Electrified Aircraft Propulsion Systems: Gas Turbine Control Considerations for the Mitigation of Potential Failure Modes and Hazards

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Outline

- Electrified Aircraft Propulsion (EAP) Systems
  - Background
  - Failure Modes and Failure Mitigation
- Example: Turbomachinery Control Considerations for Failure Mitigation
  - Identification of Failure Modes and Effects
  - Reversionary Control Modes for Failure Mitigation
  - Simulation Results
- Summary

Electrified Aircraft Propulsion (EAP) Background

- EAP relies on the generation, storage, and transmission of electrical power for aircraft propulsion
- Enables aircraft designs that apply advanced propulsion concepts such as distributed electric propulsion and boundary layer ingestion fans
- Benefits include a potential reduction in emissions, fuel burn, noise, and cost

NASA Aeronautics Strategic Implementation Plan

X-57 Maxwell
All Electric

N3-X
Distributed Turboelectric

STARC-ABL
Partial Turboelectric

Quadrotor
All Electric

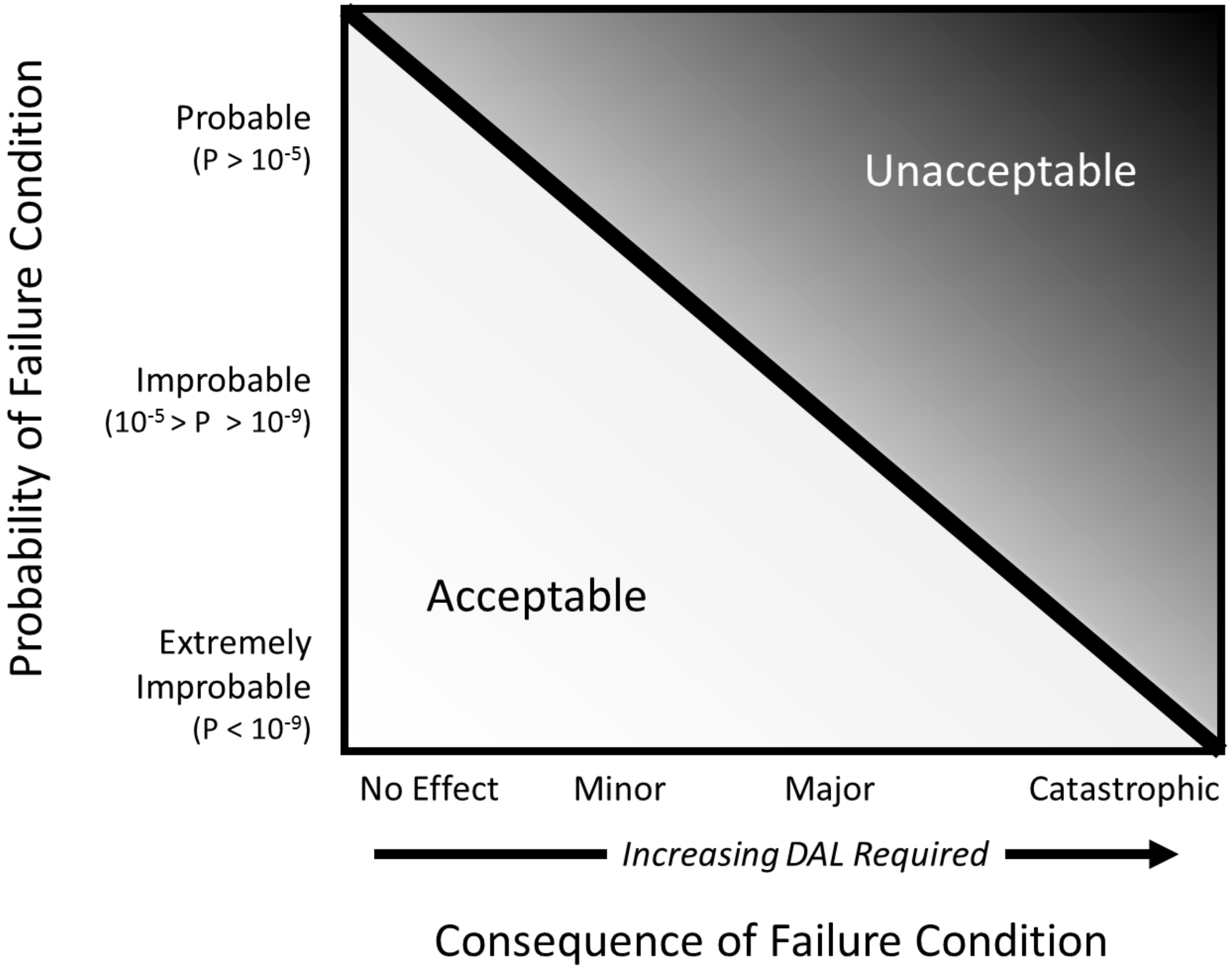
Side-by-Side Helicopter
Hybrid Electric

Tiltwing
Turboelectric

Example NASA EAP Concept Vehicles

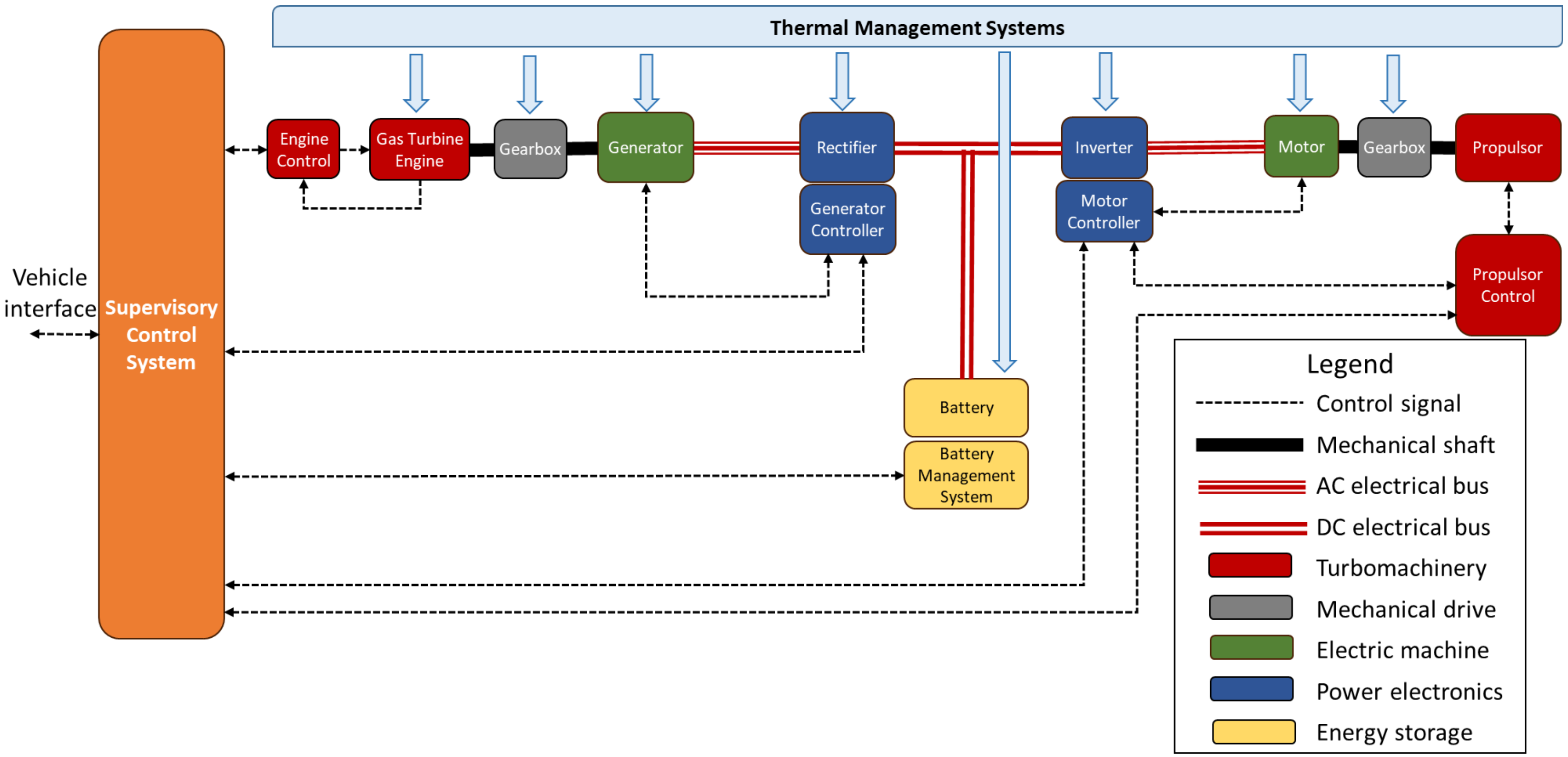
Aircraft System Development and Certification Process

- Any potential hazards in the design must be identified and appropriately mitigated
- Development includes a functional hazard assessment (FHA) conducted to identify all potential functional failures, and classify those failures according to their hazard severity
- The more severe a function's failure condition classification, the greater the development assurance level (DAL) required for the function to ensure that the probability of the hazard is acceptably low



