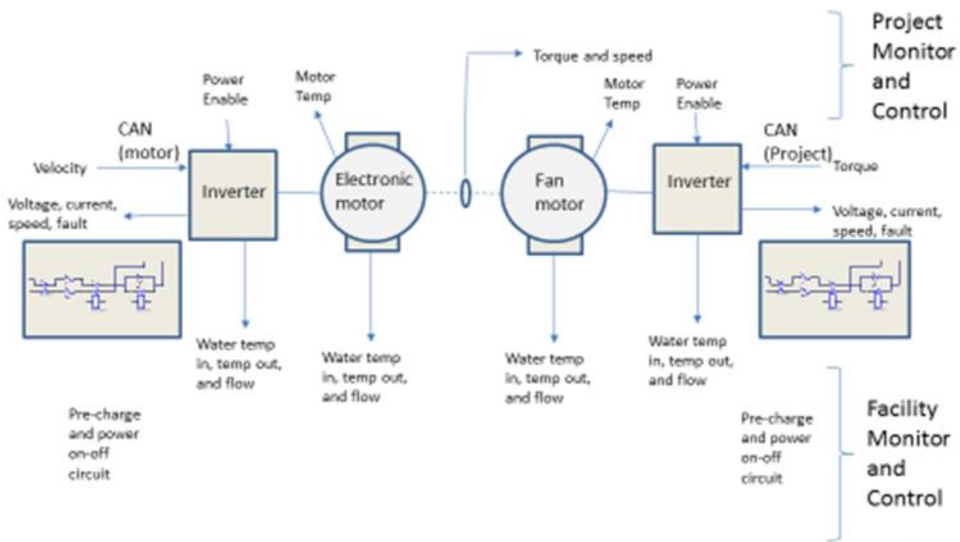


Response, Bandwidth, Shielding, Standards, and Topology

STARC-ABL Error Handling

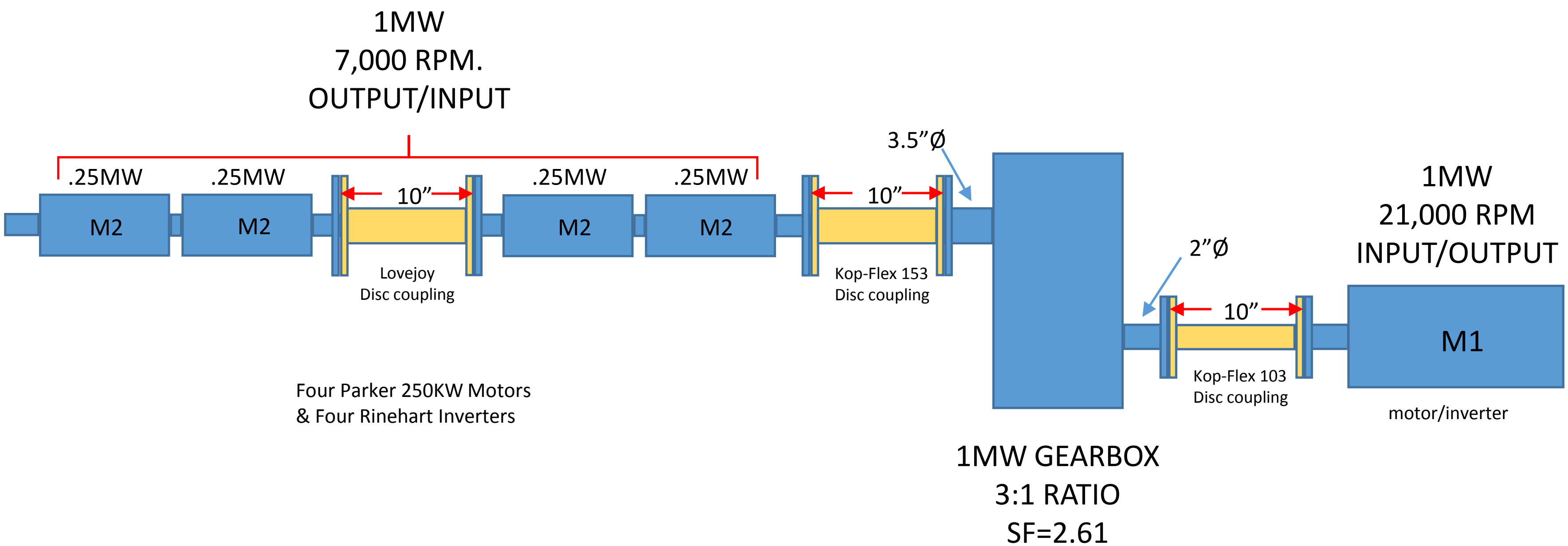


Local hardware control
Global software control



Monitor
T, V, I, RPM, signal, timeouts, and gradients

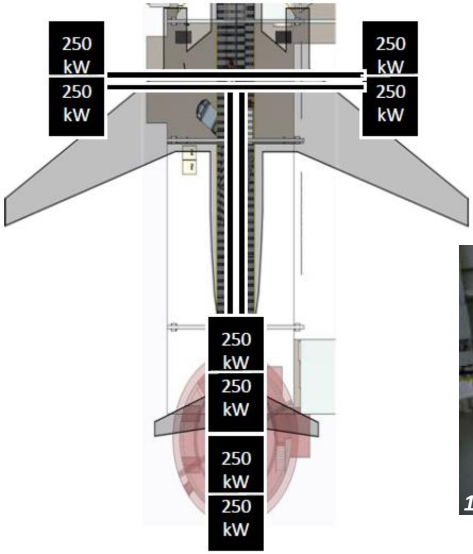
MW Research Motor Gearbox Connection to Facility Motors



Interfacing facility speed and voltage with aircraft research bus voltage and machine speed

