

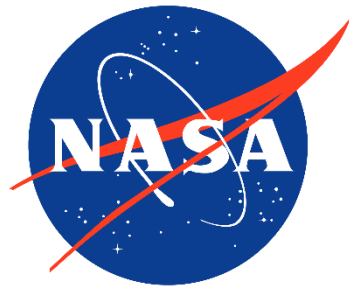
NASA Glenn

Electric Propulsion Work

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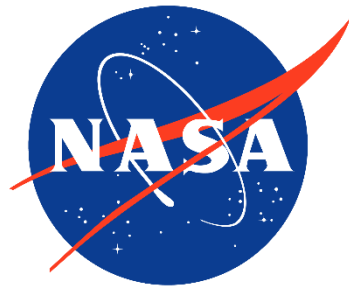
NASA Glenn Electrified Aircraft Propulsion (EAP)



Presentation Outline: *High-Voltage, High-Power EAP*

- Standards and Regulations
- Safety and Certification
- High Power Density, High-Efficiency Electric Machines and Drives
- Thermal Management
- Fault Management
- Superconducting Electric Machines
- Materials Research
- Modeling Tools
- Advanced Controls

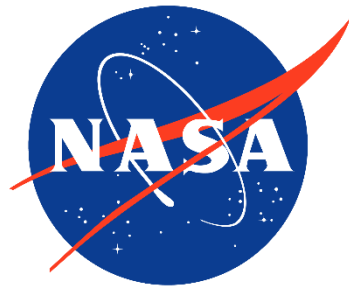
Aeronautics Research Mission Directorate (ARMD)



ARMD has 6 Strategic Thrusts

- Strategic Thrust 1: Safe, Efficient Growth in Global Operations
- Strategic Thrust 2: Innovation in Commercial Supersonic Aircraft
- Strategic Thrust 3: Ultra-Efficient Commercial Vehicles
- Strategic Thrust 4: Transition to Low-Carbon Propulsion
- Strategic Thrust 5: Real-Time System-Wide Safety Assurance
- Strategic Thrust 6: Assured Autonomy for Aviation Transformation

Revolutionary Vertical Lift Technology (RVLT) Project



Electrified Aircraft Propulsion (EAP)

- Significant investments being made

Can potentially reduce:

- Fuel burn
- Emissions/exhaust
- Noise & noise pollution
- Takeoff field length

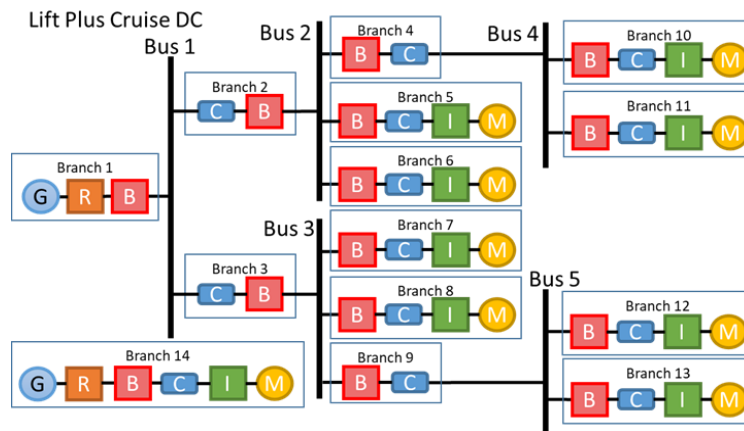
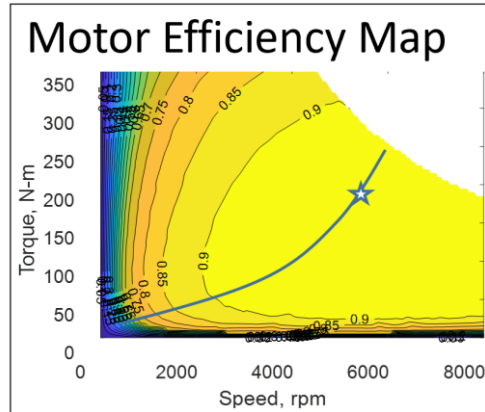
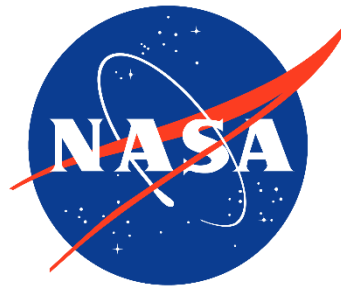
RVLT is addressing the gaps:

- Tool development
- Standards development
- Model validation
- Safety hazards and analysis

Utilizing concept aircraft to perform studies



Electrical Power System – Sizing and Analysis Tool (EPS-SAT)



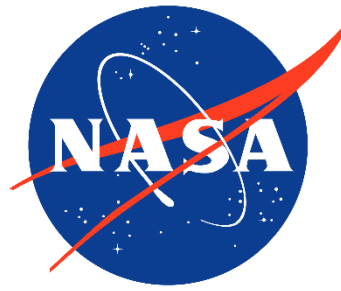
MATLAB[®]-based object-oriented framework that:

- Estimates aerospace power system performance
- Allows for component/architecture trades
- Allows for sensitivity analyses
- Exposes strengths and weaknesses of designs
- Can be used to better direct investment dollars

Supports AC, DC, and Multi-string architectures

Electrical power system reliability studies

Numerical Propulsion System Simulation (NPSS)