Relationship Between Failure Probability and Failure Hazard Category

Overview of EAP System Components



Generic EAP System Architecture

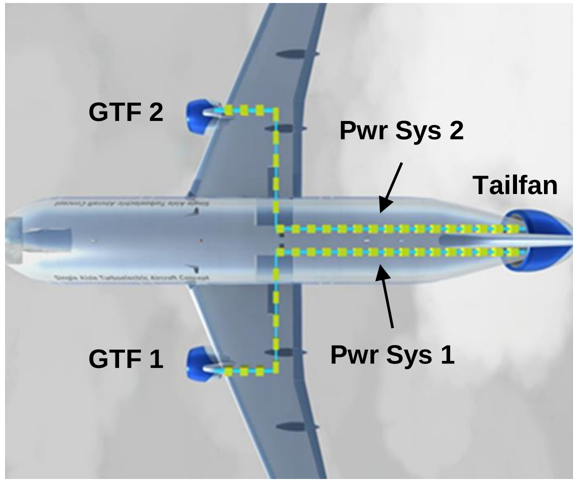
EAP System Components

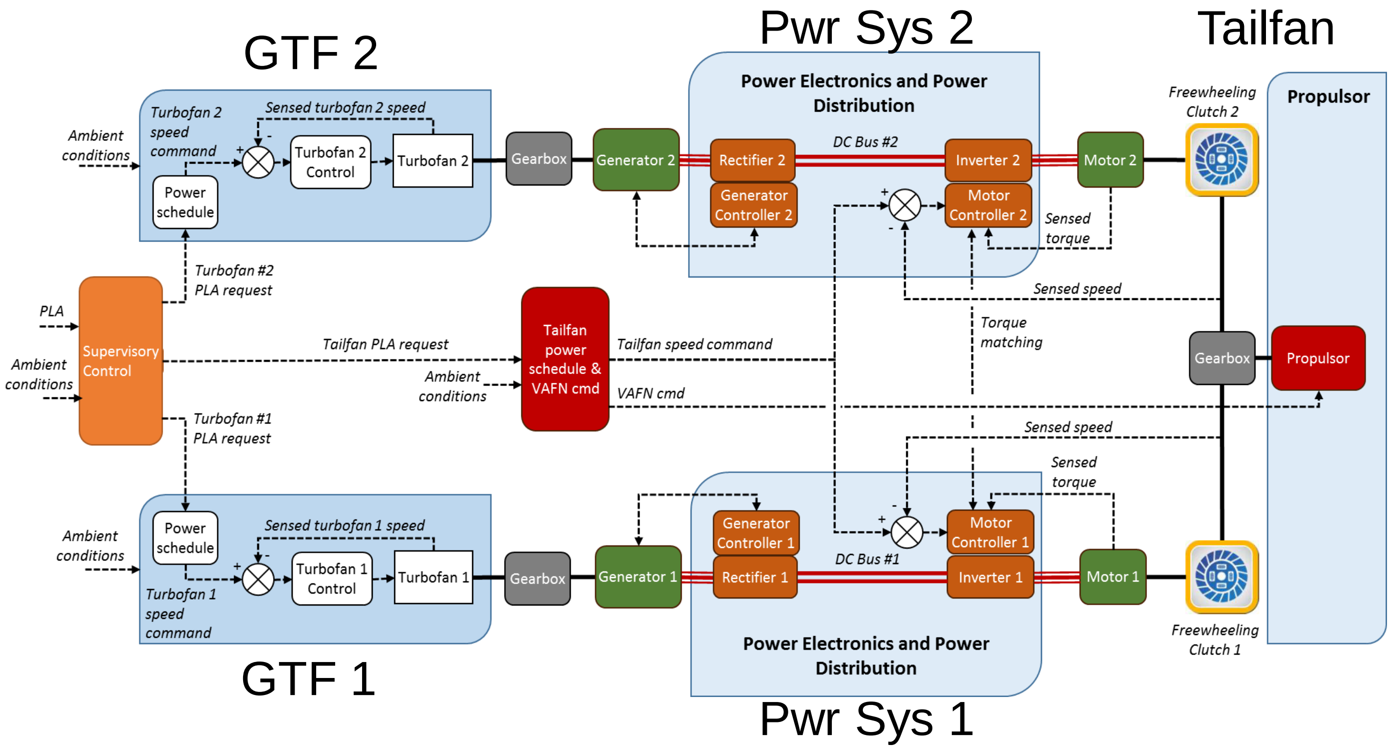
- **Supervisory Control**: Interface between vehicle and propulsion system.
- **Gas Turbine Engines**: Turbomachinery that converts fuel into mechanical power.
- **Gearboxes and Mechanical Drives**: Used for transferring mechanical power throughout EAP system.
- **Electric Machines**: Generators and motors. Used for converting mechanical power into electricity or vice versa.
- **Power Electronics and Power Distribution Systems**: Handles switching, power conversion, and transmission of electrical power throughout system.
- **Energy Storage Systems**: Systems for the storage of electrical energy such as batteries and supercapacitors.
- **Propulsors**: Motor driven propellers or fans used to generate thrust.
- **Thermal Management Systems**: Provide system cooling and heat dissapation

An Example of Turbomachinery Control Considerations for the Mitigation of EAP System Failures

NASA Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsor (STARC-ABL)

