Overview of NASA GRC Electrified Aircraft Propulsion (EAP) Controls Research

Presentation to the University of Connecticut

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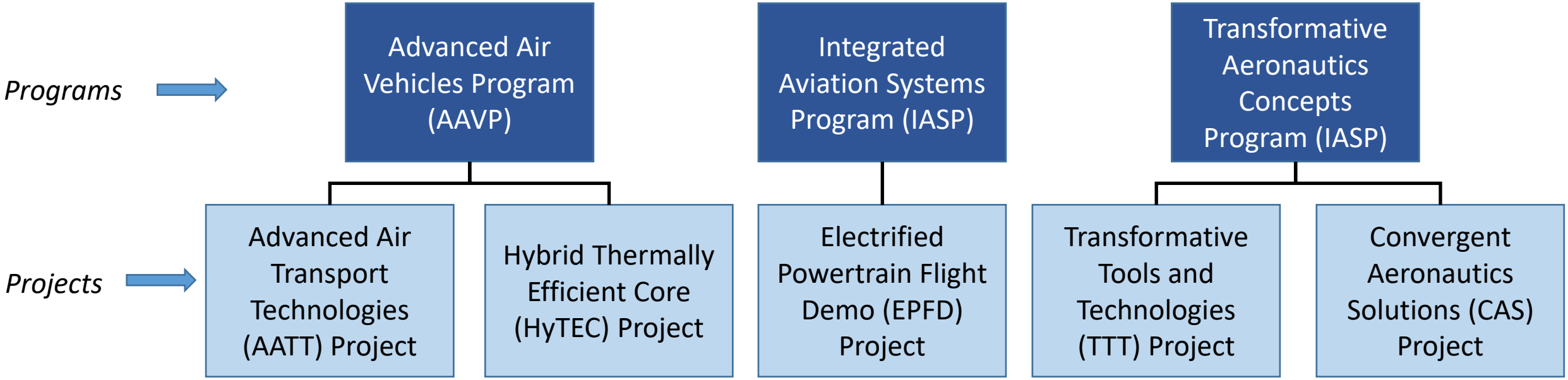
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Outline

- Program/Project Overview
- Modeling Tools
  - Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)
  - Electrical Modeling and Thermal Analysis Toolbox (EMTAT)
- Electrified Aircraft Propulsion (EAP) Control Methodologies
  - Turbine Electrified Energy Management (TEEM)
  - Integrated Control Design for Partially Turboelectric Propulsion Concept
  - Model-Predictive Control
- Control-based fault management strategies for EAP systems
- Real-Time Hardware-In-the-Loop (HIL) Facilities and Testing
  - NASA Electric Aircraft Testbed (NEAT)
  - Hybrid Propulsion Emulation Rig (HyPER) facilities
  - Sliding Mode Impedance Controller with Scaling (SMICS)
- References

Program / Project Overview

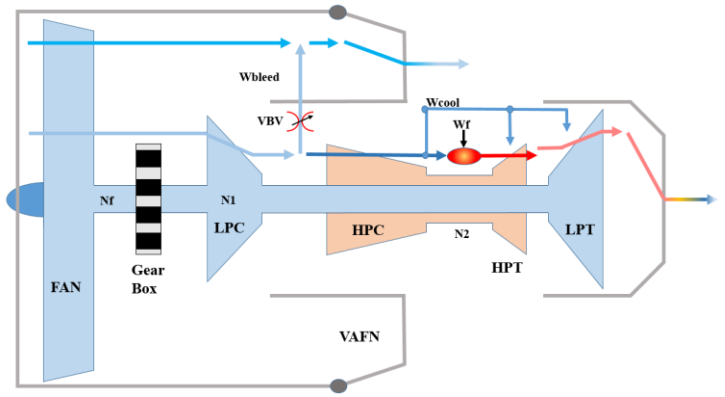
- The NASA GRC Intelligent Control and Autonomy Branch (LCC) has EAP controls research ongoing under the following NASA Aeronautics Mission Research Directorate (ARMD) programs and projects:



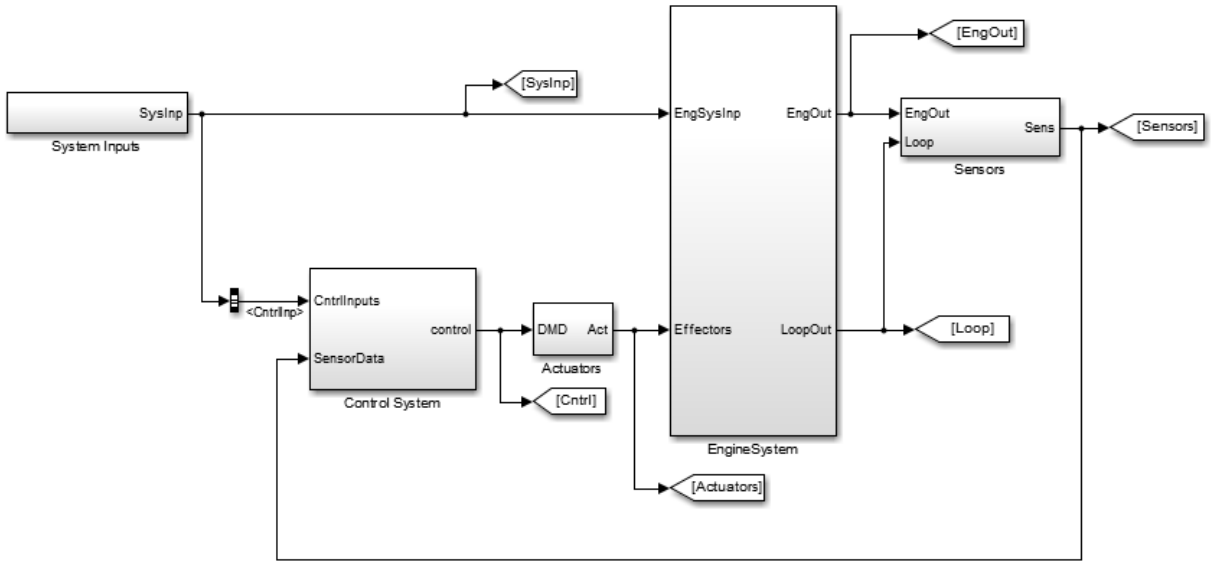
Modeling Tools

Modeling Tools: T-MATS

- Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)
- Modular thermodynamic modeling framework for building dynamic simulations
- Designed for easy creation of custom Component Level Models (CLM) of jet engines
- Although originally intended to simulate turbomachinery, it has been used for other applications, such as fuel cell modeling
- Open source available at:
  - https://github.com/nasa/T-MATS