Single-String and STARC-ABL Powertrain Configurations

Inside Altitude Chamber



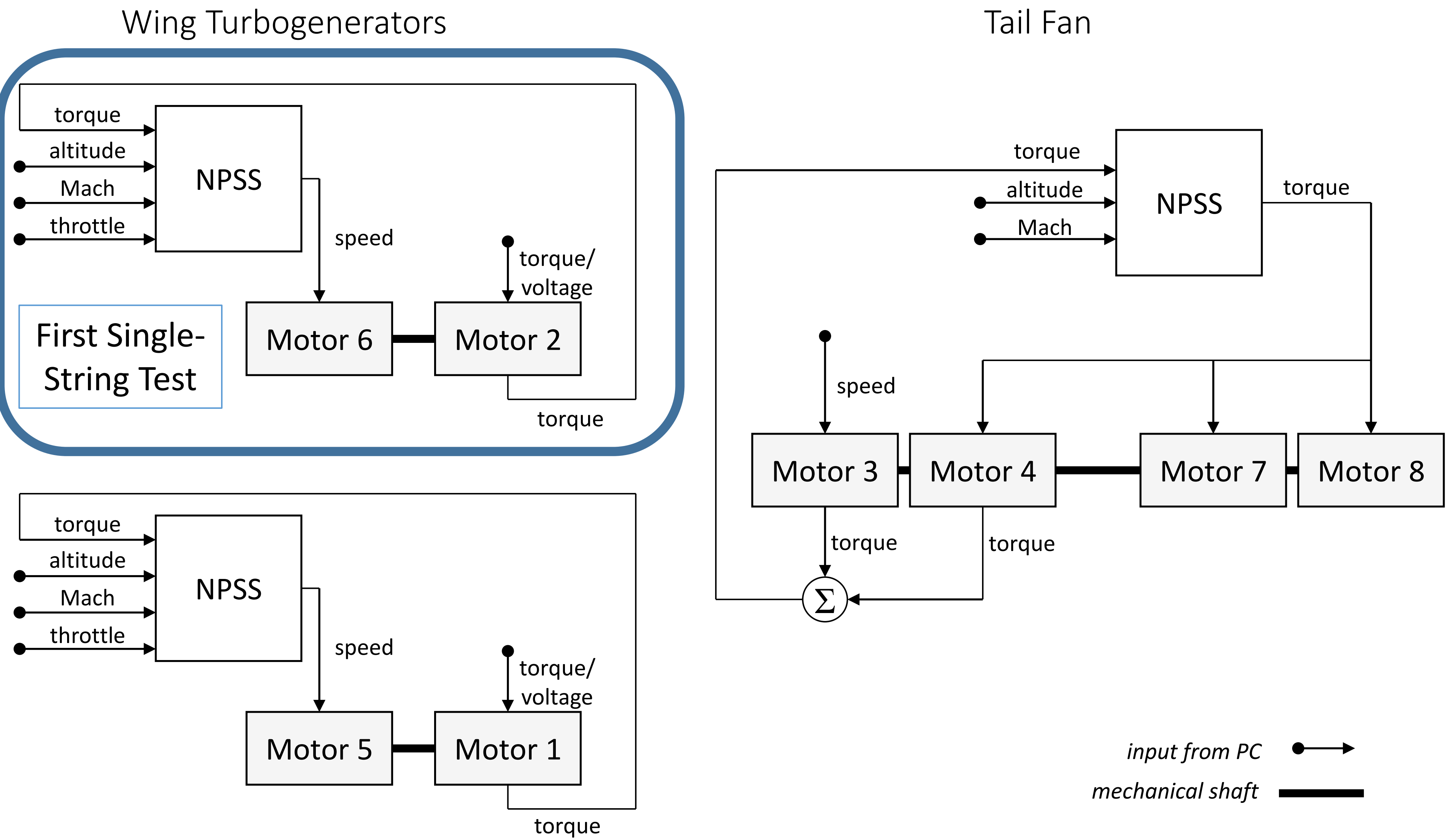
500 kW STARC-ABL Configuration

125kW Single-String

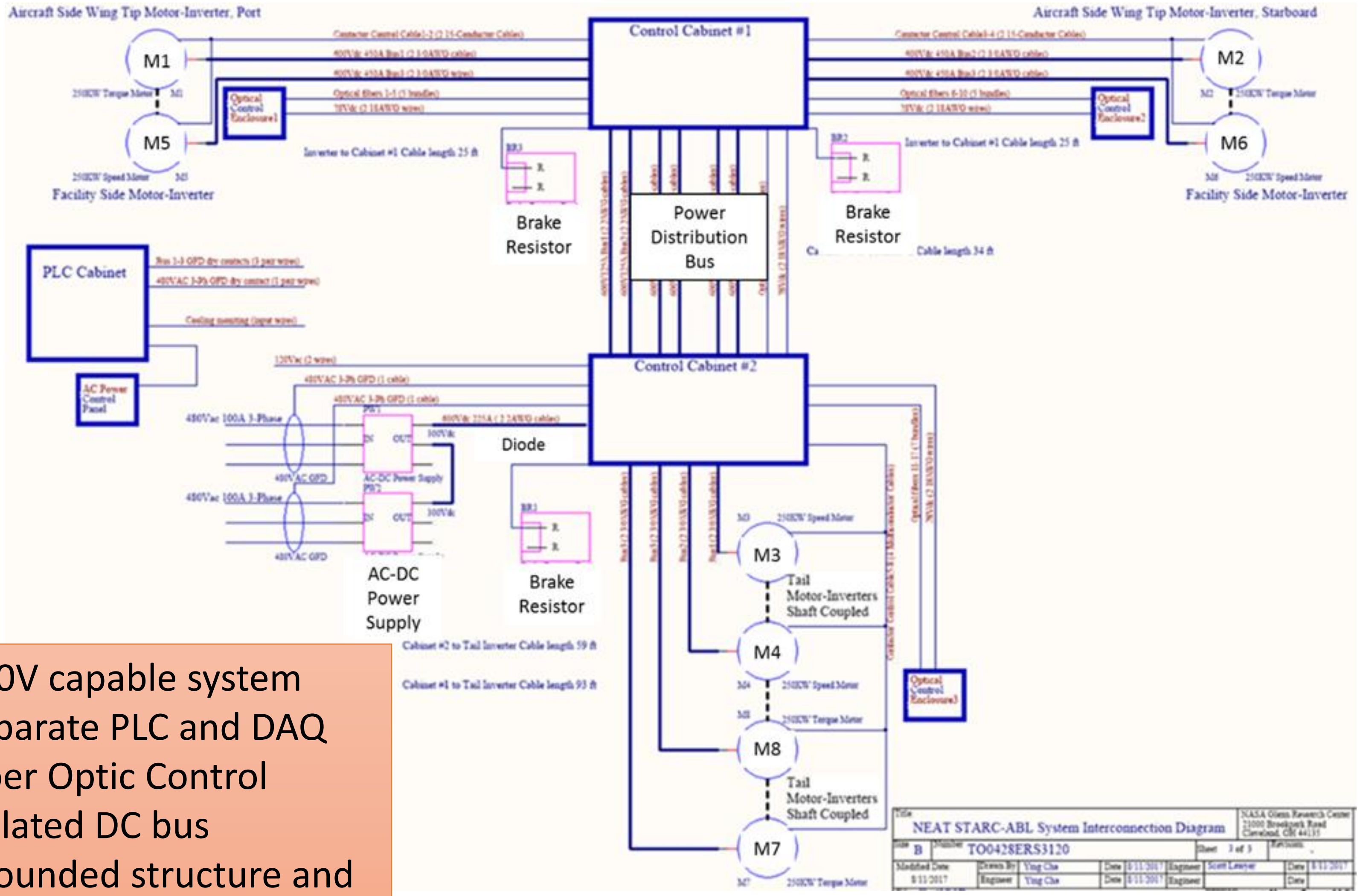
Commencement of Testing for 500 kW STARC-ABL

Full-scale Boeing 737-800 Powertrain Layout for EMI, thermal, impedance, latency, conformity, and reflections