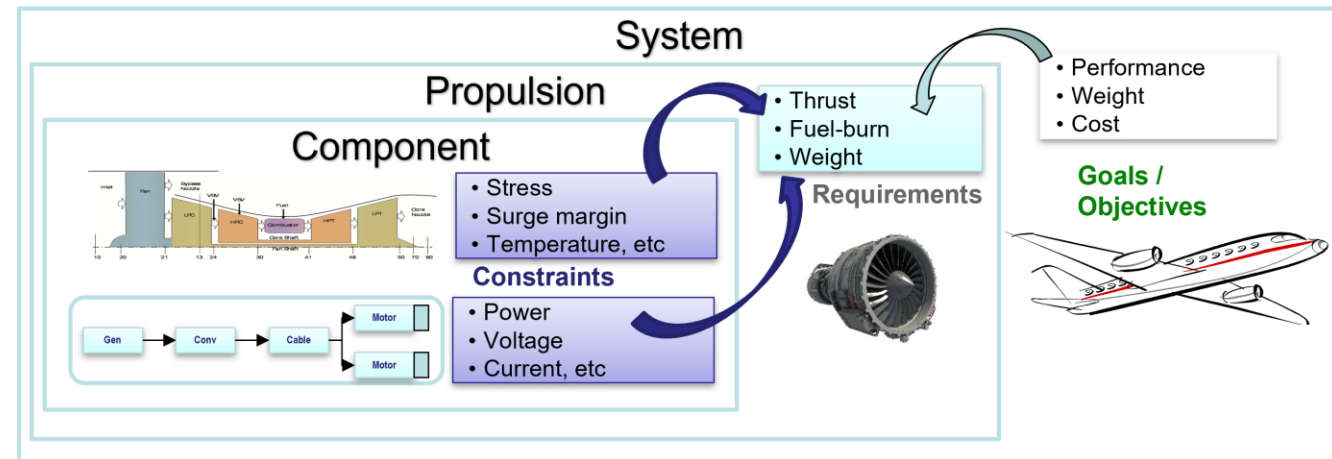


Added electrical port

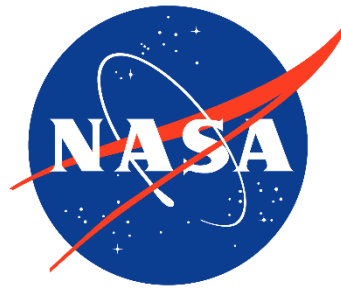
- Address fuel burn, emission, noise, cost, performance
- Consider component min/max operating conditions
- Difficulty in producing designs without simultaneous modeling

Multidisciplinary propulsion system sizing and analysis

- Turbomachinery
- Electrical
- Thermal



Standards Development – SAE Standards



AS-7499 Aircraft High Voltage Power Quality Standard

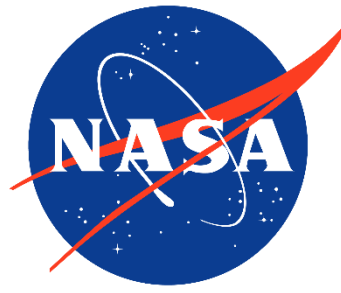
- Establishes power system boundaries
- System stability
- Fault recovery
- 'Plug and play' approach to

AS-8441 Minimum Performance Standard for Permanent Magnet Propulsion Motors and Associated Drives

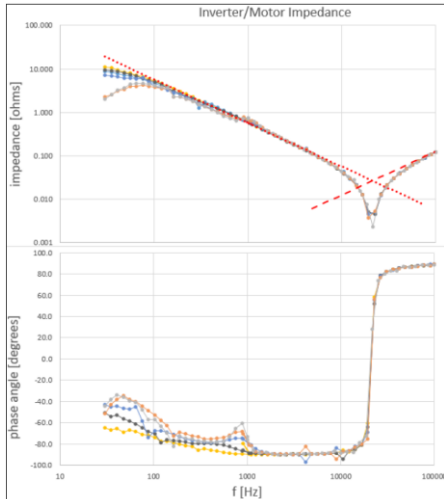
- Using PM machine as baseline
- PM-driven electric engines



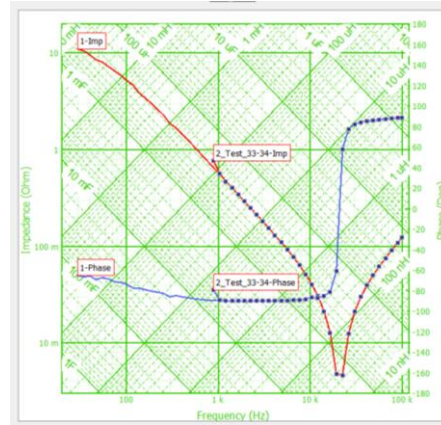
Scaled Power ElEctrified Drivetrain (SPEED)



Simulation Results



Physical Sys. Results



Capabilities

- 400 VDC and 12,000 RPM
- Up to 7 kW (dyno limit)
- Mechanical, electrical, vibration data

Testing

- Motor/inverter characterization & integration
- Baseline testing of motors for AREAL testbed
- Software model validation
- Test motor, controls, power electronics



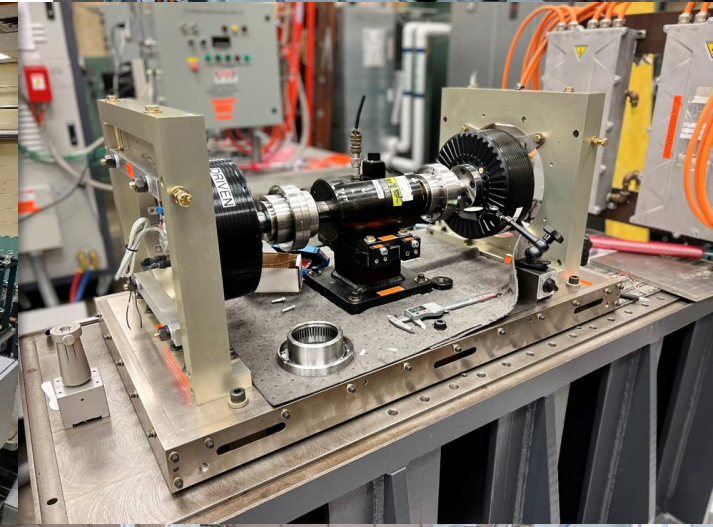
Aeronautics Reconfigurable Electrified Aircraft Lab (AREAL)