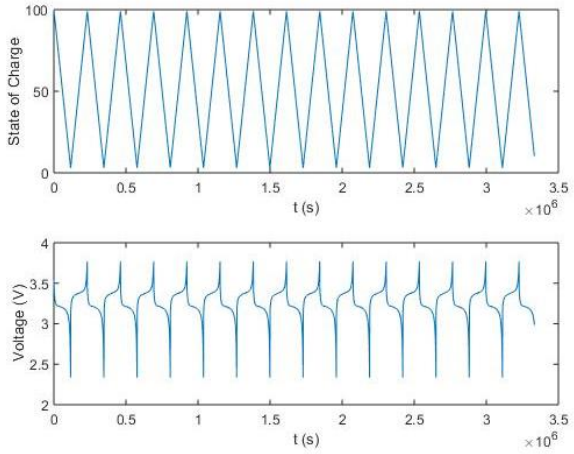


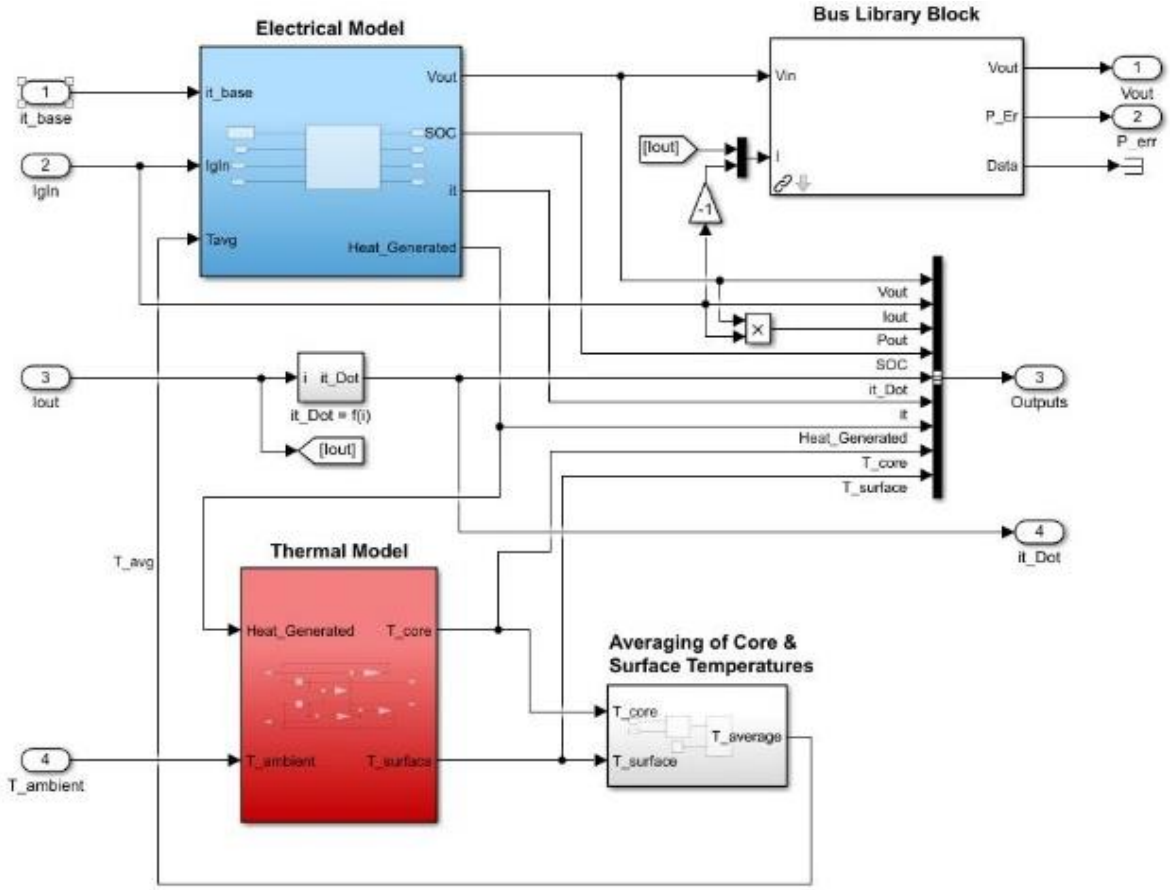
MATLAB SIMULINK toolbox modeling tool for turbofan dynamic modeling and controls studies



Modeling Tools: EMTAT

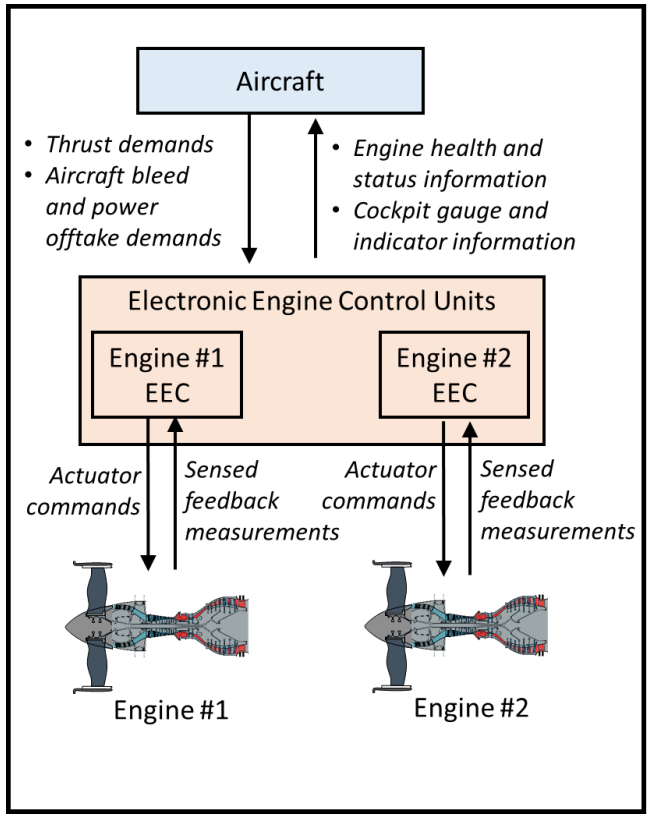
- Electrical Modeling and Thermal Analysis Toolbox (EMTAT)
- Power Flow/Physics-based Electrical/ Thermal modeling package (Beta released)
- Compatible with T-MATS
- Open source available at:
  - https://github.com/nasa/EMTAT



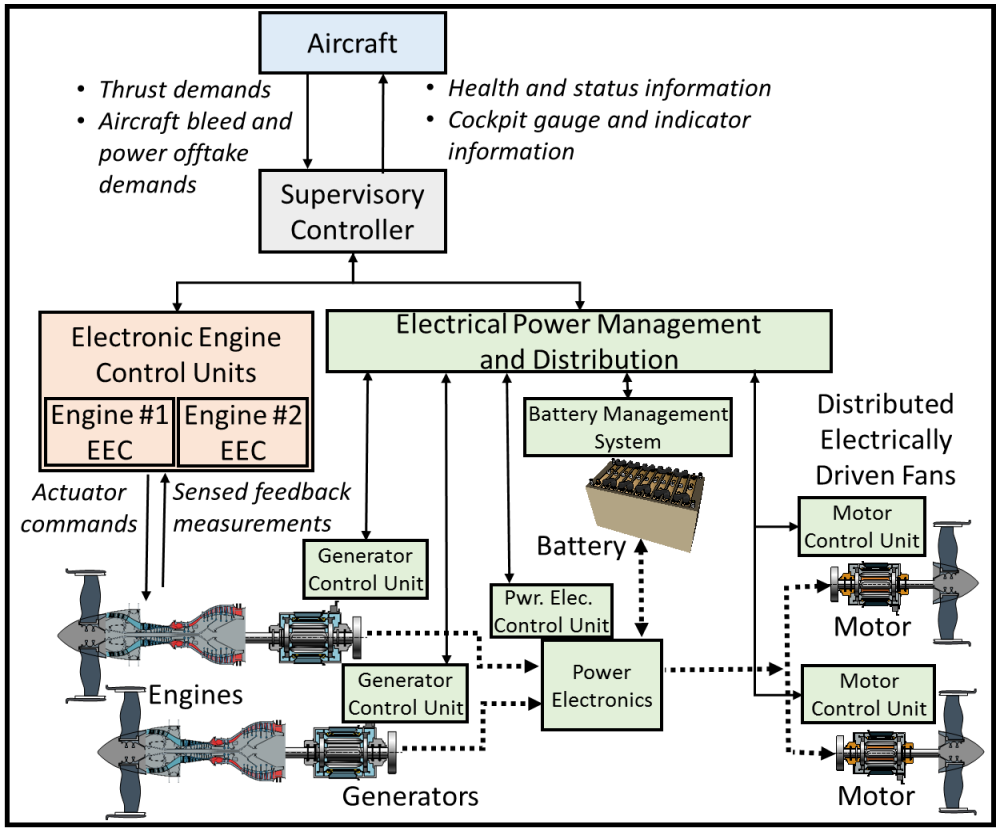


Electrified Aircraft Propulsion (EAP) Controls

Comparison of Conventional and EAP Control Architectures



Conventional Aircraft Propulsion Control Architecture

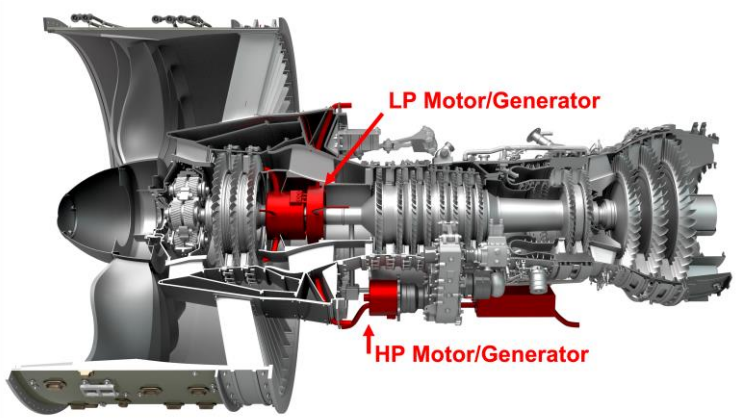


Electrified Aircraft Propulsion Control Architecture (notional)

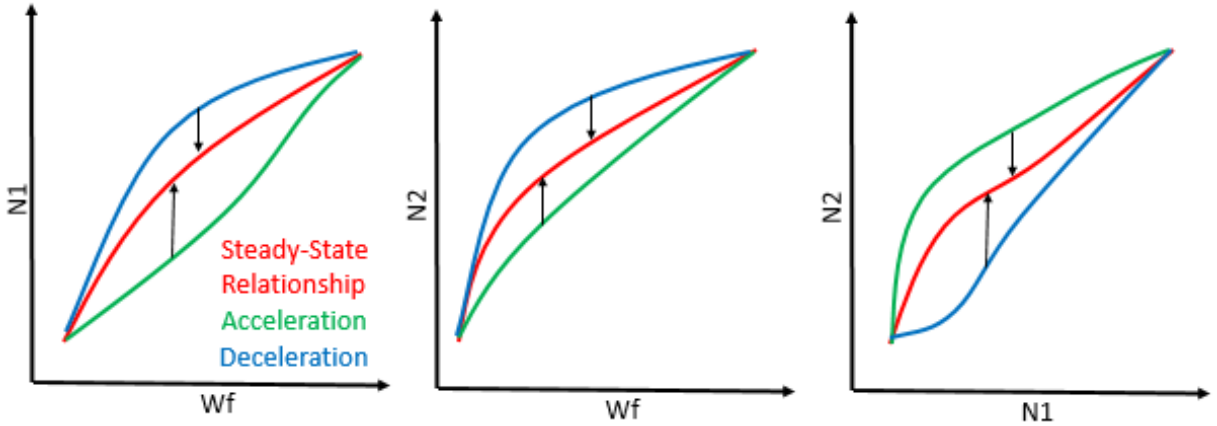
- EAP control architectures are more distributed, more complex, and more coupled
- This presents both control design challenges and control design opportunities!