NEAT NPSS Control Strategy

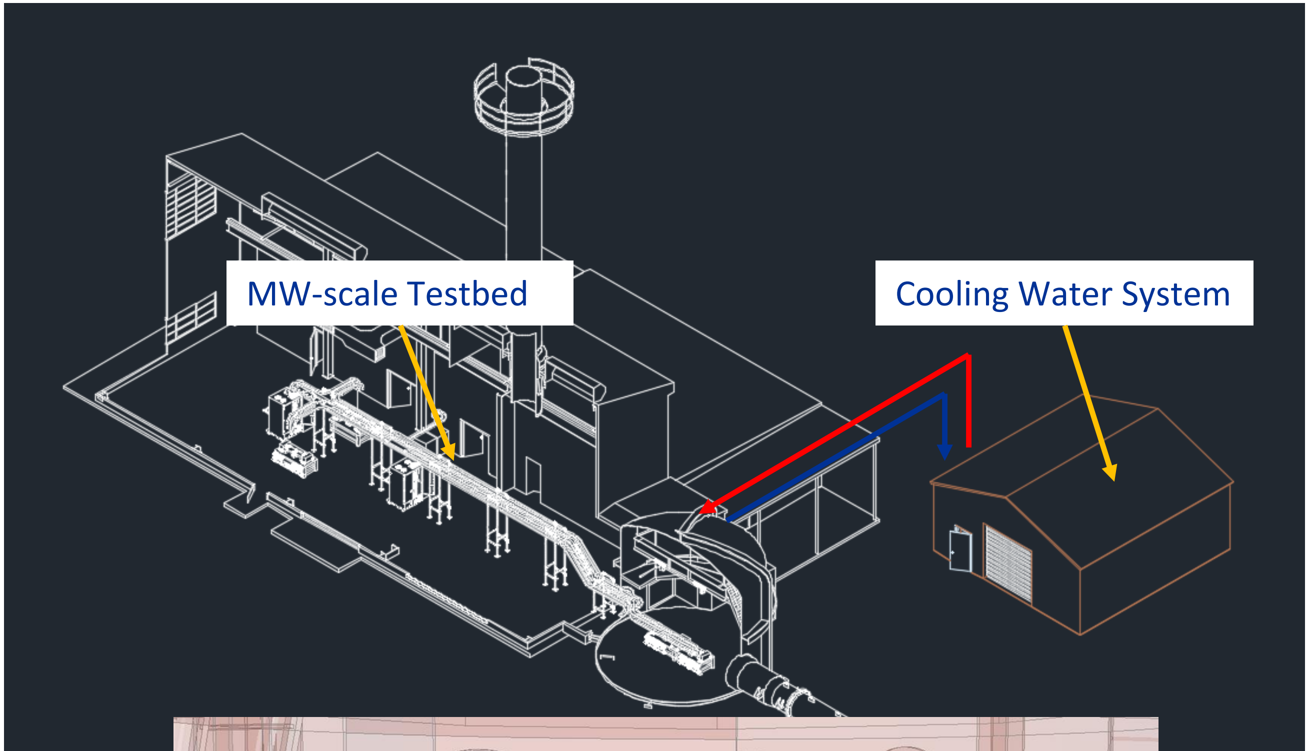


Current 500 kW STARC-ABL System Interconnections

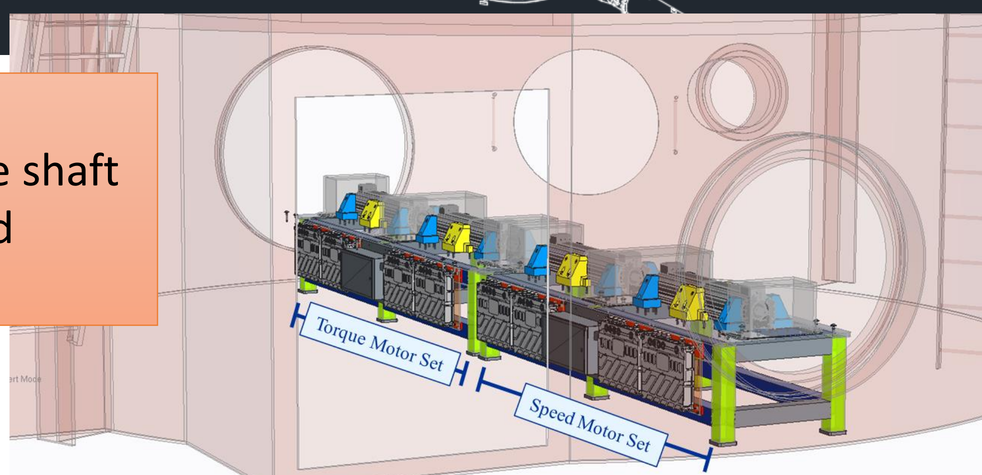


- 700V capable system
- Separate PLC and DAQ
- Fiber Optic Control
- Isolated DC bus
- Grounded structure and shielding through glands
- All COTS

Flexible Dual-Shaft Motor Integration for MW-Scale

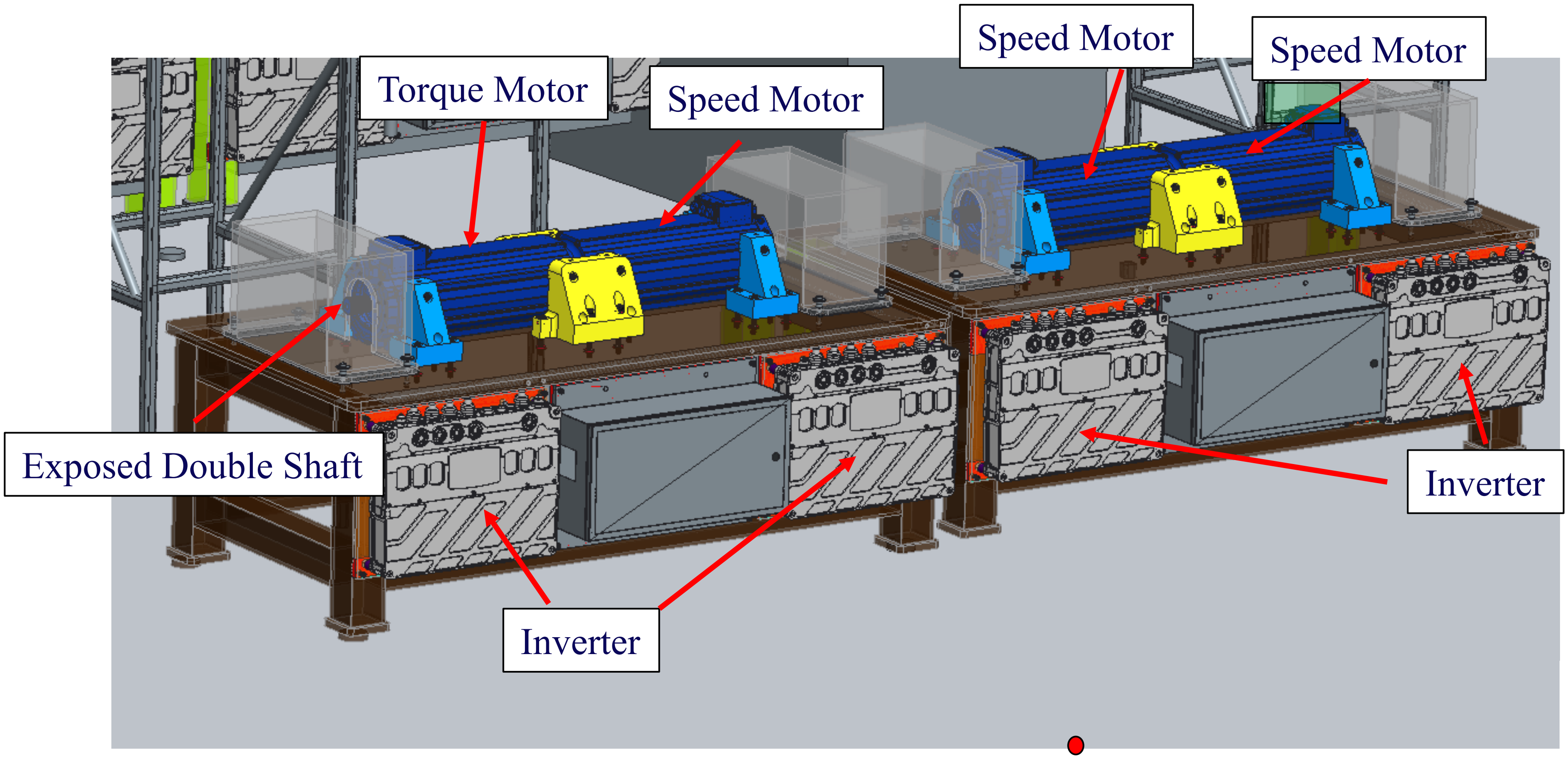


- Multiple 250kW machines on single shaft
- For cost-saving and reconfigurability