STARC-ABL Overview

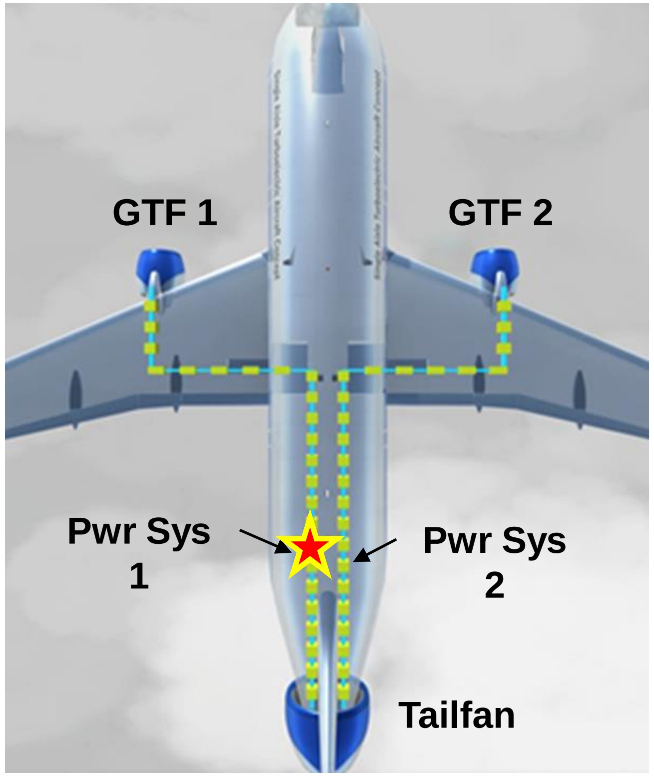




NASA Single-aisle Turboelectric AiRCraft with Aft Boundary Layer propulsor (STARC-ABL)

- Two wing-mounted geared turbofan engines (GTFs) produce thrust and supply mechanical offtake power to generate electricity
- Generators and rectifiers convert mechanical power into electricity
- Electricity transferred over two parallel direct current power buses
- Inverters and motors convert electricity into mechanical power supplied to tailfan propulsor
- Tailfan propulsor applies boundary layer ingestion for increased propulsive efficiency

STARC-ABL Subsystem Failure Modes and Coupled Effects



STARC-ABL Architecture

Coupled Failure Effects on Other Subsystems	Failed Subsystem: GTF1 Failed	GTF2 Failed	Power System 1 Failed	Power System 2 Failed	Tailfan Failed
GTF1	*Failed*	*Increased HPX*	*No HPX*	*Increased HPX*	*No HPX*
GTF2	*Increased HPX*	*Failed*	*Increased HPX*	*No HPX*	*No HPX*
Power System 1	*No Electric Power*	*Increased Electric Power*	*Failed*	*Increased Electric Power*	*No Electric Power*
Power System 2	*Increased Electric Power*	*No Electric Power*	*Increased Electric Power*	*Failed*	*No Electric Power*
Tailfan	*Reduced Electric Power*	*Reduced Electric Power*	*Reduced Electric Power*	*Reduced Electric Power*	*Failed*

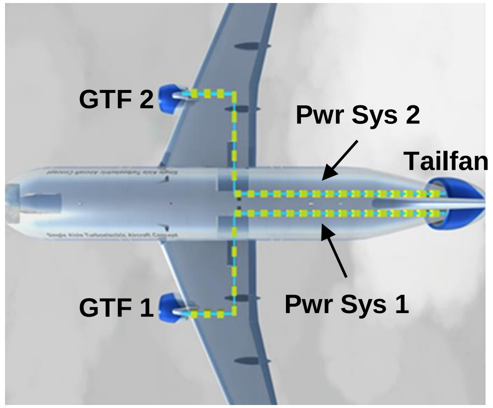
STARC-ABL Failure Modes and Effects Matrix

Failure Effects on Turbomachinery:

- *GTFs: Experience either an increase or elimination of horse power extraction (HPX)*
- *Tailfan: Experiences a reduction in available electrical power*