Turbine Electric Energy Management (TEEM) Concept

- Electric machines (EM) provide a means to change the traditional operation of a turbofan
- EM to add/remove torque from one or both turbine engine shafts to alter the shaft dynamics allowing for more consistent on-design operation.
- An electrical energy storage device is used to impulsively supply or absorb the energy added or removed from the shaft, likely a super-capacitor.



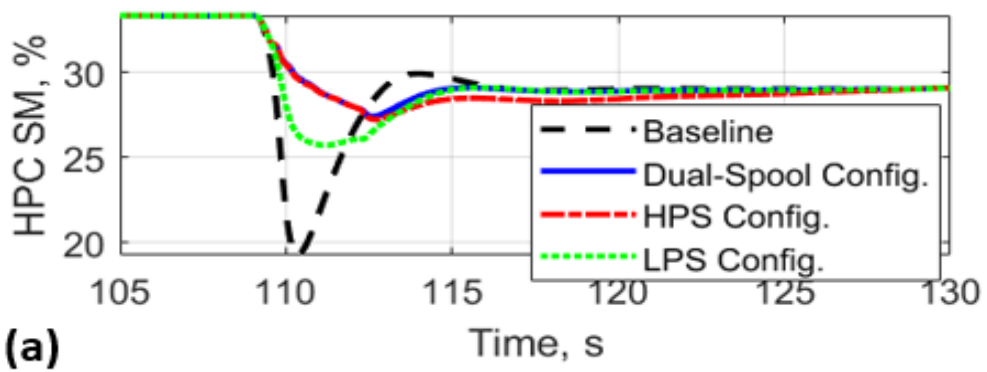
TEEM is an Additional Use of Electrical Machines Required for Other Electrified Aircraft Propulsion System Needs

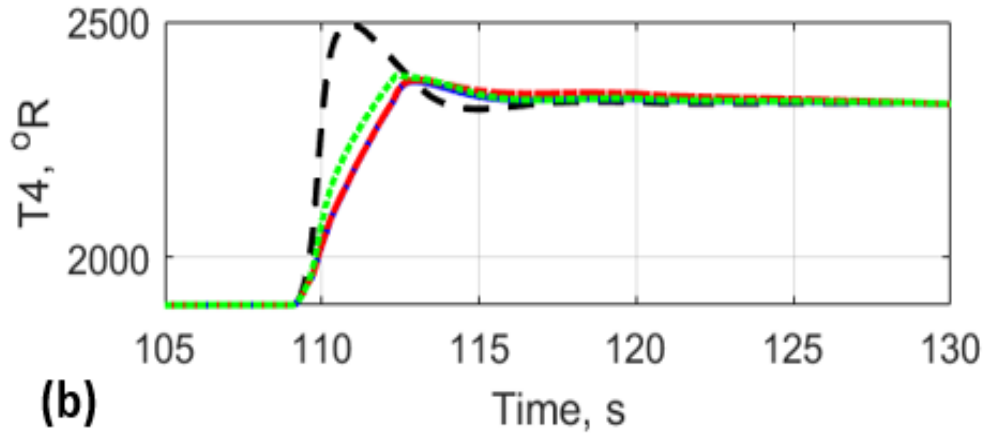


Typical shaft speed vs. fuel flow relationships as power level changes.

TEEM Results – Takeoff Transient

- Results shown for acceleration transient
  - Improved minimum HPC SM by 6-7%
  - Reduced peak turbine inlet temperature
- Energy supplied by super-capacitors is about the amount of energy present in a common car battery
- TEEM controller is only active for short periods of time on an intermittent basis

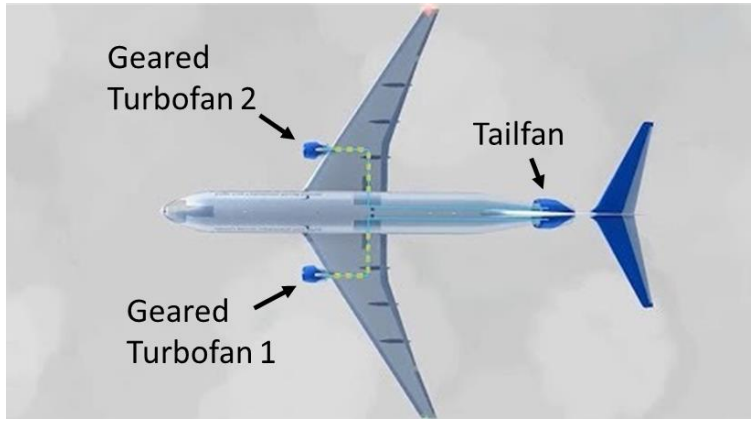




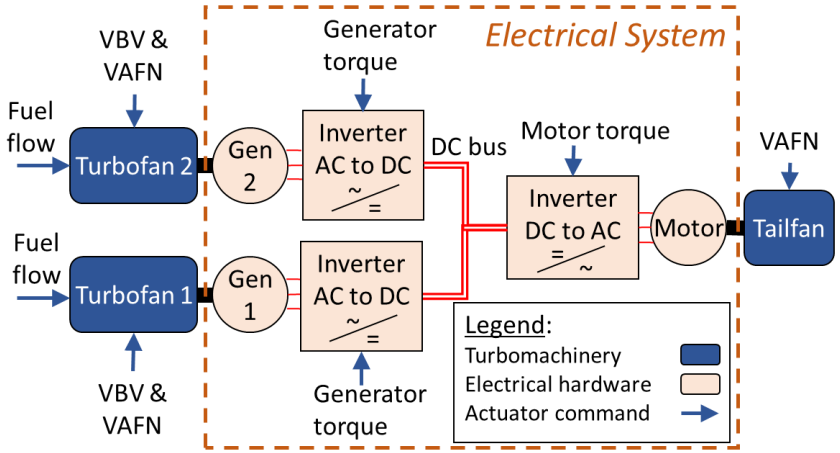
Integrated Control Design for a Partially Turboelectric Propulsion Concept

- Single aisle Turboelectric AiRCraft with Aft Boundary Layer propulsor (STARC-ABL)
- Partially turboelectric propulsion aircraft concept proposed by NASA
  - Two wing-mounted geared turbofan engines
  - Electric motor-driven boundary layer ingestion tailfan propulsor
  - Generators attached to turbofan low-pressure shafts supply electric power to tailfan motor over a high-voltage DC power bus
- Under nominal steady-state conditions the system operates in a state of "balanced" equilibrium

A system-level control strategy is required to enable transients and off-design operation!