Capabilities

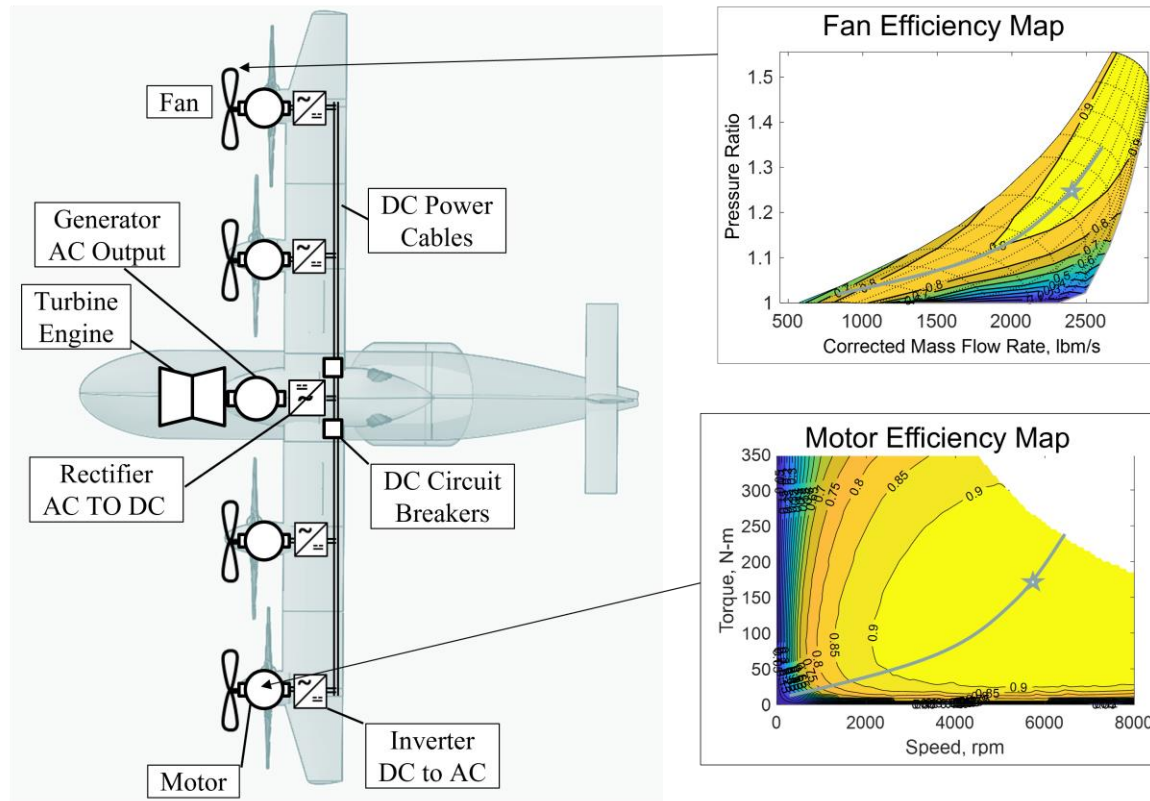
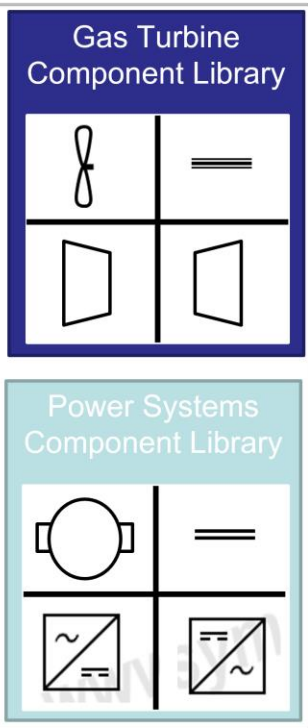
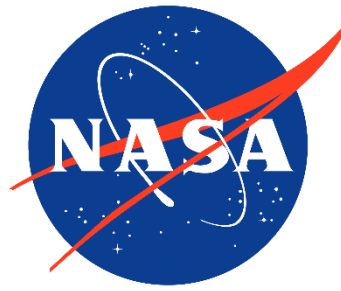
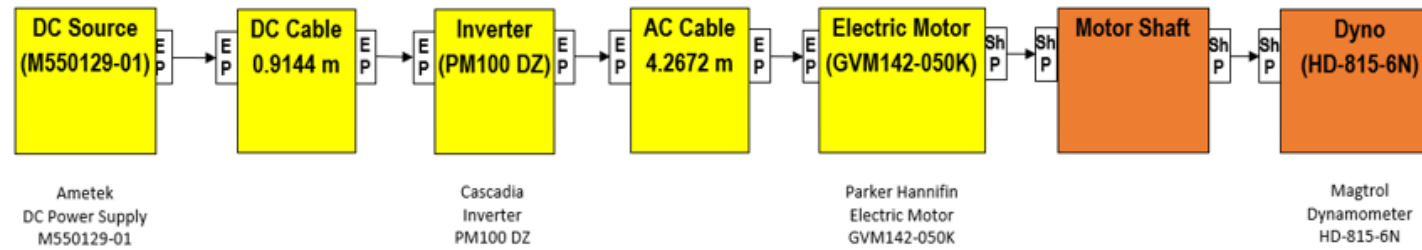
- 1 kVDC peak
- 200 kW nominal source capacity
- Emulated, reconfigurable system
 - Single-string, multi-string
- Power quality investigations
- Fault capability