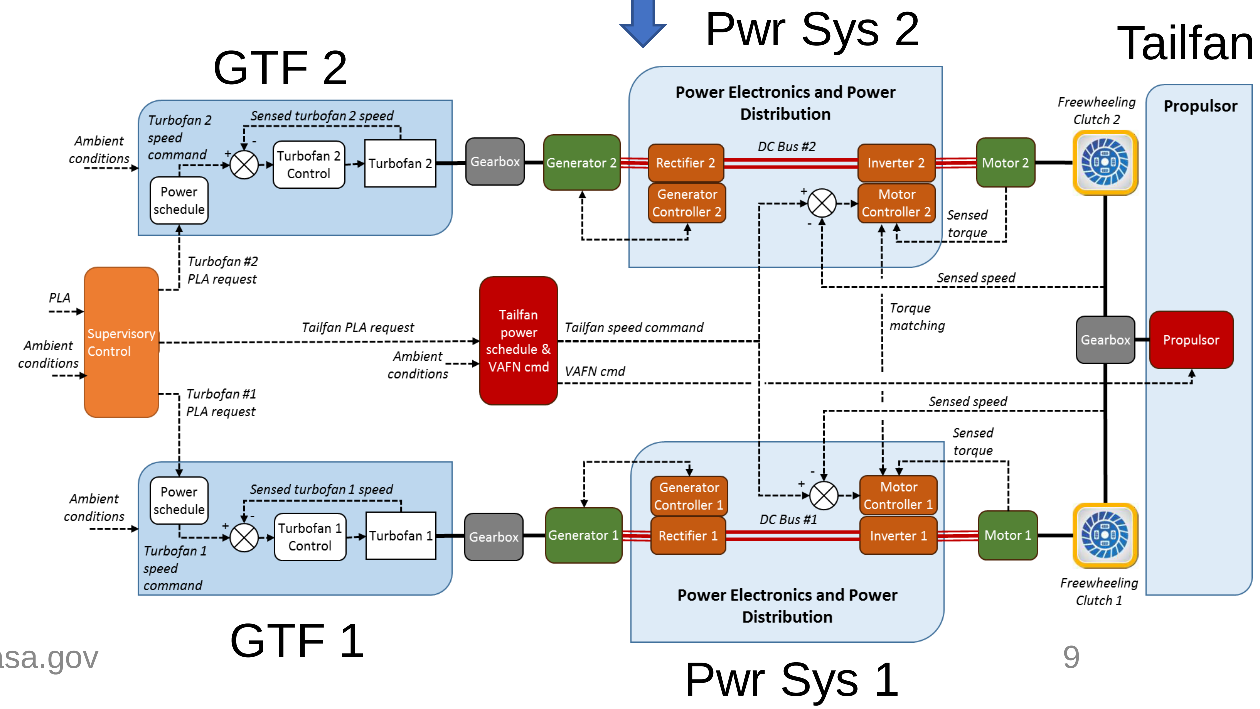
STARC-ABL Propulsion System Simulation

- Coded in MATLAB® Simulink®
  - Turbomachinery coded in Toolbox for Modeling and Analysis of Thermodynamic Systems (T-MATS)
  - Electrical component coded using a power flow modeling approach
  - Separate controllers for each GTF and the Tailfan



GTF and Tailfan Controllers

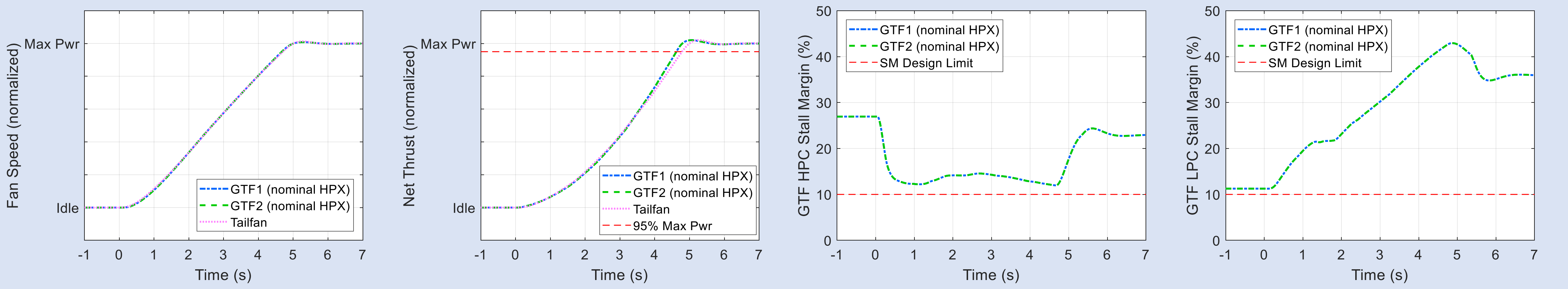
	GTF Control	Tailfan Control
Power schedule	• Power Lever Angle (PLA) commands target fan speed (N1)	• Power Lever Angle (PLA) commands target fan speed (N1)
Primary control loop	• Modulates fuel flow (Wf) to achieve target N1	• Modulates motor power to achieve target N1
Transient control schedule	• Wf/Ps3 vs N1	• N1dot vs N1
Variable geometry	• Variable Area Fan Nozzle (VAFN) • Variable Bleed Valve (VBV)	• Variable Area Fan Nozzle (VAFN)
Control limits	• Speeds, fuel flow, Wf/Ps3	• Speed, motor power



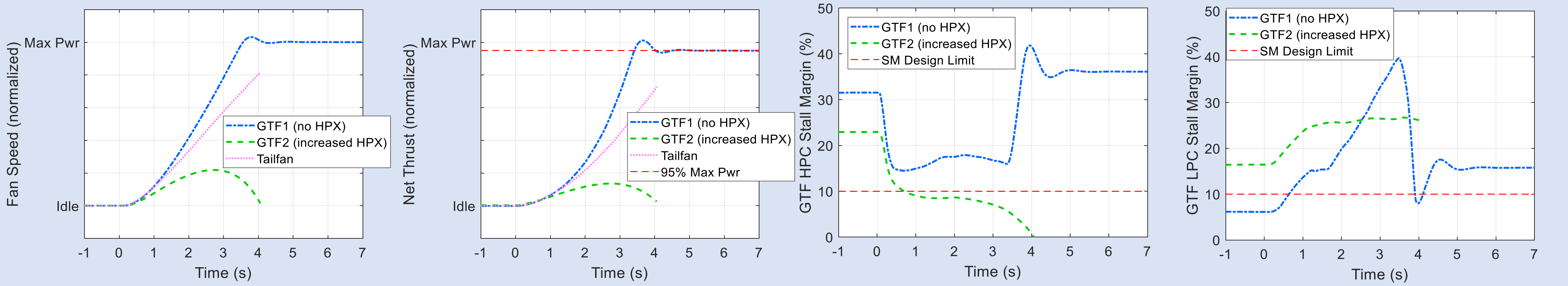
STARC-ABL GTF and Tailfan Acceleration Response: Nominal Response versus Unmitigated Failure Response

- Idle to maximum power throttle command introduced at the 25k feet, 0.6 Mach flight condition
- Response evaluated under nominal conditions and with a failure in Power System 1