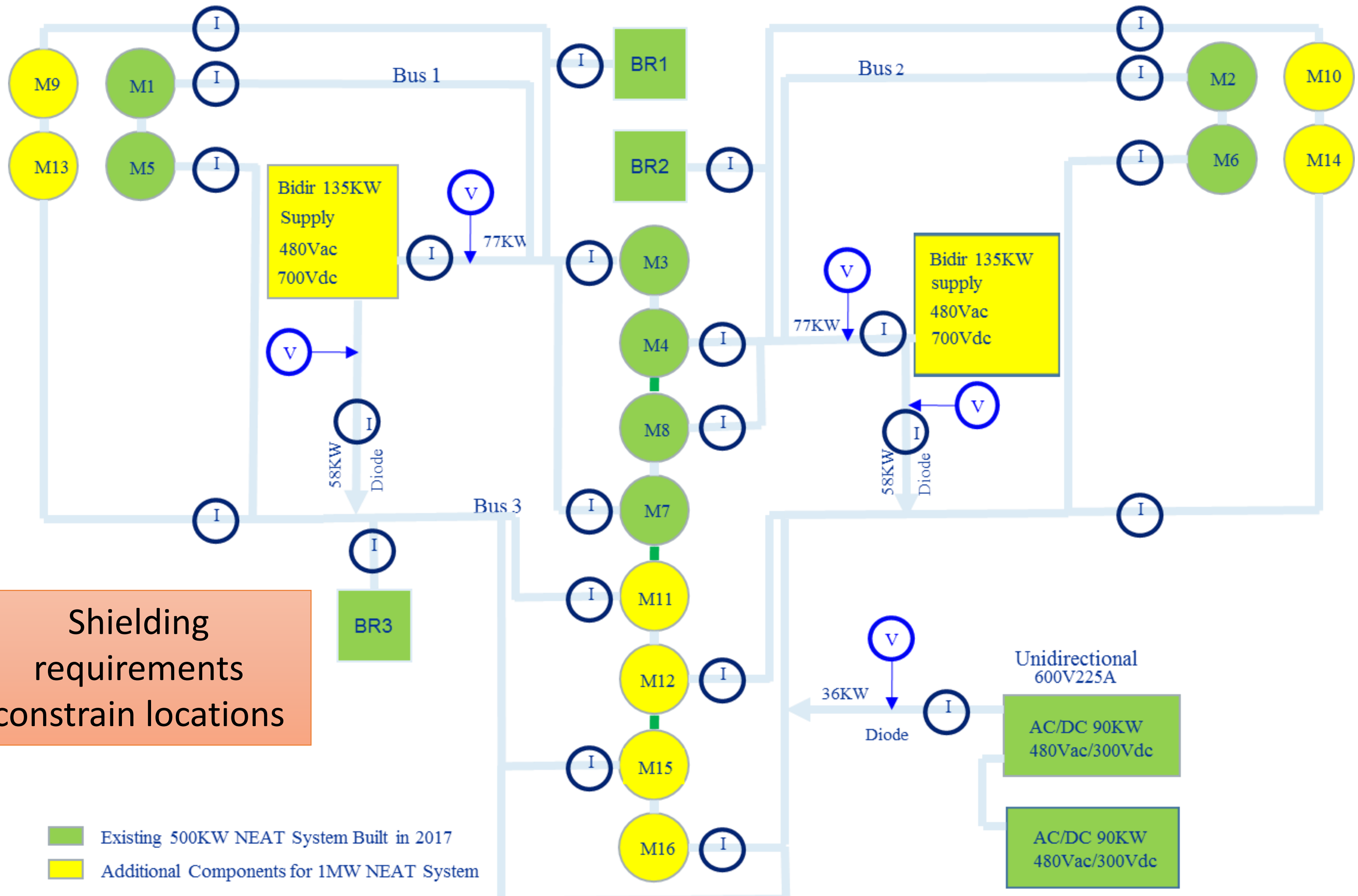


500 kW Motor and Ducted Fan Emulation

Provide actual dynamic altitude conditions up to 50,000 feet while also providing actual loading via NPSS real-time emulated ducted fan