Testing

- Nominal, transient, fault operation
- Characterization and response

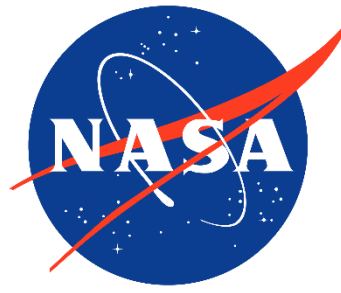


Model Validation

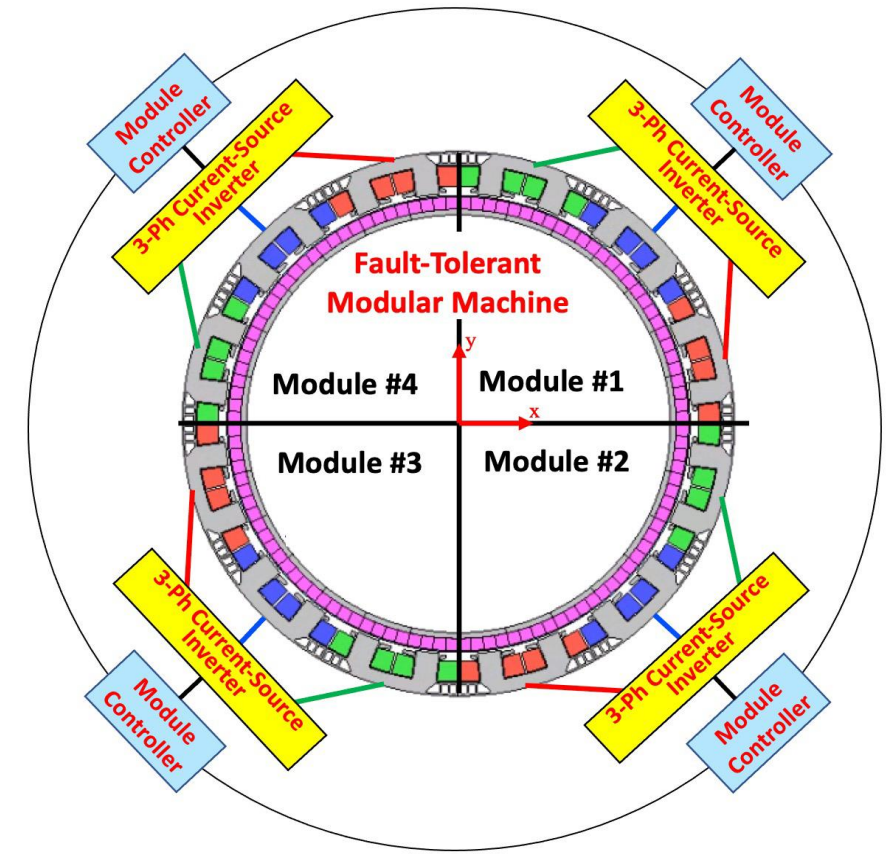


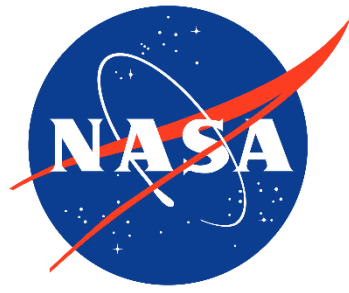
- Validation of analysis tools
 - Simulink models
 - EPS-SAT models
 - NPSS models
- Testbed data
 - Electrical impedance
 - Power quality
 - Physical motors
 - Fault injection
 - Efficiency

Motor/Drive Research



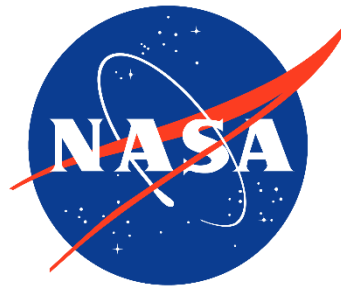
- NASA ULI Project: Integrated Motor/Electronics Design led by the Ohio State University
 - Modular motor and drive design
 - Integrated motor, drive, and thermal
 - 1 MW target
- RVLT-funded spin-off of ULI design through the University of Wisconsin
 - Fault-tolerant motor and drive concept
 - Integrated motor and drive
 - 20 kW demonstrator to be delivered 2024
- NASA SBIR Phase II: High Power Density Induction Motors and Drives Aircraft Application by Ohio State University and Hyper Tech
 - Integrated motor and drive design
 - Navigate away from permanent magnets
 - 2 MW target





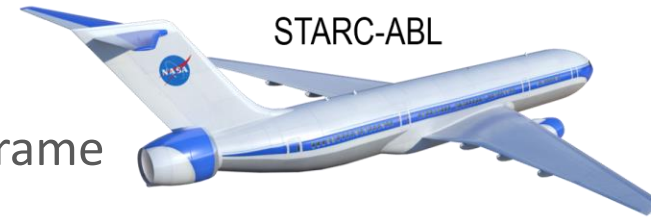
Questions/Discussion About RVLT?

Advanced Air Transport Technology (AATT) Project



System Level

- Airplane concepts & systems analysis tools
- Boundary layer ingestion and other propulsion airframe integration benefits
- Electric system architectures
- Test capabilities



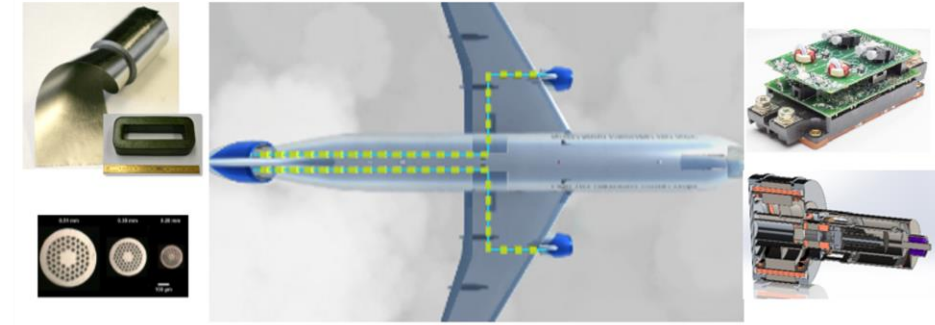
STAR-ABL



PEGASUS

Electrical Powertrain Technologies

- All-, hybrid-, turbo-electric systems
- Electrical power components (e.g. machines, converters, circuit interrupters)
- Advanced materials

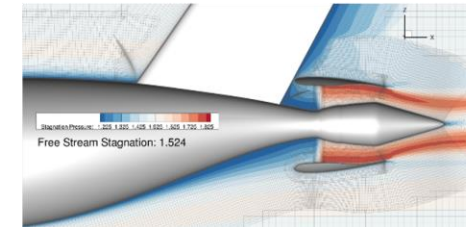


EAP Powertrains

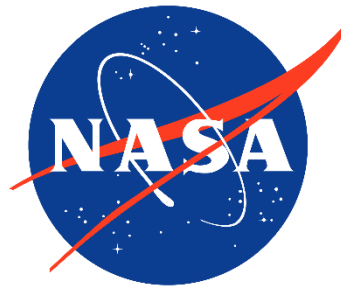
Coupled turbine systems

- Integrated Electrical Machines
- Small core turbomachinery
- New material systems

Tailcone
Thruster CFD
Assessment

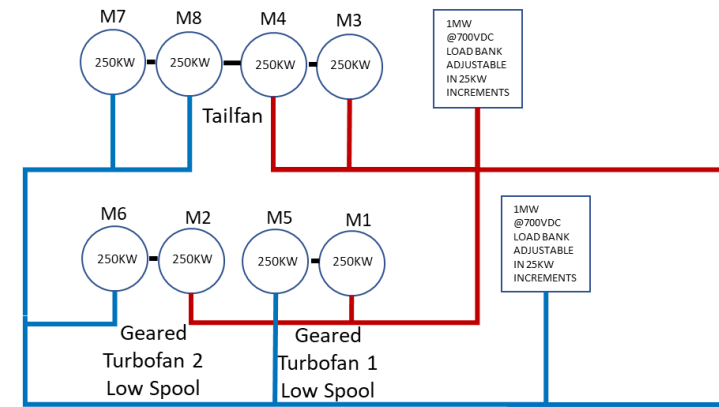


NASA Electric Aircraft Testbed (NEAT)