STARC-ABL EAP Concept



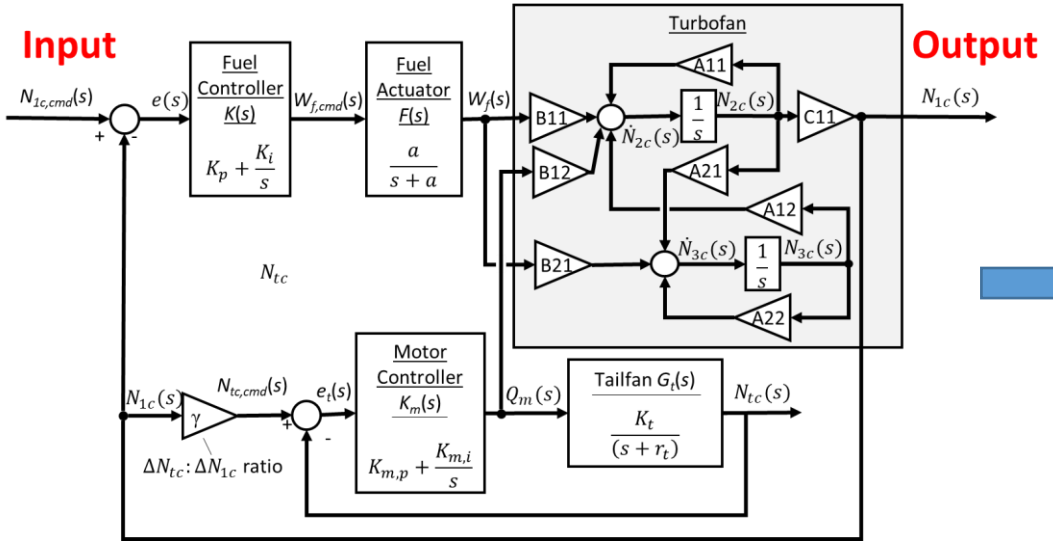
STARC-ABL Propulsion Architecture

STARC-ABL Integrated Control Design Details

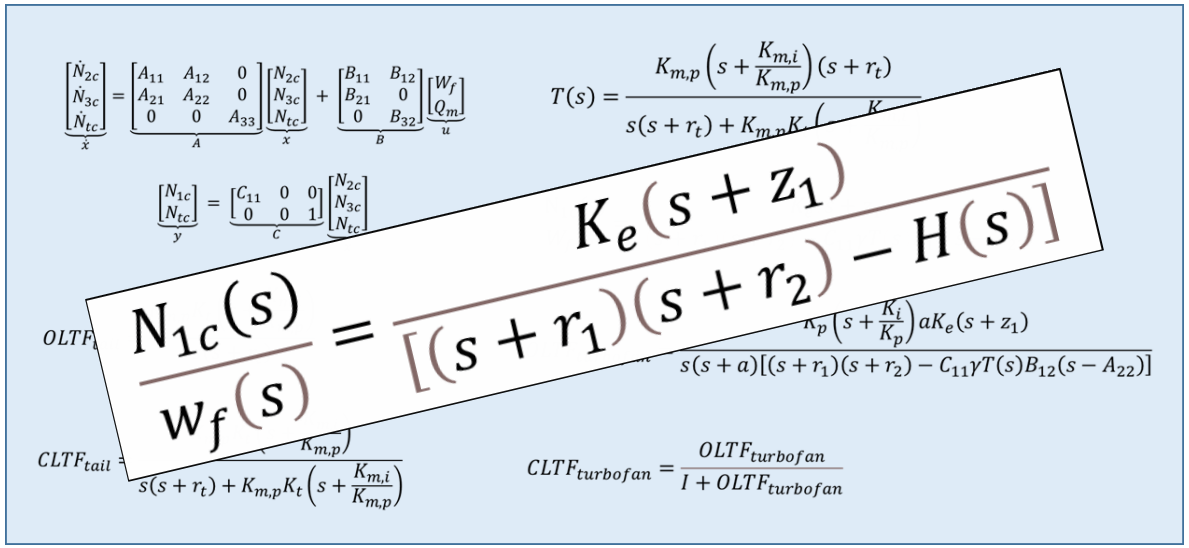
Implemented a single throttle input control strategy

- Both turbofans receive the same throttle command (denoted as power lever angle (PLA))
- Tailfan receives a "synthesized" throttle input calculated as a function of average turbofan speed

- Simplifies turbofan control design to a single-input single-output (SISO) control problem!
- Allows derivation of SISO linear transfer functions and application of classical linear control design techniques!



STARC-ABL Closed-Loop Control Architecture

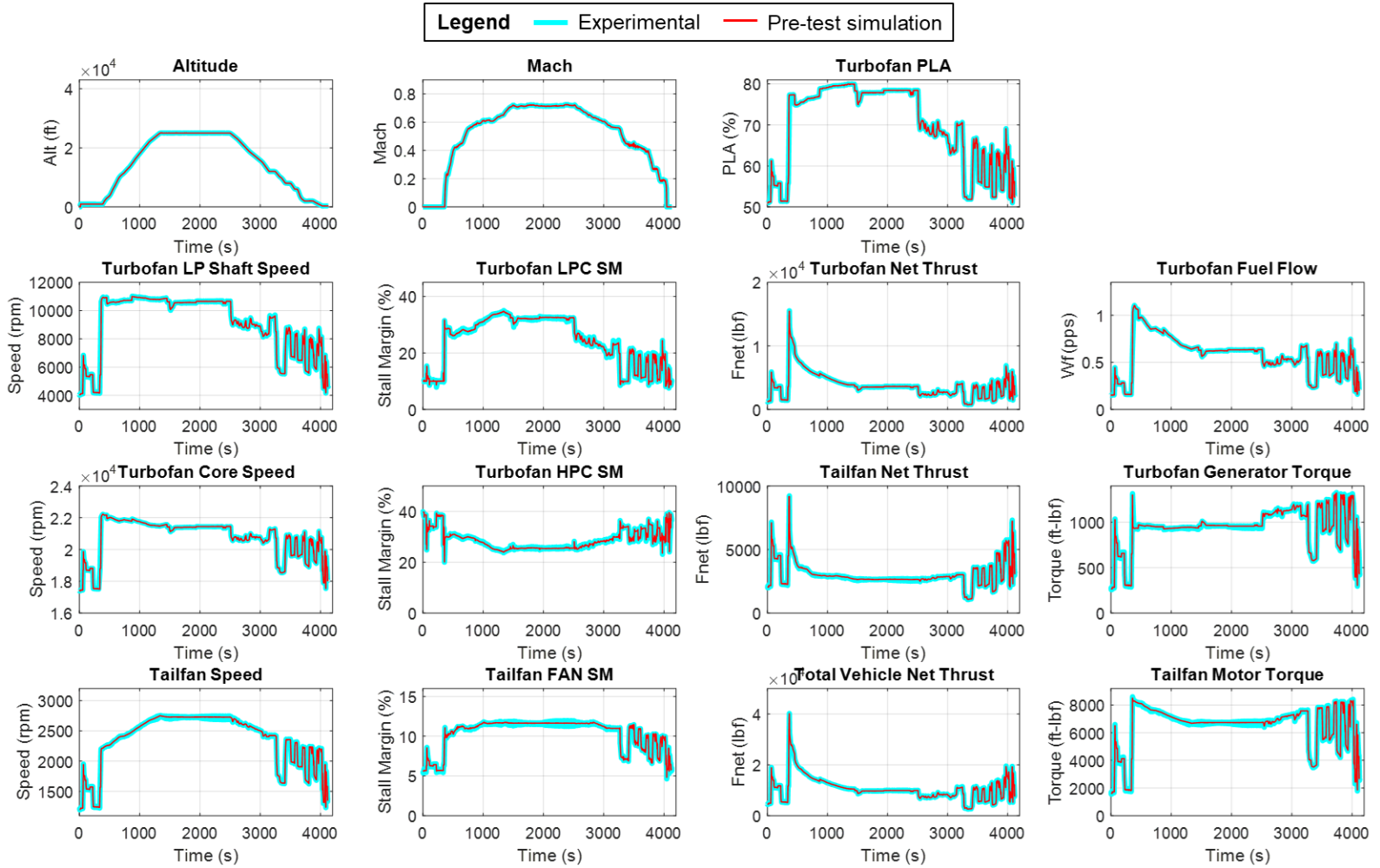


Derivation of Linear Transfer Functions

For additional details on the STARC-ABL integrated control design:
Simon, D.L., Bianco, S.J., Horning, M.A., (2023), "Integrated Control Design for a Partially Turboelectric Aircraft Propulsion System," ASME-GT2023-100921, ASME Turbo Expo Conference, Boston, MA, June 26-30.

NEAT STARC-ABL Controls Test Results: Mission Profile Test Cards

- NASA Electric Aircraft Testbed (NEAT) test of STARC-ABL Integrated Control Design
  - Hardware-in-the-loop test performed at NEAT during summer of 2022
- Mission profile test cards:
  - Subjects the integrated control design to realistic variations in flight conditions and throttle inputs
  - Test cards completed under nominal turbomachinery health conditions and repeated under (simulated) degraded health conditions
- Findings:
  - No issues encountered
  - Control design, real-time simulation, and electrical system hardware operated as expected



Actual Mission Profile Test Card Results

MPC for Electrified Aircraft Propulsion

- Investigating model predictive control (MPC) architectures for control of electrified aircraft propulsion systems.
- Have implemented centralized and distributed MPC on the electrified Advanced Geared Turbofan 30,000lbf thrust engine.
- Design included accommodations for Turbine Electrified Energy Management (TEEM) strategy.
- Current research towards hierarchical MPC for supervisory approach to energy management.