Nominal Response

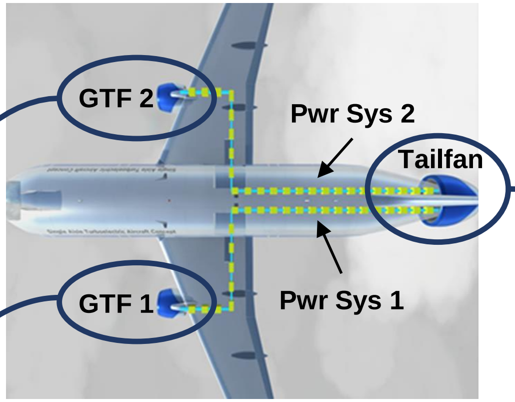


Unmitigated Power System 1 Failure Response



STARC-ABL Reversionary Control Logic for Failure Mitigation

<u>Geared Turbofan (GTF) Reversionary Control Modes:</u>
- VBV schedule updates to maintain LPC operability
- Fuel controller updates to maintain HPC operability and symmetric acceleration response

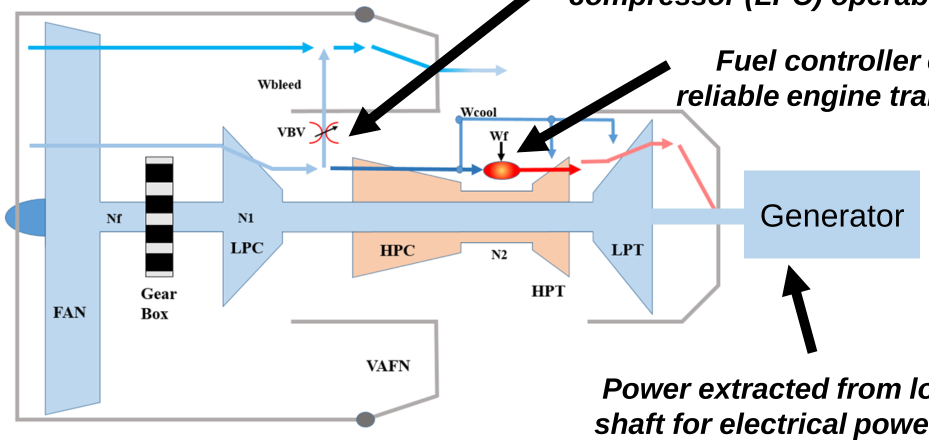


STARC-ABL Architecture

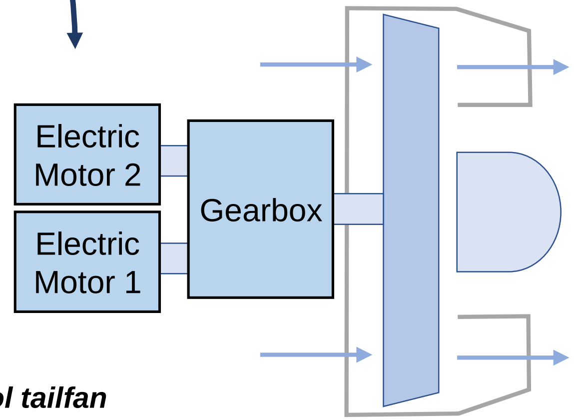
<u>Tailfan Reversionary Control Mode:</u>
- PLA schedule and acceleration schedule updates to maintain GTF compressor operability and symmetric acceleration response