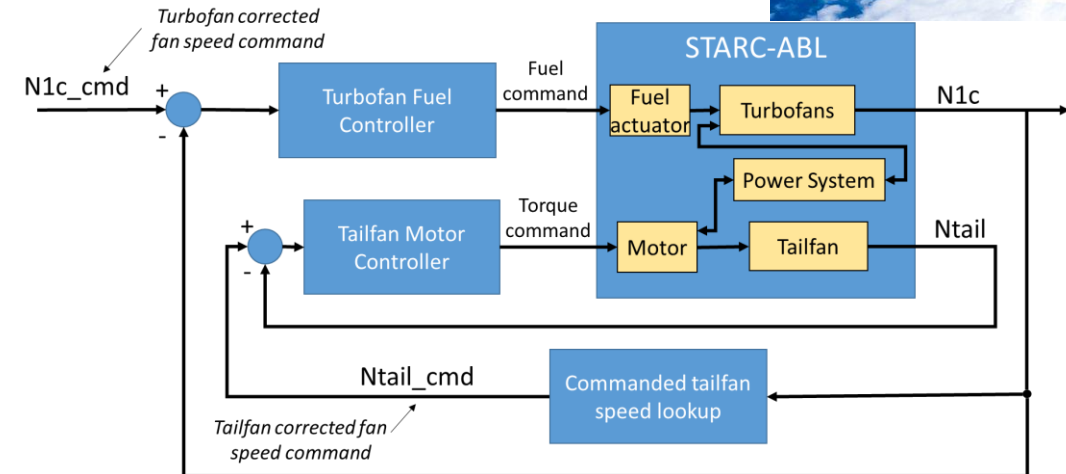


Most recent NEAT testing

- Controls-based methods to manage faults and off-nominal conditions in highly coupled EAP systems
- Subscale STARC-ABL power system and turbomachinery shaft loads
- Real-time simulation of control system and turbomachinery dynamics
- Scheduling of thrust split between turbofans and tail fan
- Integrated control coordinating operation of turbofans and tail fan subsystems while allowing operability to be maintained during transients
- Demonstrated robust control system operation during throttle transients at various simulated flight conditions and during full-mission profiles under both nominal and simulated degradation scenarios

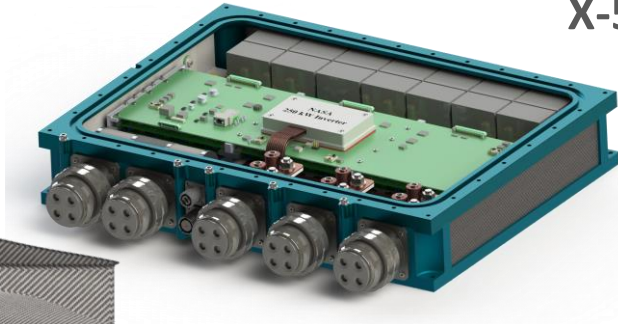
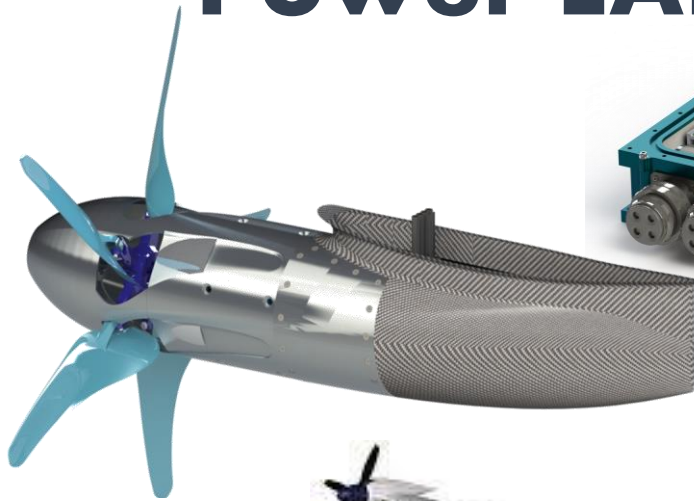
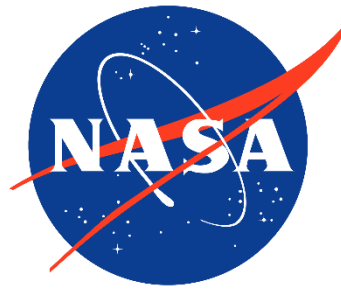


NEAT STARC-ABL Hardware Configuration



STARC-ABL Integrated Control Architecture Illustrating Coupling Between Turbofans and Tailfan

Advanced Power Electronics for High-Power EAP



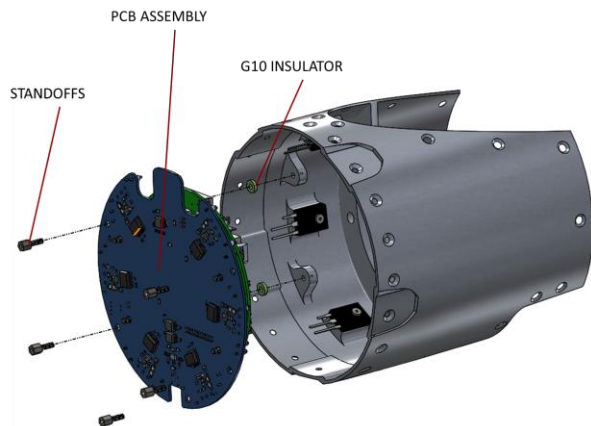
X-57 High Lift Motor Controller

- 12 kW inverter
- 460 V Battery system (538V max)
- 1 kg weight limit
- Outer mold line cooling – high efficiency required
- 98% Efficient
- 40W of loss per MOSFET
- 1.2kV SiC FET provides margin for transients, overshoot
- Glenn developed the high lift motor controllers, and the new modification to the cruise motor controllers

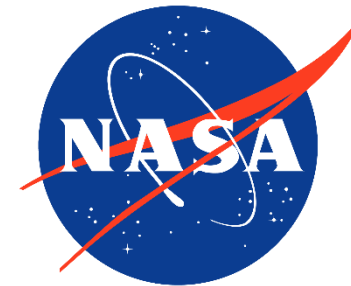


AATT Advanced Power Electronics – 250 kW inverter

- 1kV DC bus (330Arms / phase)
- 72x 120A SiC 1.2kV MOSFETs
- 3 Level neutral point clamped topology
- Each FET only sees half bus voltage
- Interleaved phase legs for current sharing
- Stretch goals: 99.5% efficient, 20 kW/kg