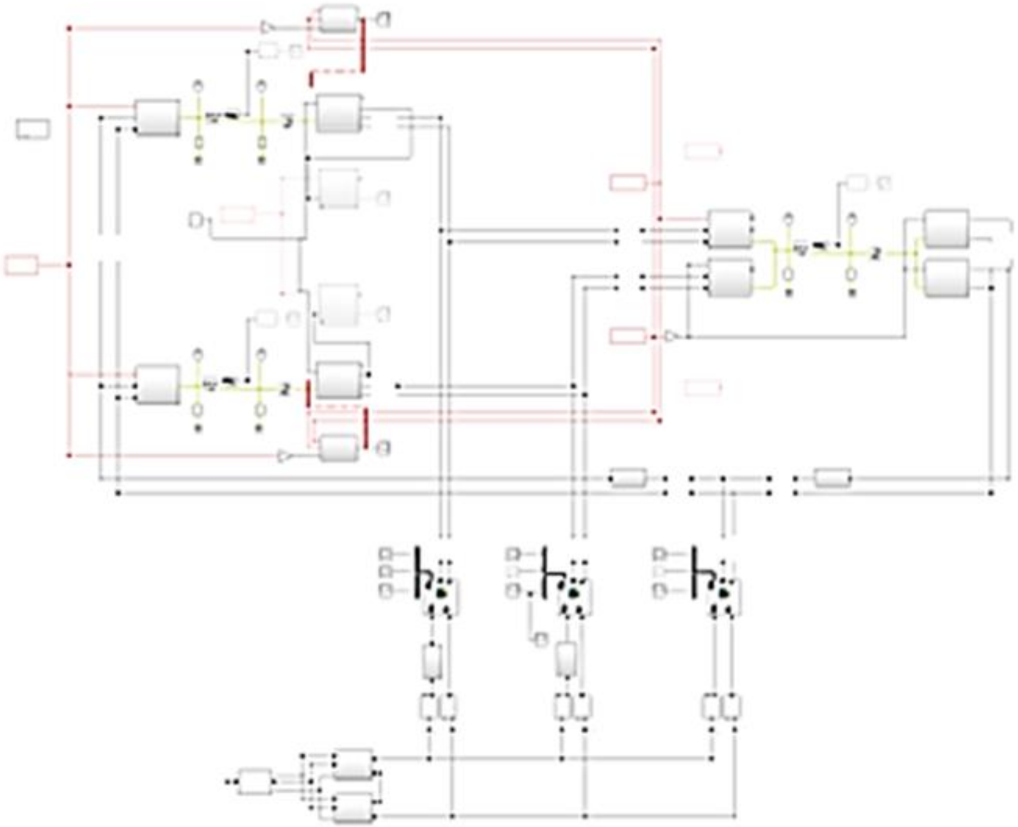


Instrumentation Challenges and Implementation



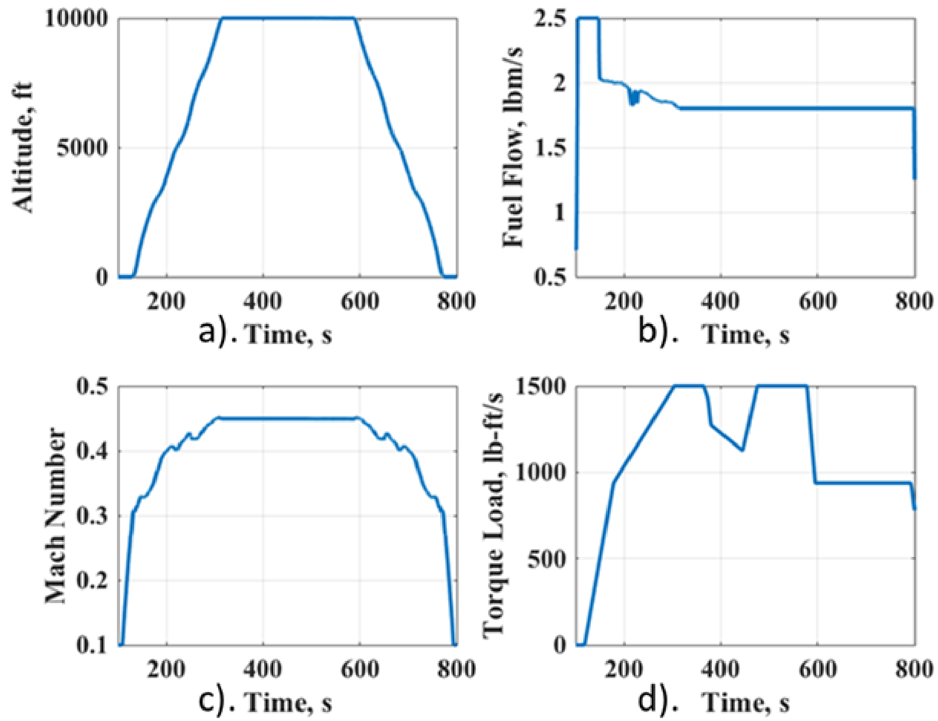
Shielding requirements constrain locations

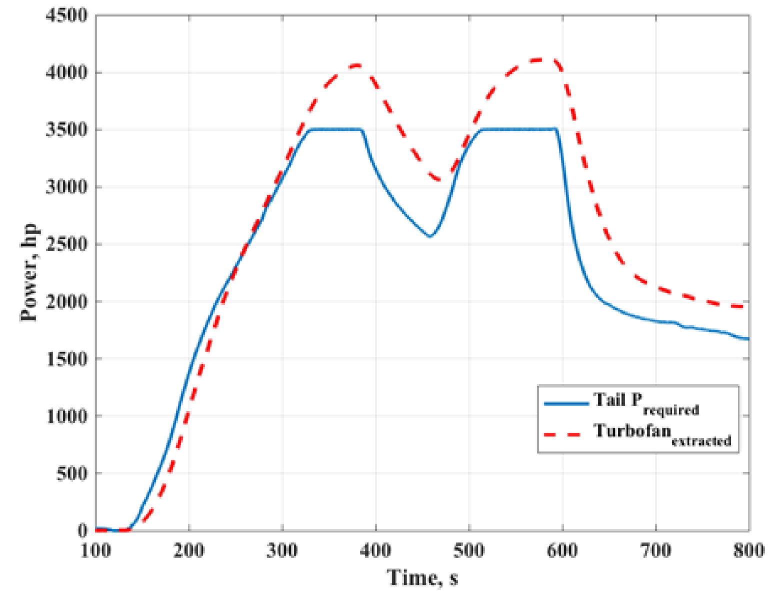
Dynamic Power System Model



- NPSS – S-Code – Matlab/Simulink/Simpowersystems Powertrain Model
- Scaled torque and inertia terms for dynamic similitude
- T-MATS compatibility
- High-speed Dewesoft DAQ for validation

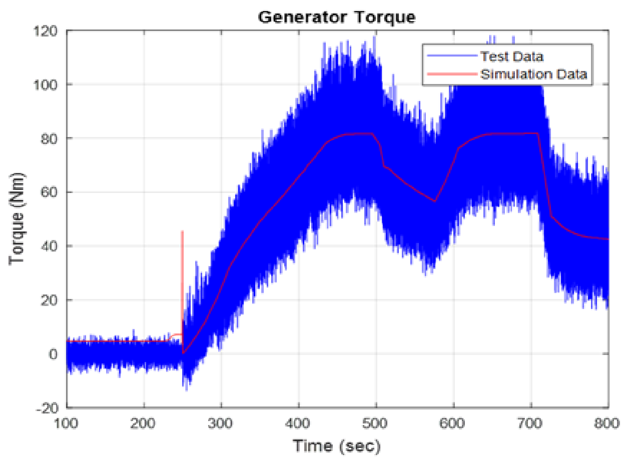
Flight Profile for NPSS Testing

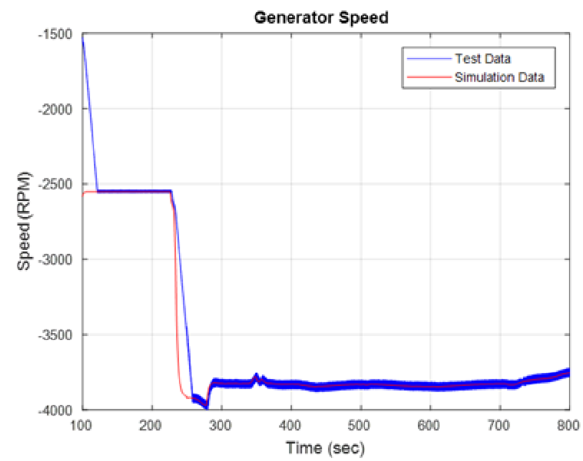


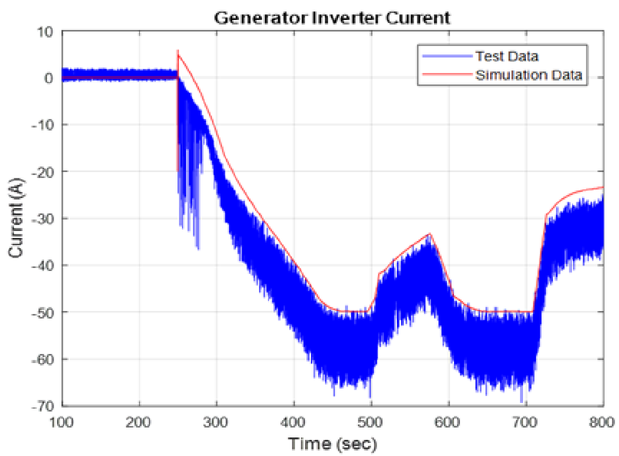


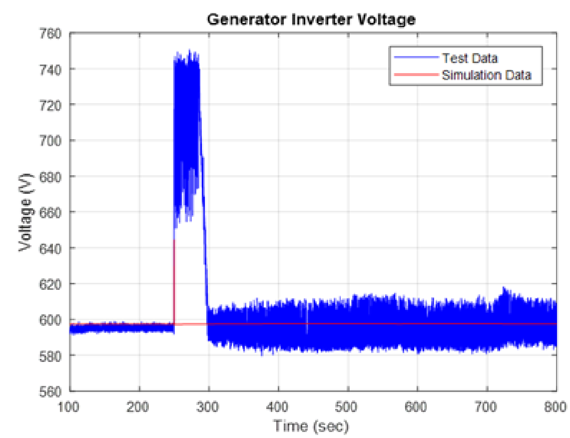
- Representative profile to compare NPSS controls at NEAT
- Note delay in power required to power extracted due to communication delays