MPC for Electrified Aircraft Propulsion

Centralized MPC cost function:

$$J(\delta y, \delta u) = \int_t^{t+T} ||\delta\tilde{y}(\tau)||_Q^2 d\tau + \int_t^{t+T_u} (||\big(\delta \mathrm{u}(\tau) - \delta u(\tau - T_s)\big)||_R^2 + ||\delta u_{washout}||_P^2) d\tau$$

where

$$u_{washout} = (-ae^{-at})^{-1})[M_{LPS} \;\; M_{HPS}]^T$$

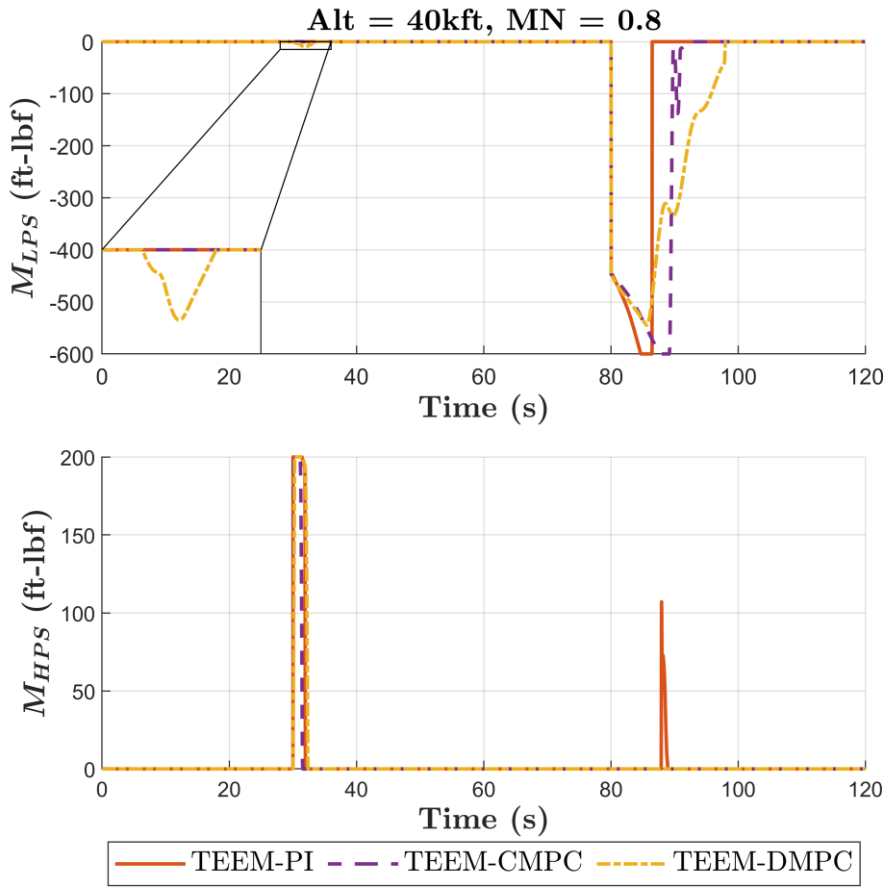


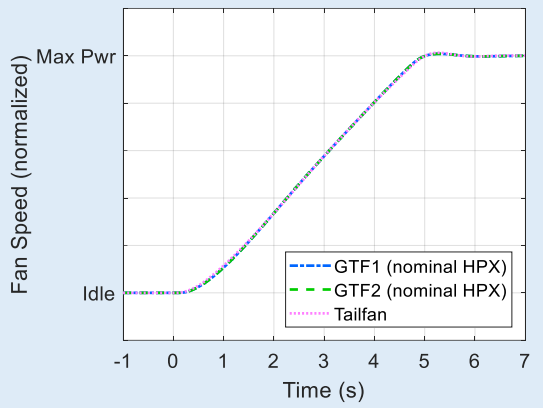
Figure #: Resultant controller motor torque trajectories at cruise condition.

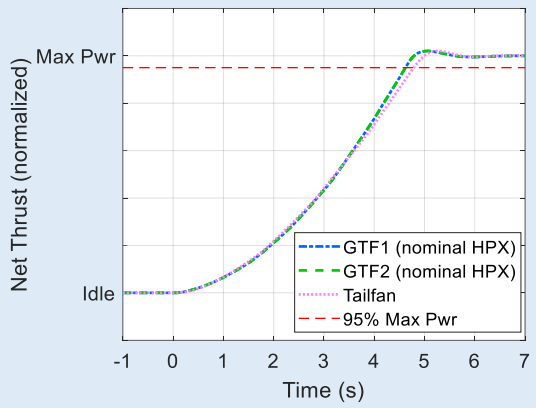
Electrified Aircraft Propulsion Control-Based Fault Management

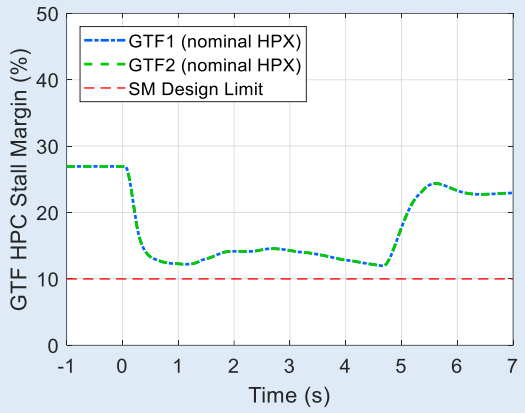
STARC-ABL GTF and Tailfan Acceleration Response: Nominal Response versus Unmitigated Failure Response

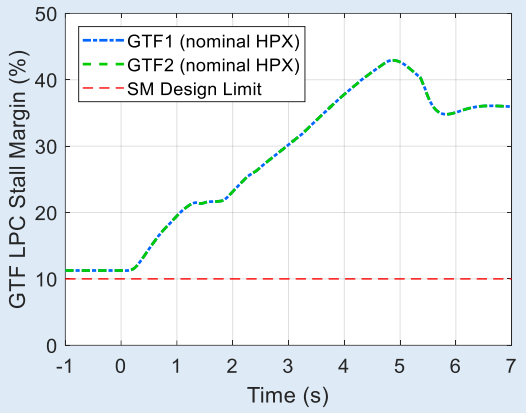
- Idle to maximum power throttle command under nominal conditions and with a failure in Power System 1