High-Power-Density, High-Efficiency Electric Machines



Ambient $>13 \text{ kW/kg}$, 96% efficient

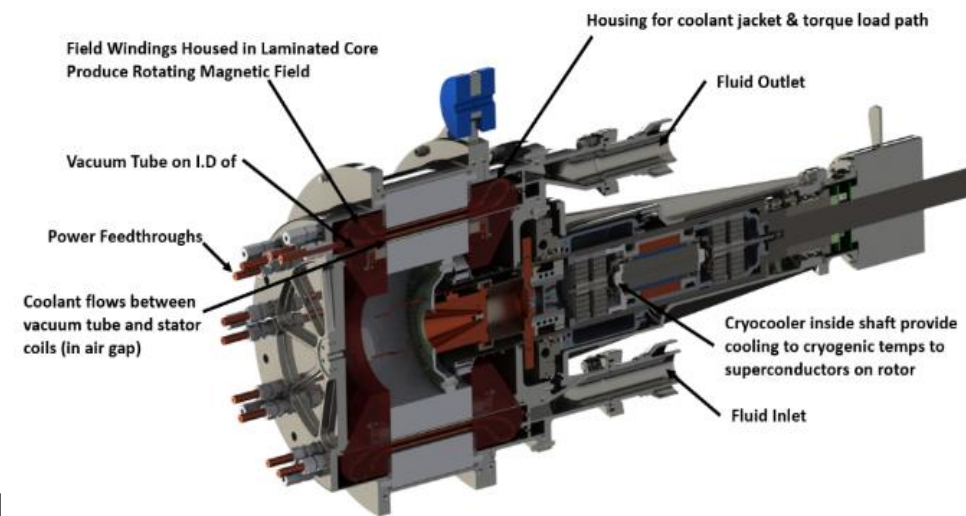
- Ohio State University Induction
- University of Illinois and Hinetics Permanent Magnet
- University of Wisconsin Permanent Magnet (OSU-led ULI)

Partially Superconducting $>16 \text{ kW/kg}$, 98% efficient

- NASA High Efficiency Megawatt Motor Wound Field

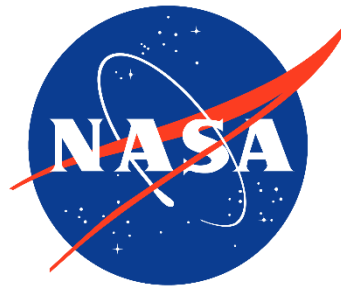
Superconducting $>16 \text{ kW/kg}$, 99% efficient

- NASA addressing challenges for fully superconducting machines
- AC loss studies
- University of Illinois CHEETA program (ULI)



High-Efficiency Megawatt Motor

Fault Management and Materials

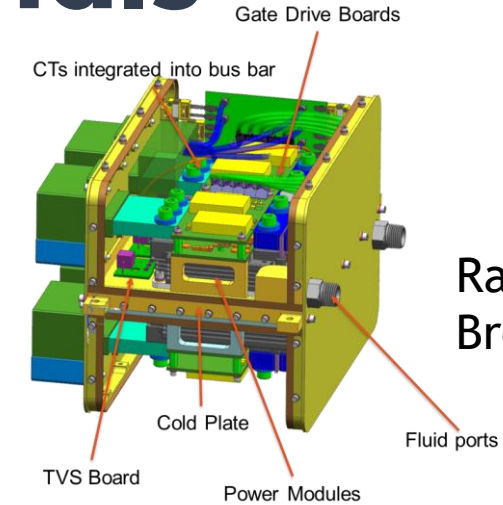


Circuit Breaker (MW scale, $\sim 1\text{kV}$, 1000A , $>100 \frac{\text{kW}}{\text{kg}}$, $<100\mu\text{s}$ response)

- Pratt and Whitney (P&W, RTX, and Collins Aerospace)
- General Electric Aviation (GEA and GE Research)
- Naval Post-Graduate School-POC

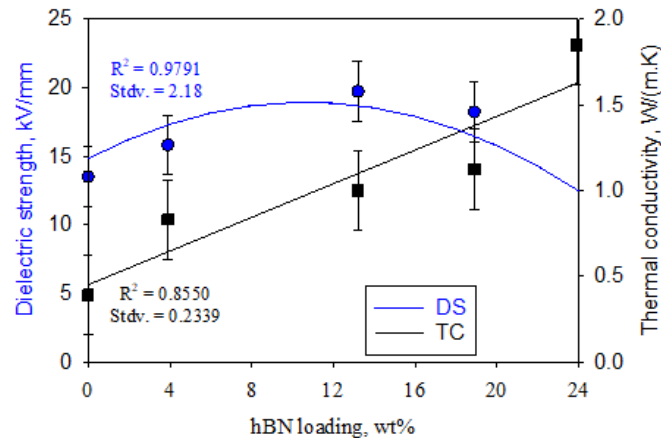
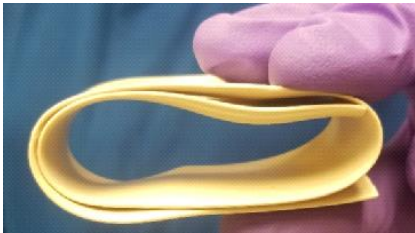
Materials Studies

- Custom devices from NASA soft magnetic materials
- Lifetime modeling for insulations systems
- Multifunctional insulation systems for electric machines



Raytheon Circuit Breaker

Electric Machine Insulation Development

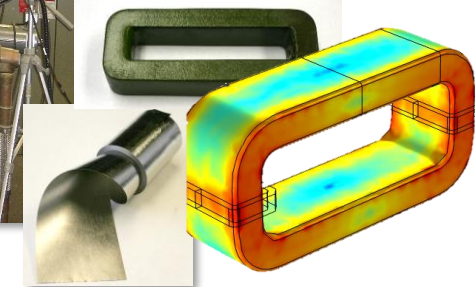


Insulation development addressed thermal challenges in power dense MW scale eclectic machines

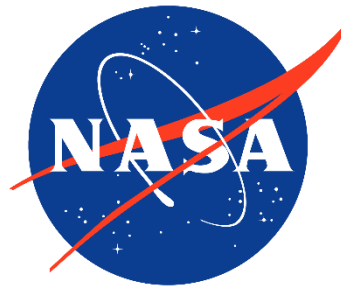
Induction Filters for Advanced Power Electronics



Magnetic cores designed to handle switching high switching frequencies of advanced power electronics