Generator M1 Model Validation



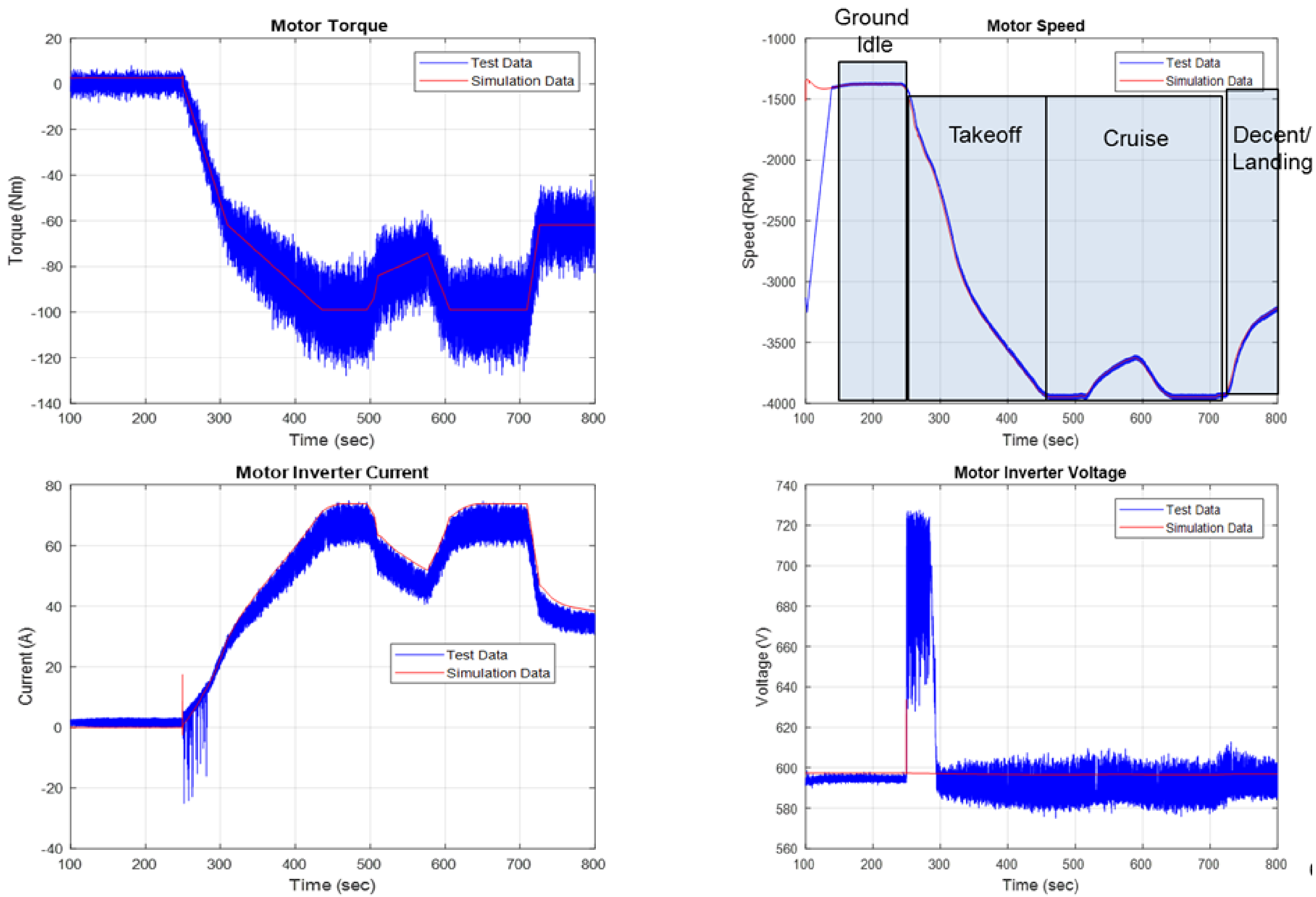






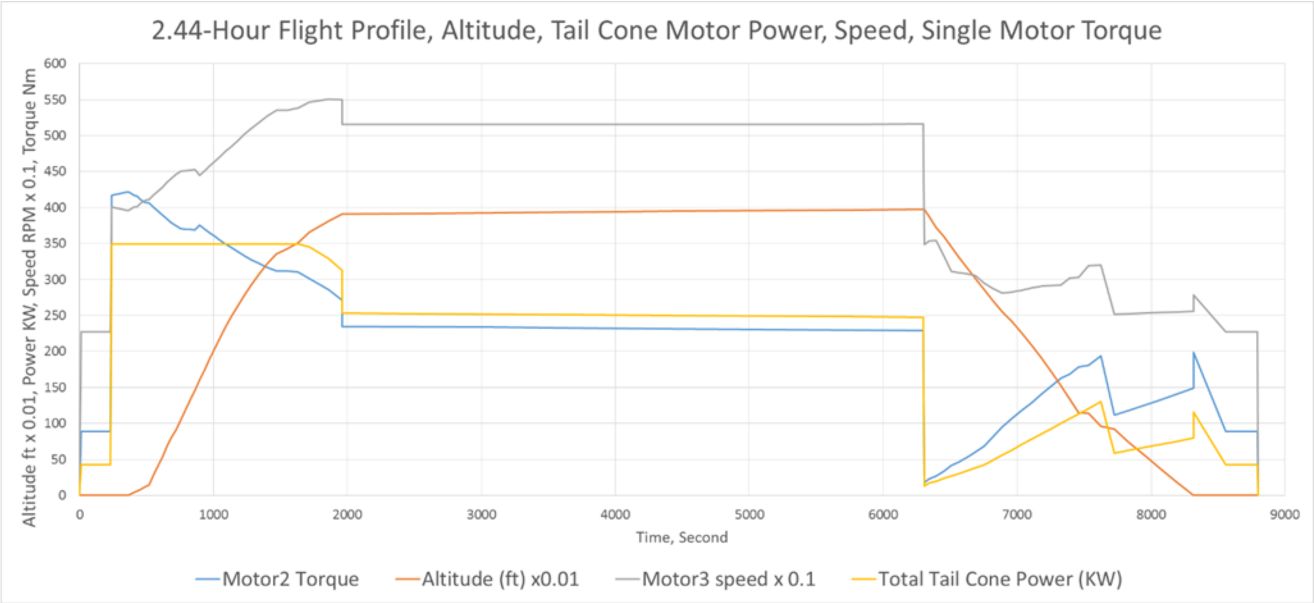
Very good agreement between predicted model data and hardware results