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

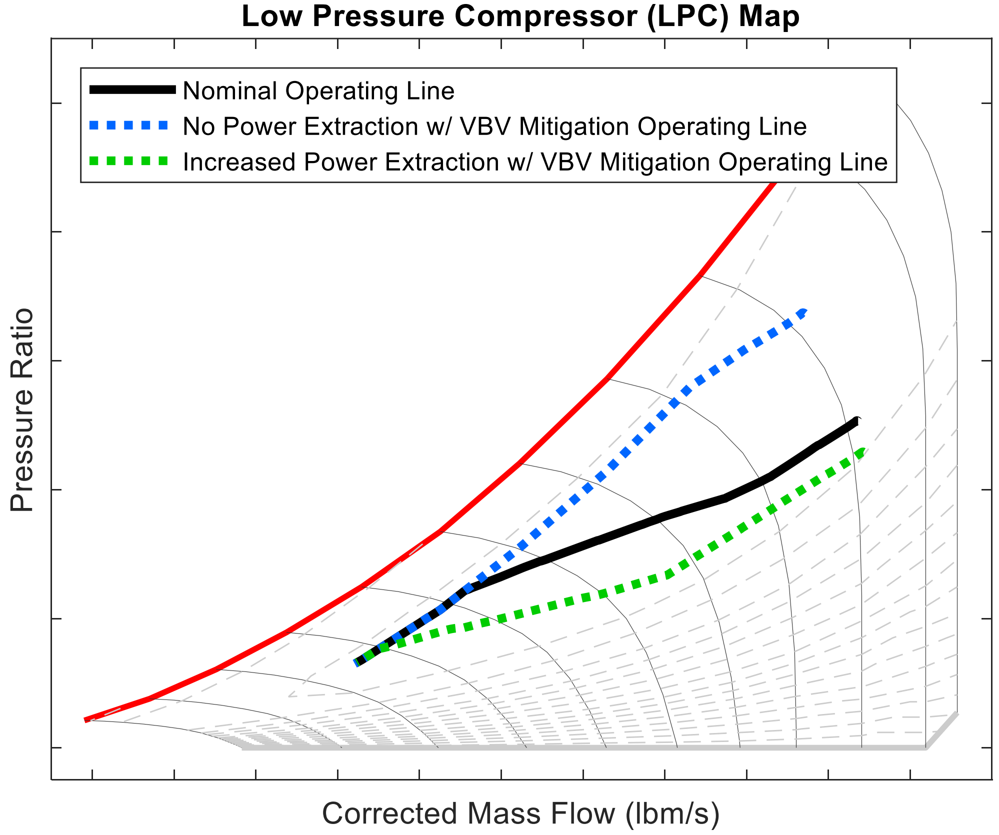


Motor controllers control tailfan speed and transient operation

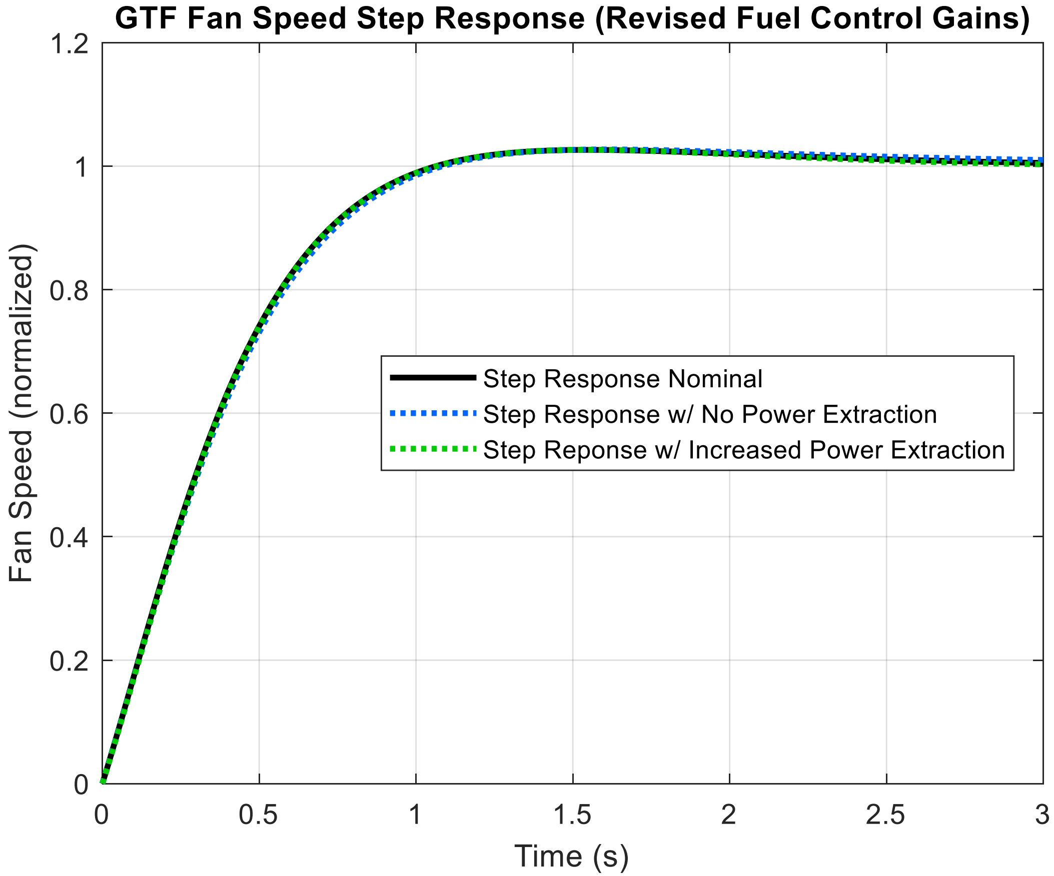
Power Extraction Fault Mitigation (cont.)
(Revised GTF and Tailfan Control Logic)

(results shown at Altitude = 25k feet, Mach = 0.6 operating condition)