Nominal Response

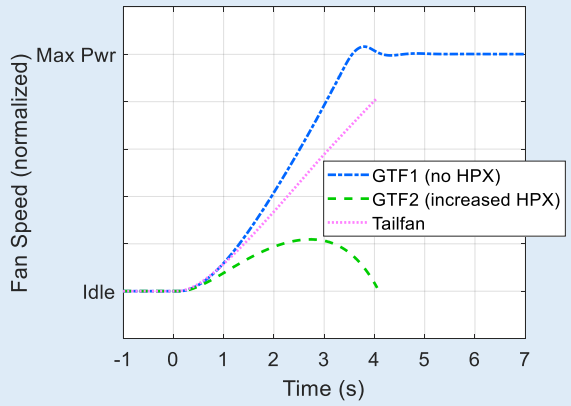


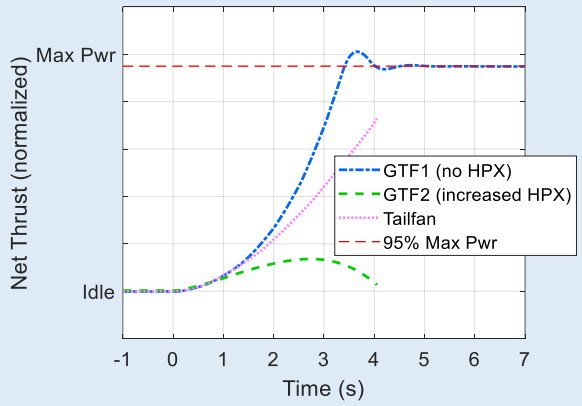


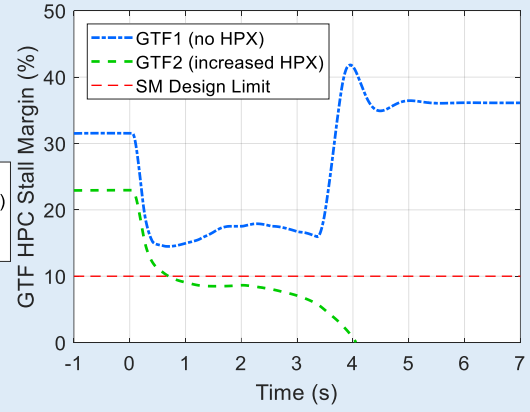


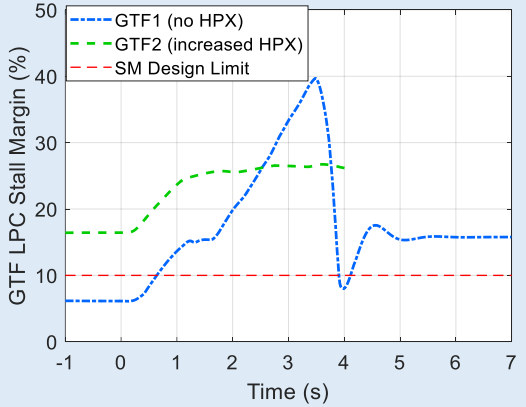


Unmitigated Power System 1 Failure Response





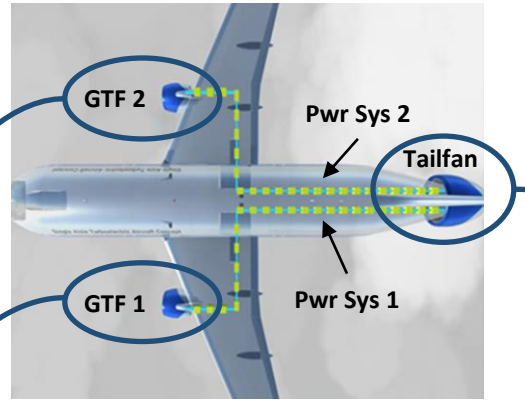




STARC-ABL Reversionary Control Logic for Failure Mitigation

Geared Turbofan (GTF) Reversionary Control Modes:

- VBV schedule updates to maintain LPC operability
- Fuel controller updates to maintain HPC operability and symmetric acceleration response



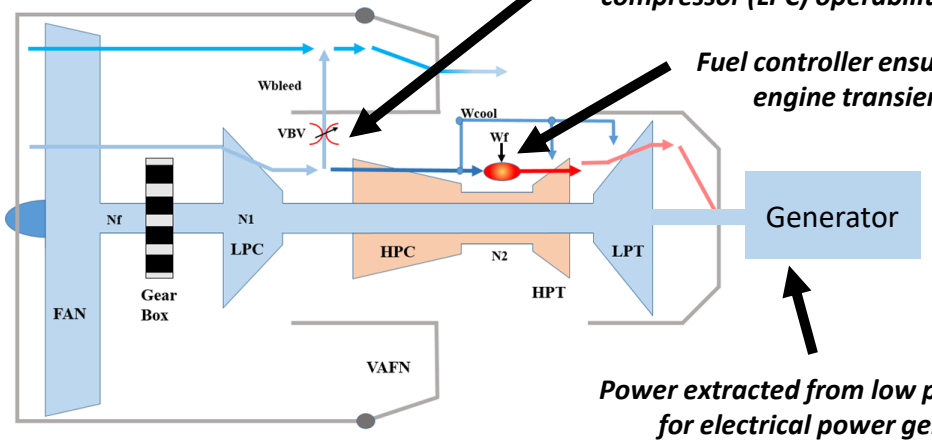
STARC-ABL Architecture

Tailfan Reversionary Control Mode:

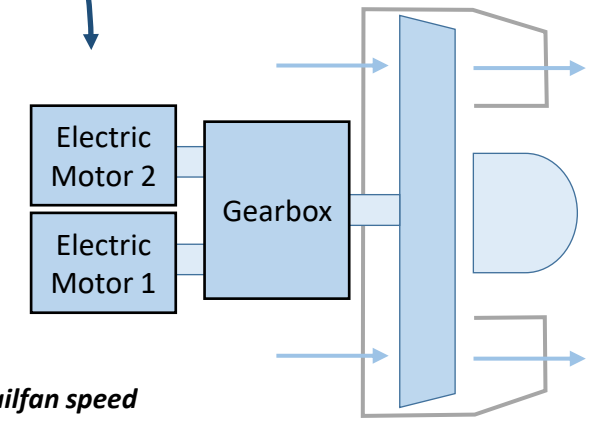
- PLA schedule and acceleration schedule updates to maintain GTF compressor operability and symmetric acceleration response

Variable Bleed Valve (VBV) maintains low pressure compressor (LPC) operability

Fuel controller ensures safe, reliable engine transient operation



Power extracted from low pressure shaft for electrical power generation

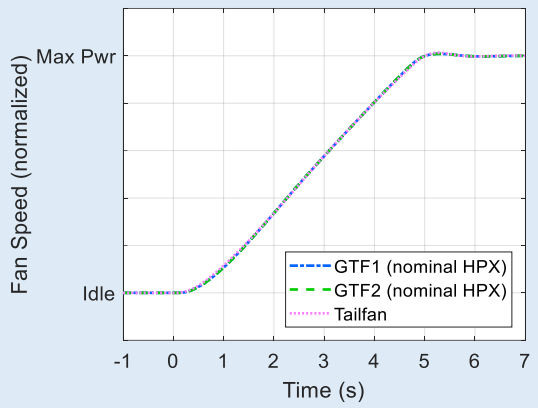


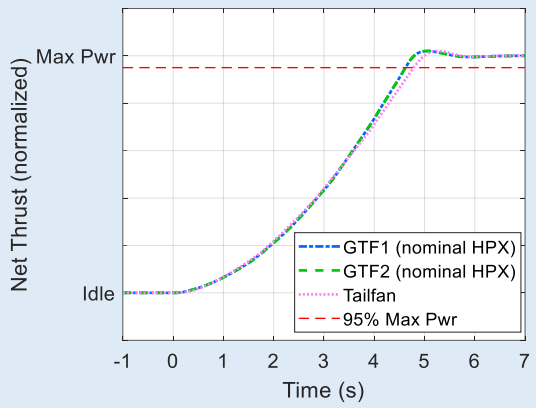
Motor controllers control tailfan speed and transient operation

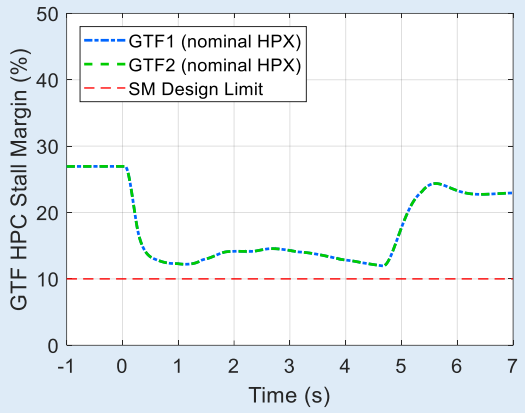
STARC-ABL GTF and Tailfan Acceleration Response: Nominal Response versus Mitigated Failure Response

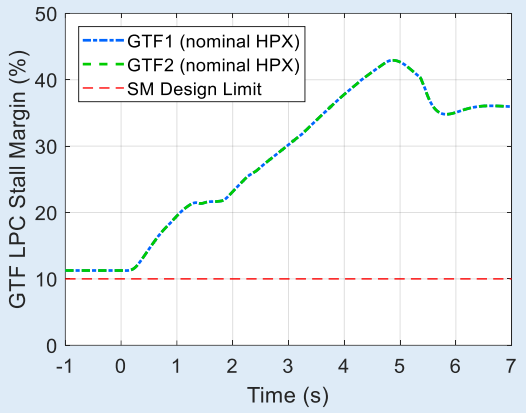
- Reversionary Control Modes Enable Turbomachinery to Continue to Operate in the Presence of a Failure!