Motor M3 Model Validation



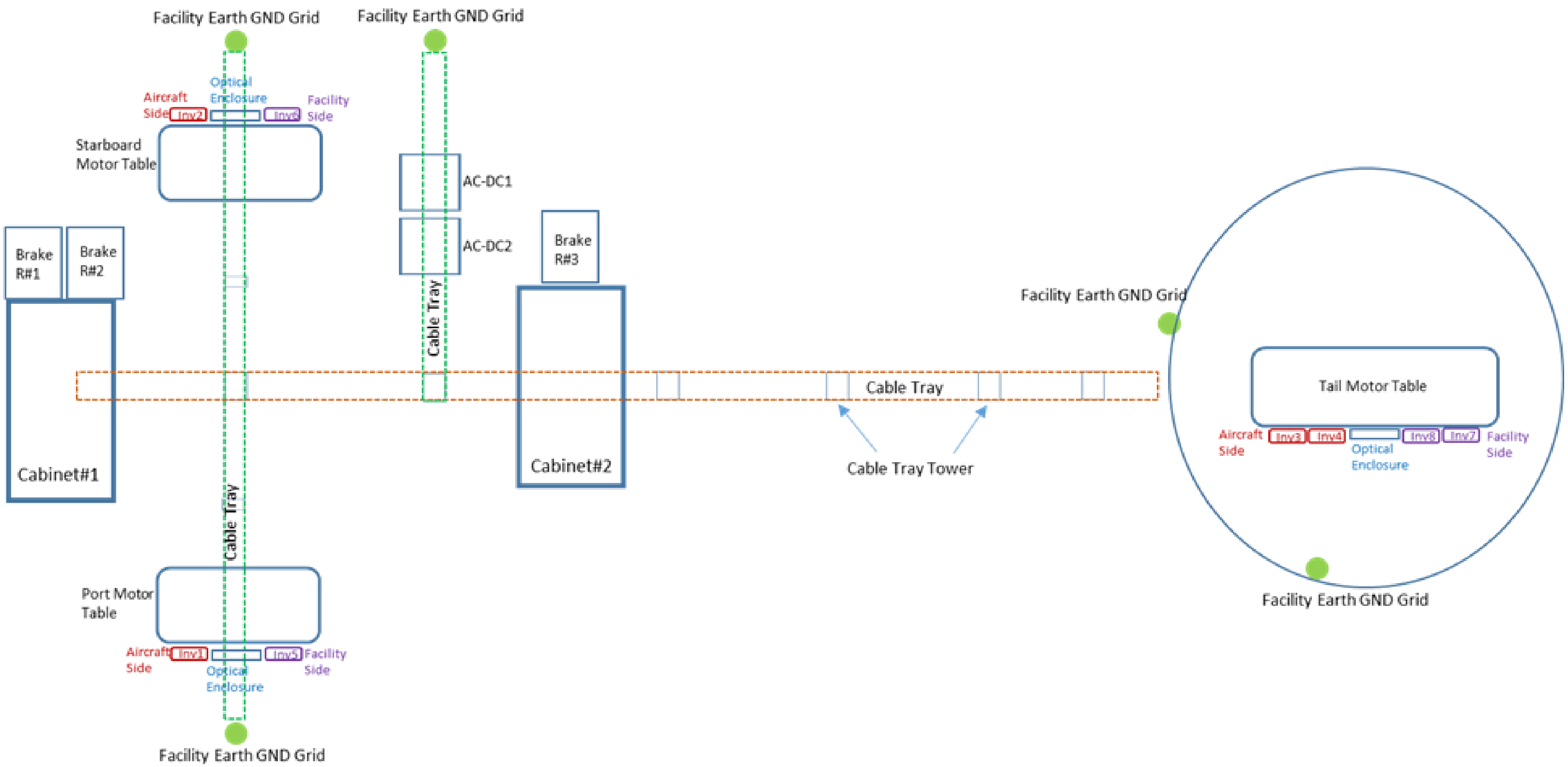
Very good agreement between predicted model data and hardware results

Full STARC-ABL Flight Profile – 900 NM



CHALLENGE	MITIGATION
Thermally managing the motors	Changing the coil configuration
Addressing EMI between the controls and inverter	Insuring good shielding contact end-to-end
Load balancing the system	High-speed DAQ
Communication delays	Fiber optics and ARINC 664 Protocol
Bus transients and power quality improvement	Smart energy storage
Fault management with a complex system	Federated detection and control at inverters

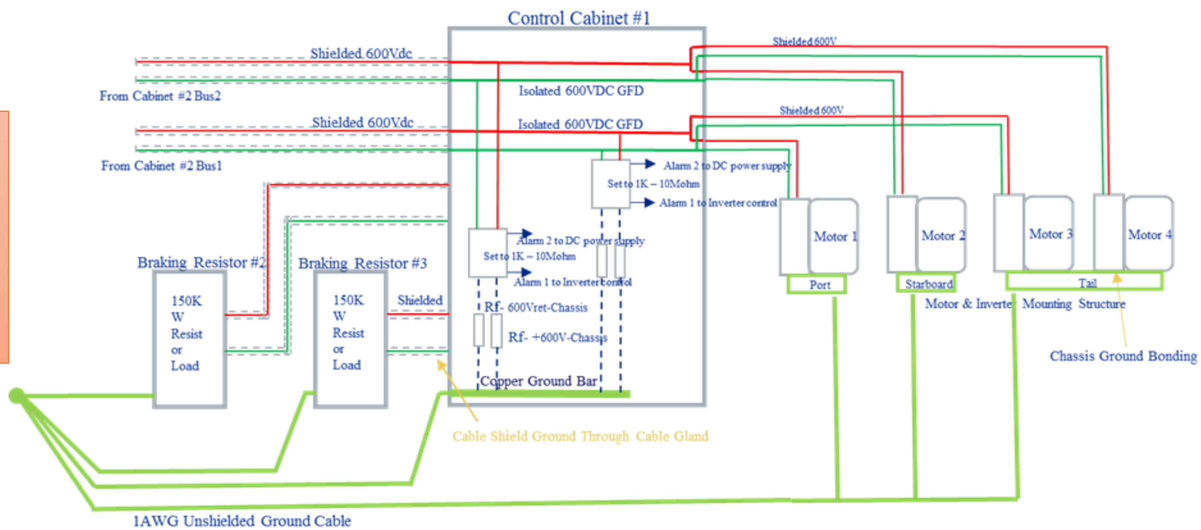
Current 500 kW STARC-ABL System Grounding



Building grounding loop has effective 500 milliohm resistance.
Aircraft standard is closer to 2 milliohm so will modify in the future.