Electricified Powertrain Flight Demonstration (EPFD)



Goals:

- Accelerate US industry technology readiness and competitiveness
- Facilitate new aviation industry S – curve
- 2030-2035 EIS: Thin haul to next generation SA

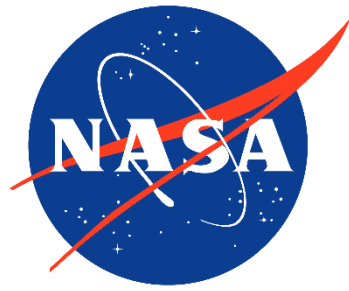
Objectives:

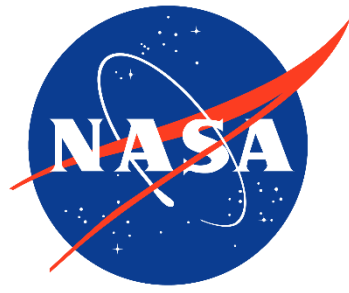
- Identify/retire barrier technical and integration risks
- Conduct at least two EP – based flight demonstrations in the MW class
- Identify and address standards and regulations gaps to enable timely EP market penetration



Future Work

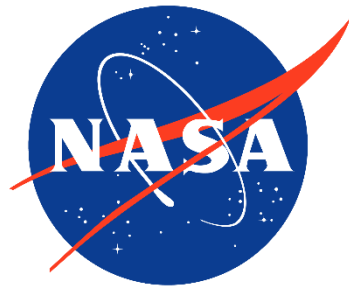
- Continue to work with government agencies and industry on standards and regulations and problem solving
- Single string and multi-string testing
- Emulation of full DC propulsion systems
- Model validation and associated hardware testing
- Improving safety and reliability of motors and inverters
- Improving power density and efficiency of electrified aircraft power train components





Acknowledgements

- Revolutionary Vertical Lift Technology (RVLT) Project
- Advanced Air Transport Technology (AATT) Project
- Transformational Tools and Technologies (TTT) Project



Additional

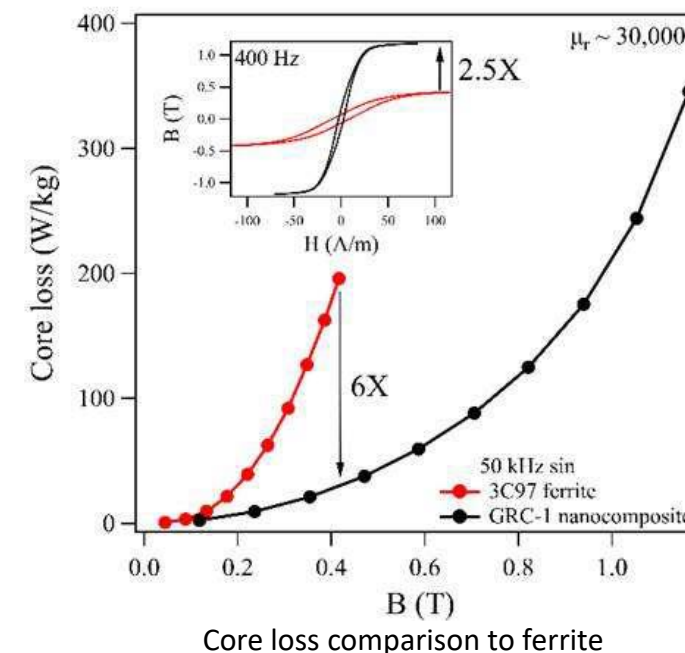
Advanced Magnetic Materials

- Advanced Magnetic Materials

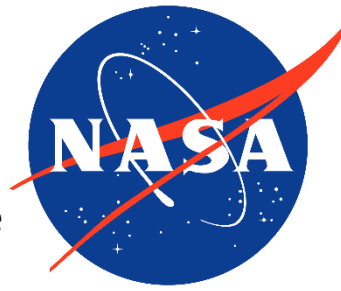
- Full range of modeling, processing and characterizing capability to enable custom components
- GRC provided test cores for RTX inverter
 - dV/dt filter – 1000 A graded permeability cores
 - EMI filter – Design in progress...
- Evaluating against COTS cores and identifying needs
- Current needs include high temperature ($\sim 300^\circ\text{C}$) and packaging to meet DO-160G vibration requirements
- Transition successful technologies to commercial production