Nominal Response

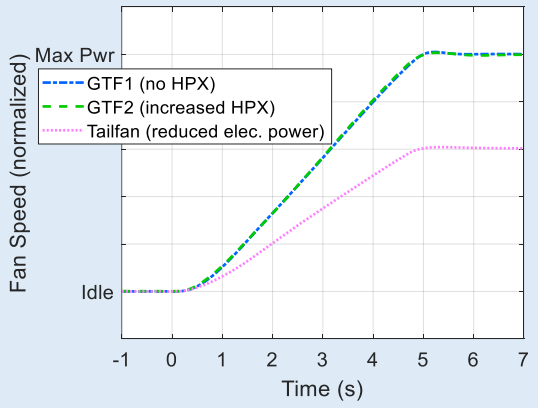


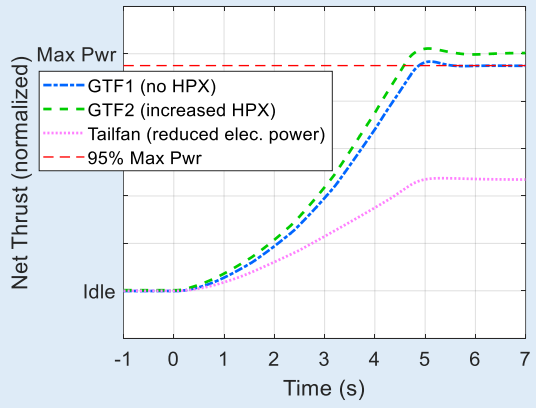


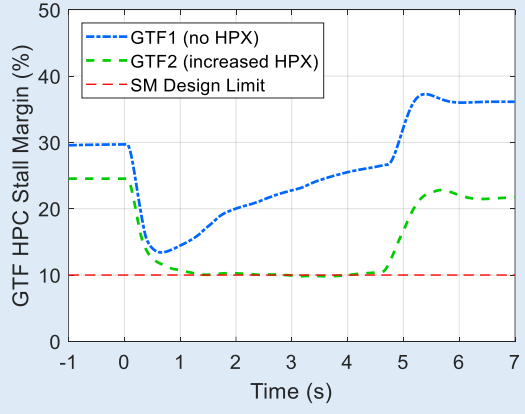


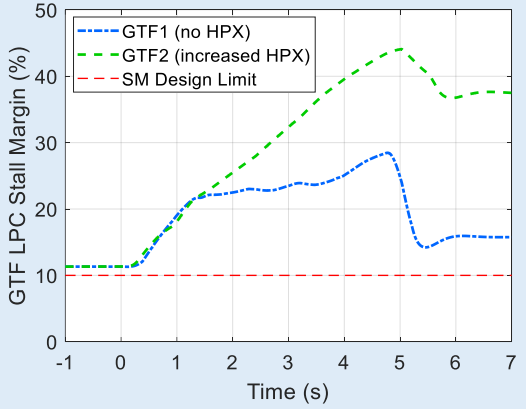


Mitigated Power System 1 Failure Response









Test Facilities

Facility: NASA Electric Aircraft Testbed

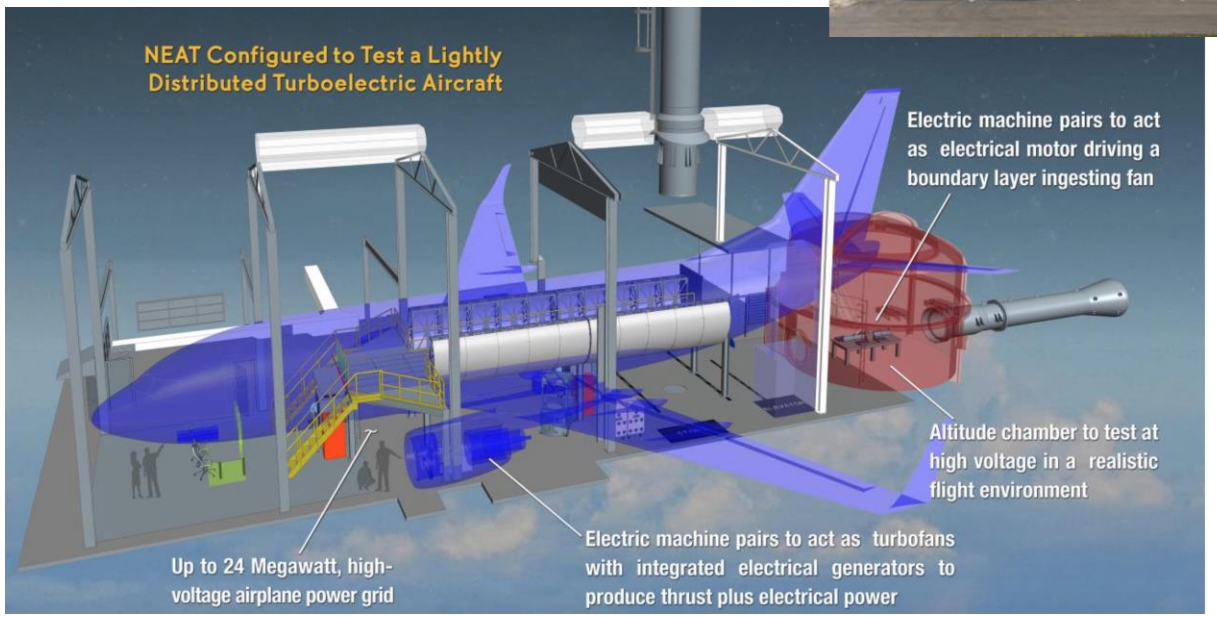
- NEAT testbed to enable large scale flight like powertrain testing at ambient and flight conditions

- Enables hardware in the loop testing of EAP supervisory and fault mitigation controls

Bus Architecture

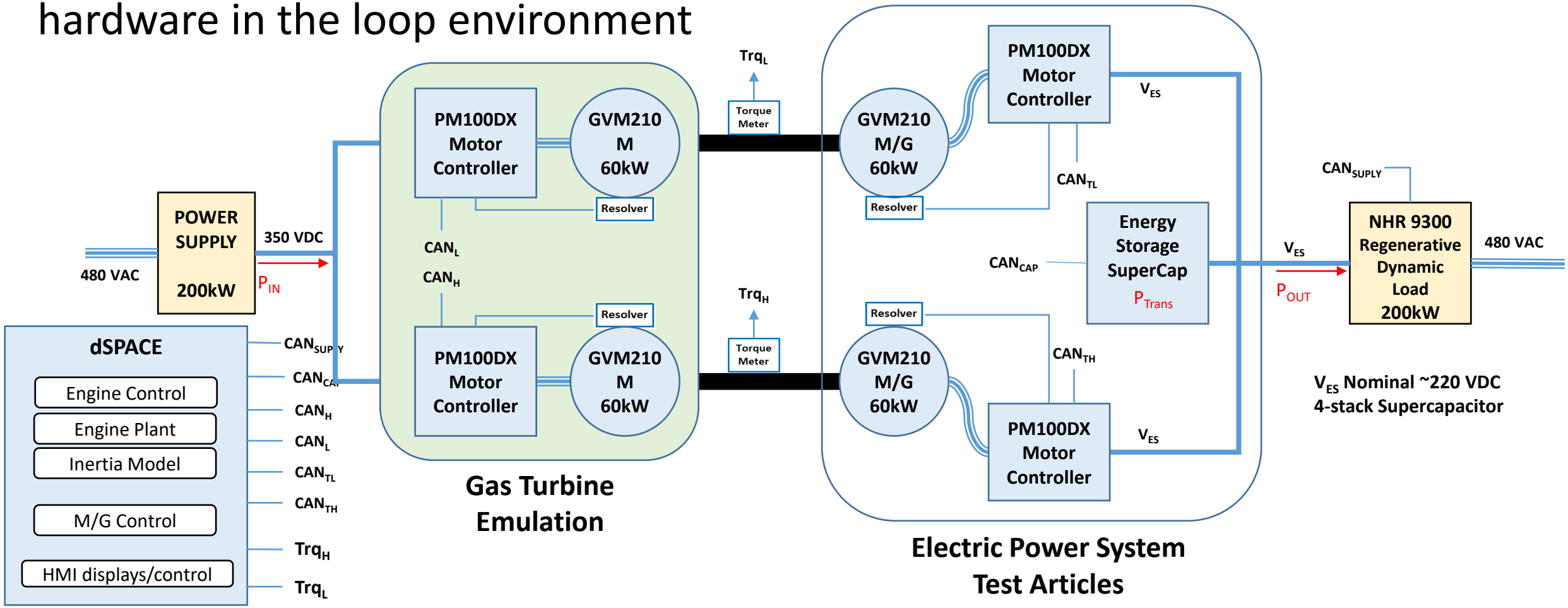
- **MW Inverters & Rectifiers**
- **MW Motors & Generators**
- **System Communication**
- **EMI Mitigation**
- **System Fault Protection**





Facility: Hybrid Propulsion Emulation Rig (HyPER)

HyPER facility is being used to test EAP turbofan concepts in a small-scale hardware in the loop environment