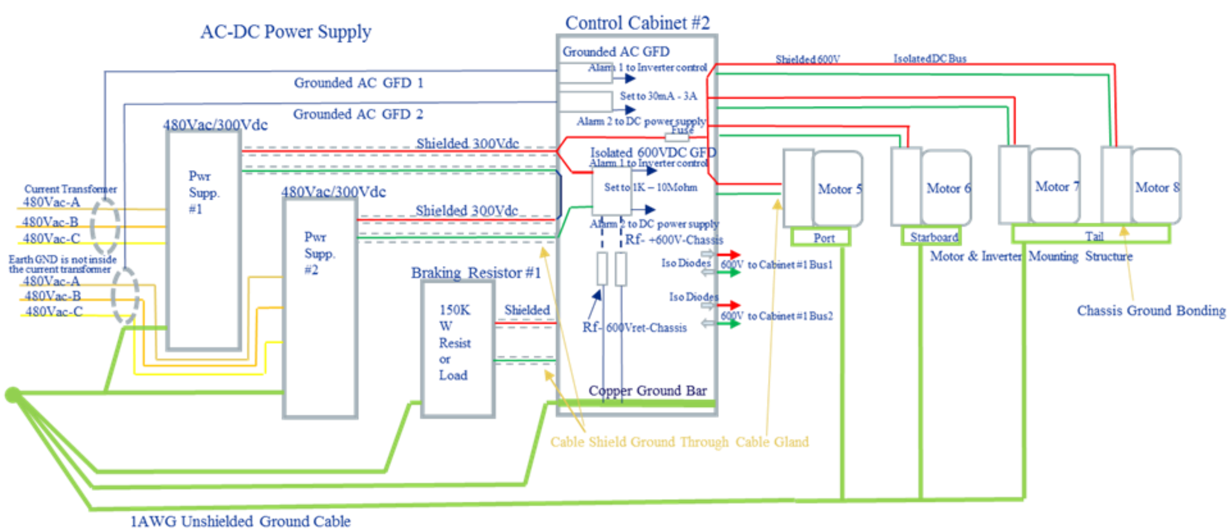
Fault Management

DC Insulation Resistance Monitoring



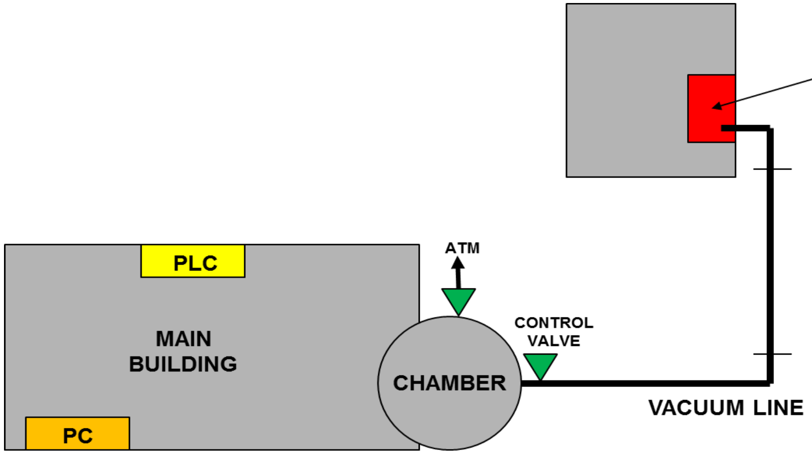
Maintain bus voltage limits with braking resistors and one-way diode power supplies

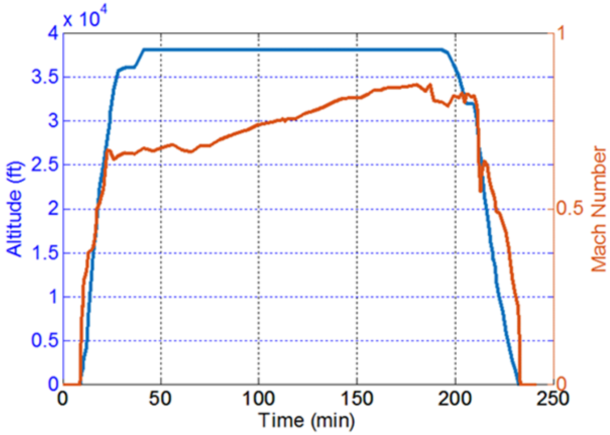
AC Ground Fault Detection



Structure and EMI Shield Grounded

Flight Altitude Powertrain Component Capability

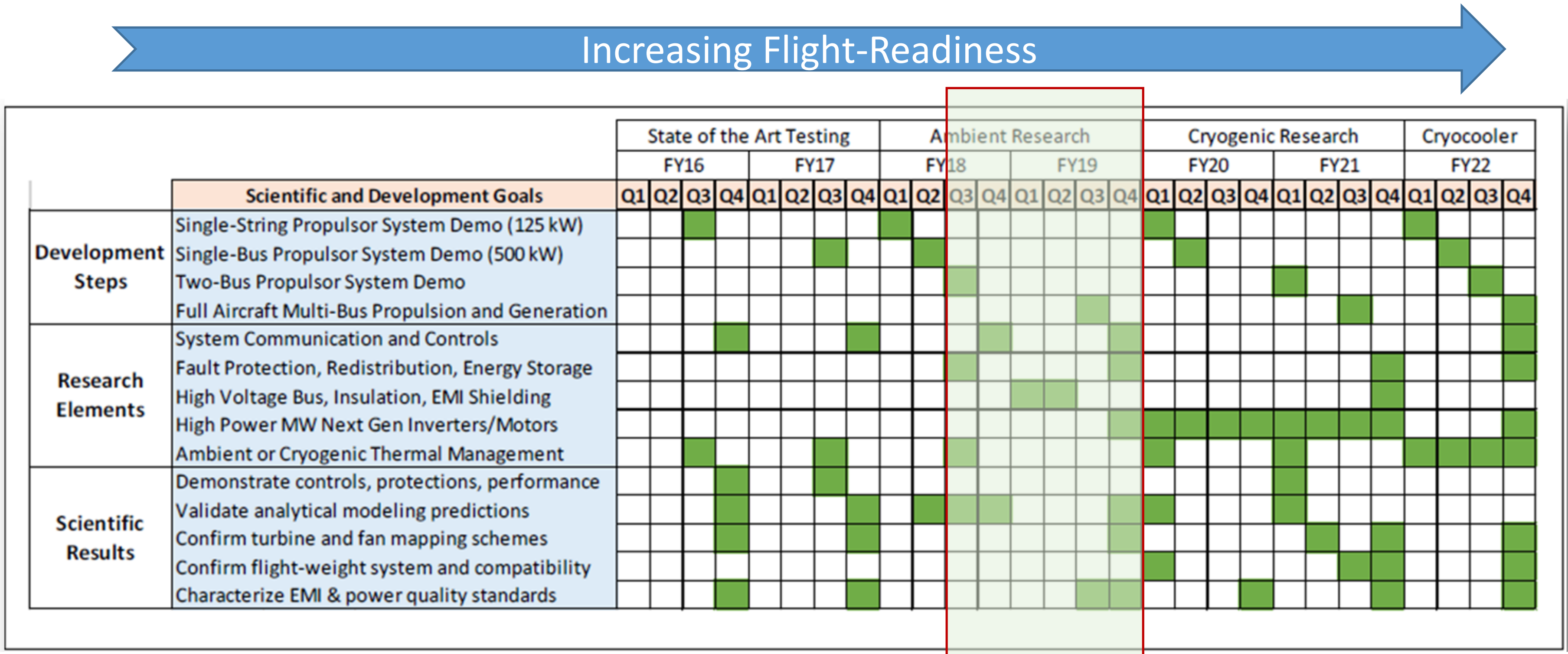




Lessons Learned

- EMI shielding is critical for safe and proper operation of the powertrain even with DO-160G compatible equipment
- Federated fault response with localized feedback/controls are important for orderly shutdown sequencing
- Electric machines can be scaled and controlled to simulate a turbine and ducted fan operation
- System interactions between components must be tested to account for common modes, grounding loops, electrical and mechanical resonant conditions
- Spline coupling selection impacts controllability
- Turbine and Electric Powertrain modeling can be very accurate if the component controls are fully characterized
- Optical fiber and digital instrumentation are required for robust communication and sensors
- Higher voltage and current present new issues such as insulation resistance breakdown and power quality challenges when operating near rated equipment limits
- Torque measurements are effected by cogging, EMI, torsional resonance, spline back-lash, and acquisition rates
- Shielding throughout the powertrain limits the ability to acquire data from transducers forcing calculated results via inverter software measurements.

Next Steps



- Smart energy storage and fault management
- Triple redundancy
- Aircraft Grounding Scheme
- Dual-Spool Power Extraction
- Real-time turbine and ducted fan emulation
- Altitude
- Flight-Weight Components

Summary

- Flexible Electric Aircraft Testbed Completed First STARC-ABL Flight Profile
- Full-scale Single-Aisle Electric Aircraft Powertrain
- Continue to add to capabilities (power, voltage, cooling, altitude)
  - Up to 24-48MW with regeneration
  - 50,000 feet altitude in 15 minutes
  - >1MW thermal management
  - Full-size and safe with remote control