dV/dt cores delivered Feb 2022

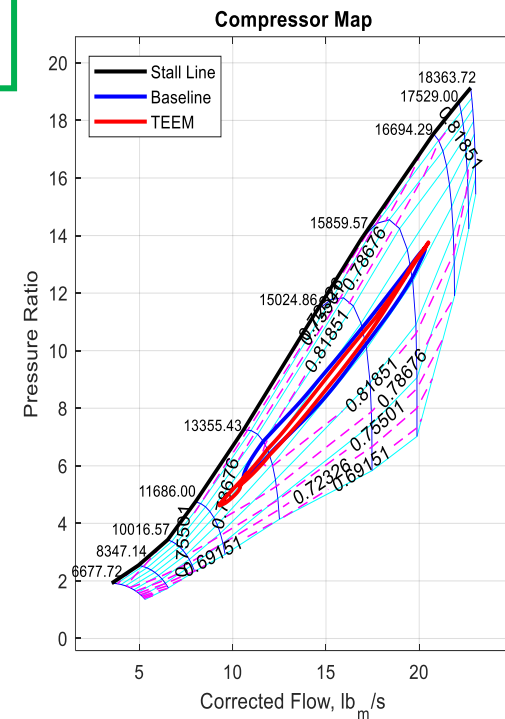
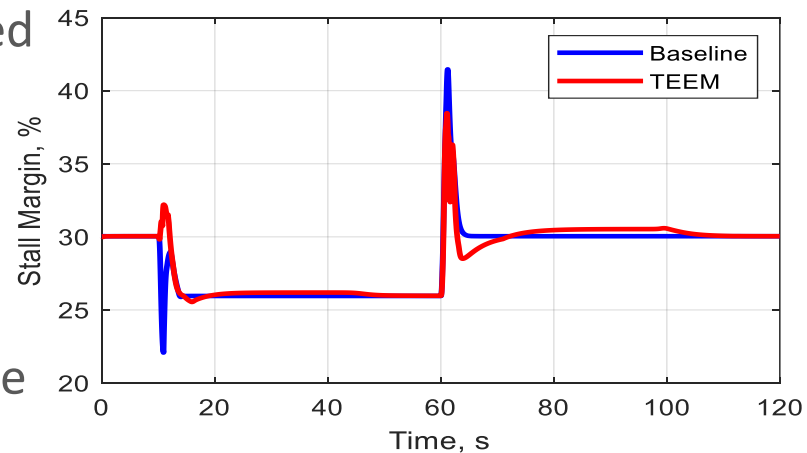
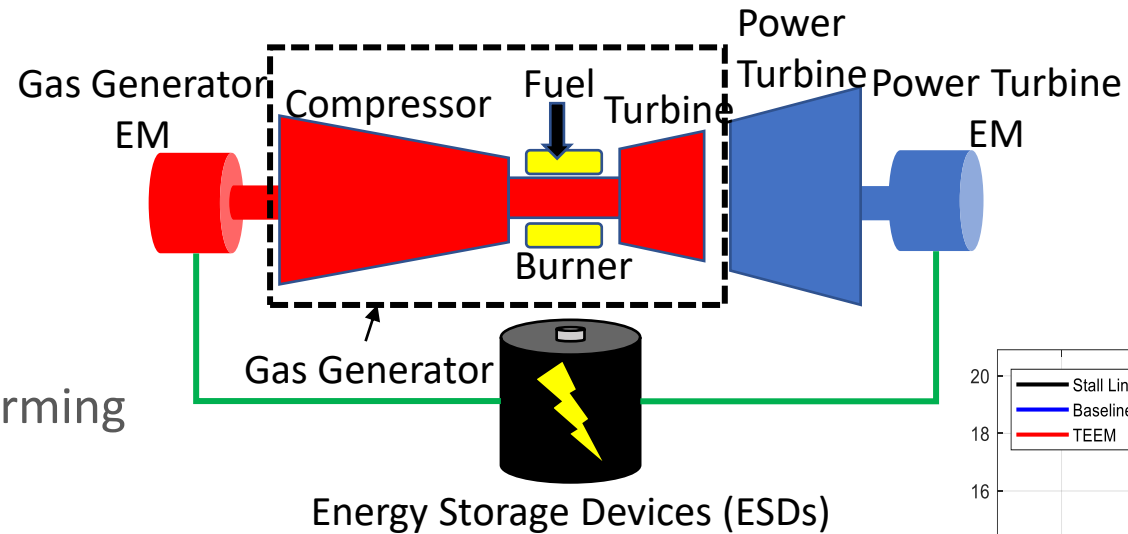


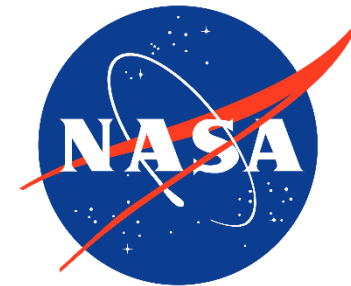
Turbine Electric Energy Management (TEEM)



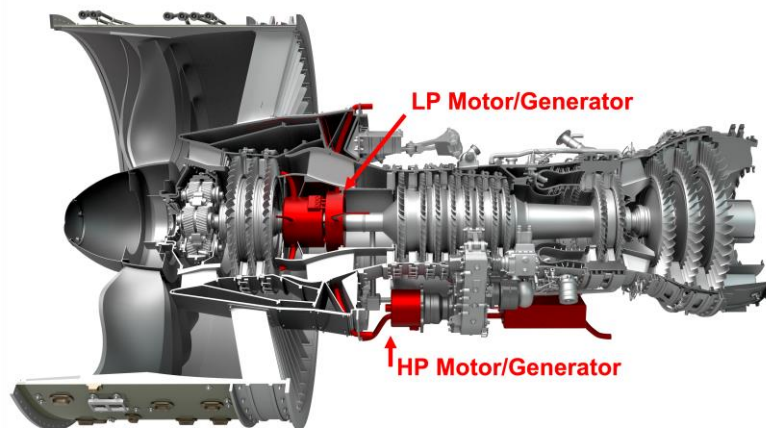
TEEM is about managing energy in an electrified turbine engine propulsion system

- Goal: Improve operability of the turbomachinery → enable better performing engine designs and/or enhance aircraft capabilities and safety
- The Means: electric machines (EMs) coupled to the engine shaft(s)
 - EMs are new actuators that can alter engine operation
- Superior Transient Operability Improved minimum stall margin during acceleration and tighter control of operating point on the map

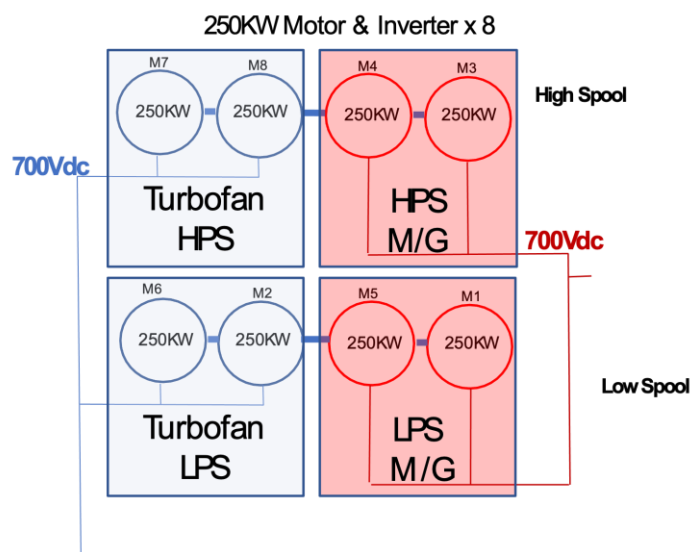




Turbine Electric Energy Management (TEEM)



- Advanced control logic for electrified propulsion systems that combine gas turbine and electrical components to reduce fuel burn and emissions.
- Real-time demonstration of a controls concept to optimize energy usage of a hybrid-electric propulsion system during transient operation
 - Experiment Electrical System: electric machines, inverters, load bank, and power supply
 - Real-Time turbofan simulation using dSPACE computer for Engine shaft speed, torque, and inertia are expressed by a pair of electric motors
- Demonstrated the ability of TEEM to dynamically alter shaft speed to maintain the designed operating line performance during engine transient operations.
- Demonstrated dynamics of full-scale hybrid turbofan model and mechanically coupled EM system using Adaptive Sliding Mode Inertia Controller and Scaling algorithm.



NEAT TEEM Hardware Configuration