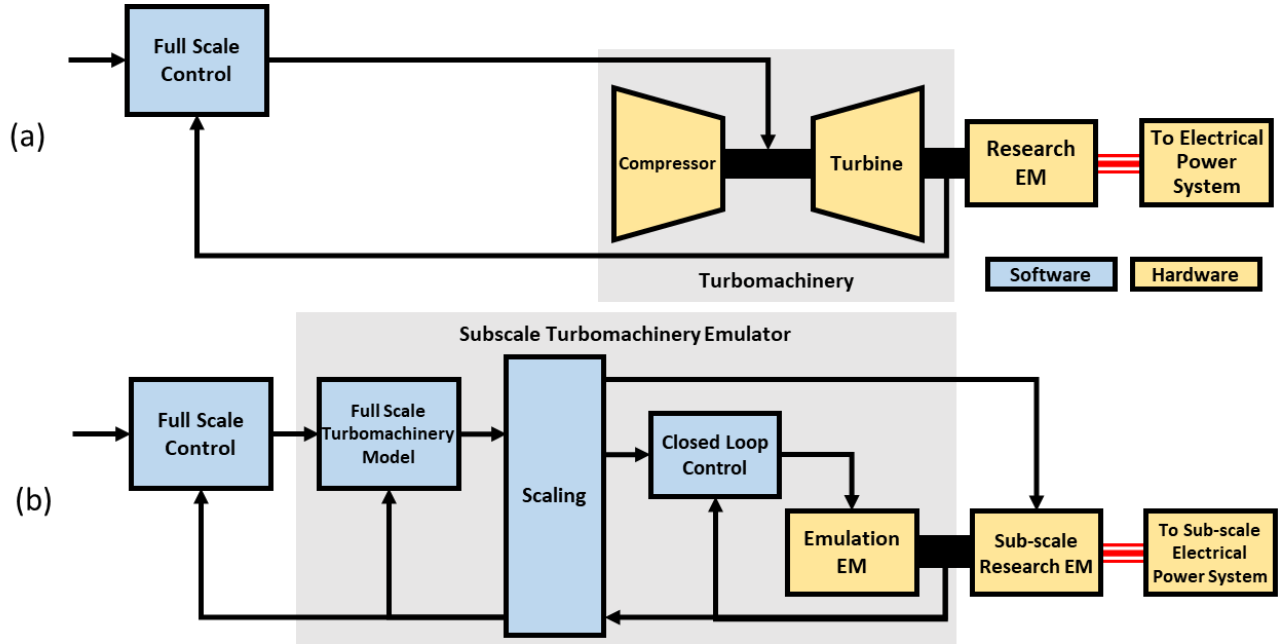


Sliding Mode Impedance Controller with Scaling (SMICS)

- Problem: NEAT and HyPER facilities do not include gas turbine engine turbomachinery
- Solution:
  - SMICS replaces turbomachinery/rotors with an electric machines, closed loop control and scaling algorithm, and full-scale turbomachinery/rotor model.
  - Scales down electromechanical system requirements to use off-the-shelf components
  - Enables testing of full-scale EAP control algorithms using sub-scale electromechanical hardware

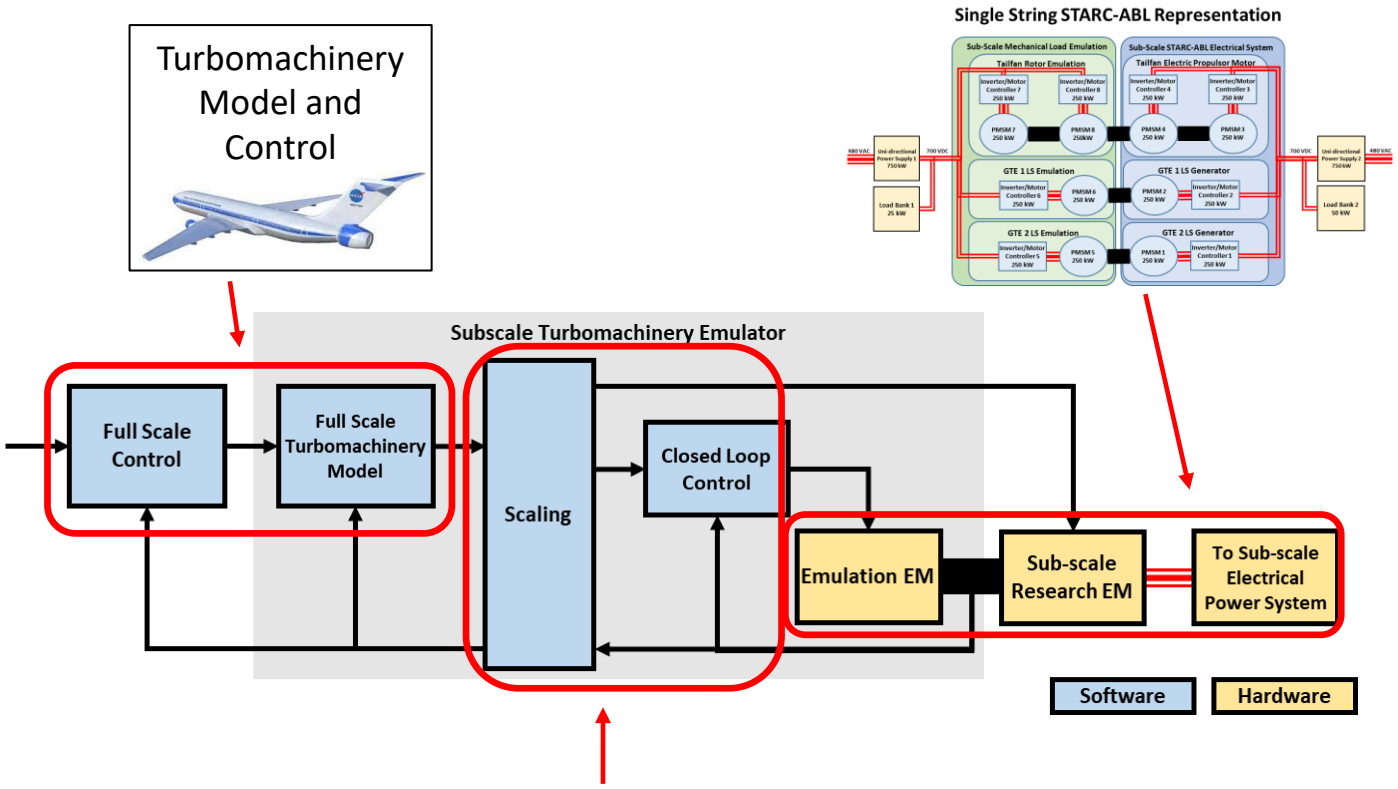
<u>With</u> Turbomachinery Present

<u>Without</u> Turbomachinery Present



SMICS Concept

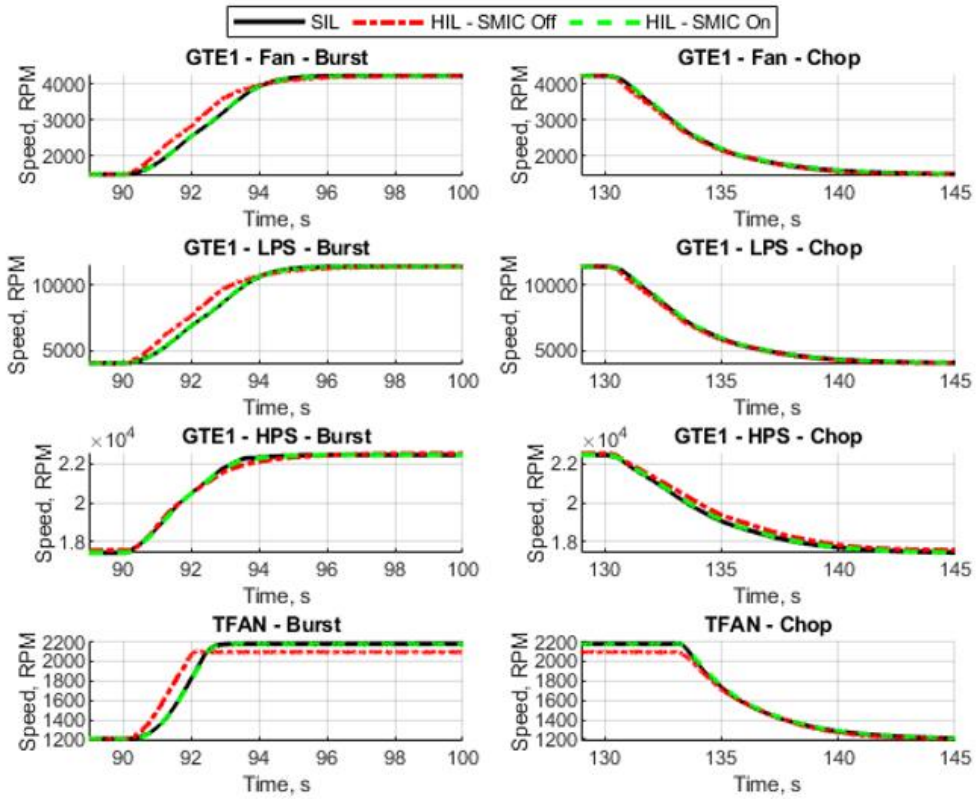
SMICS (continued)



Sliding Mode Impedance Controller with Scaling (SMICS)

$$T_M = \frac{J_P}{\frac{\beta}{\alpha} J_E}\left[\beta T_E + \beta T_G + \eta sat\left(\frac{s}{\phi}\right) + K_P s + K_I \int [s]\, dt + K_D \dot{s}\right] + B_P \omega_P - \beta T_G$$

SMICS Implementation



Rotor Speed Responses with SMICS ON vs SMICS OFF

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