1. Revised GTF Variable Bleed Valve (VBV) Schedule



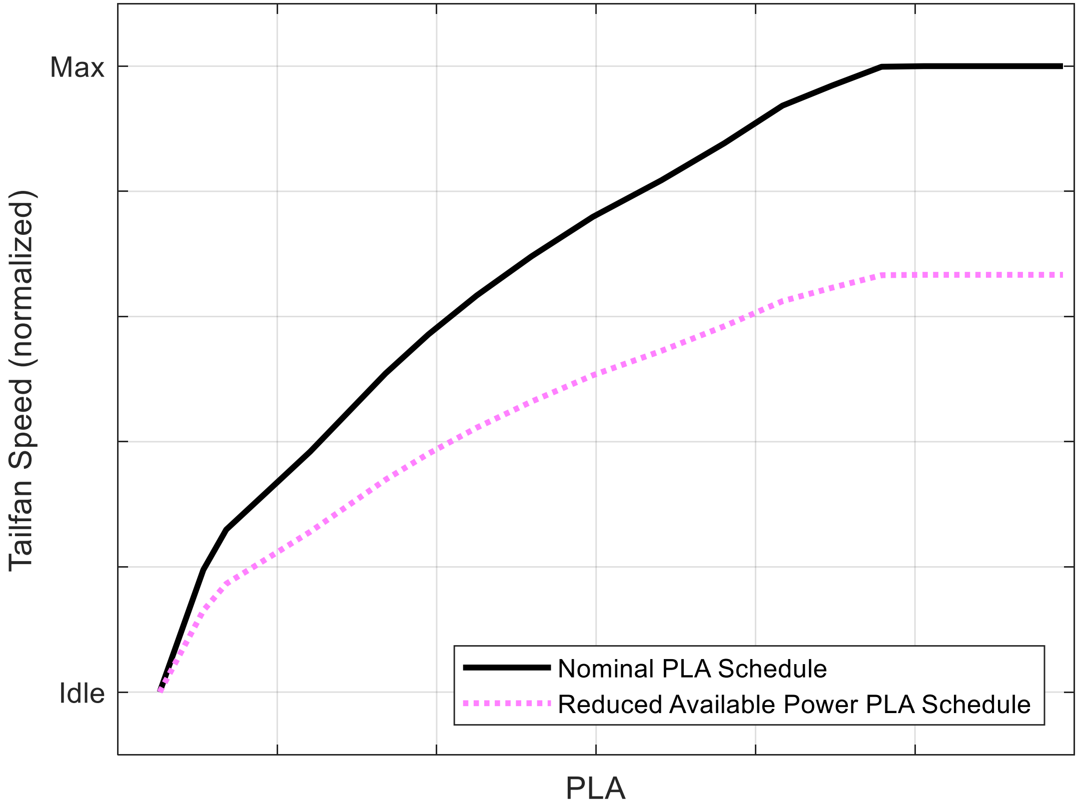
2. Revised GTF Fuel Control Setpoint Control Gains



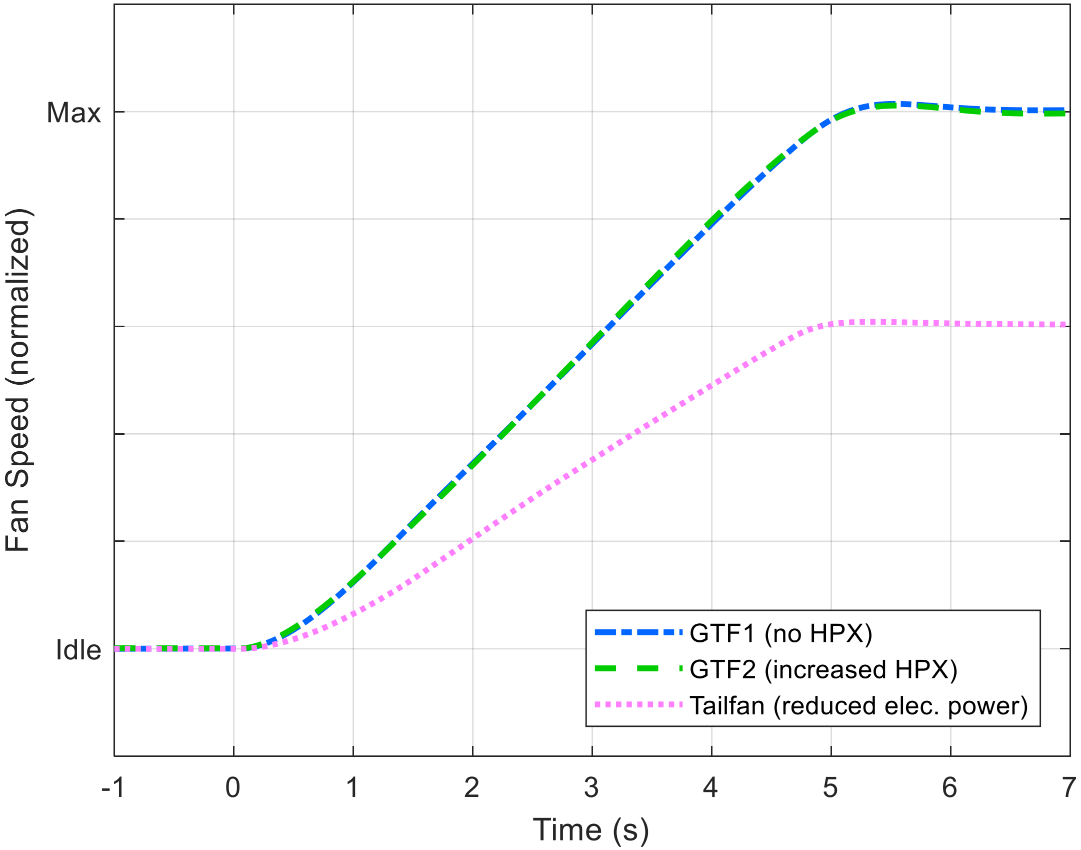
Power Extraction Fault Mitigation (cont.)
(Revised GTF and Tailfan Control Logic)

(results shown at Altitude = 25k feet, Mach = 0.6 operating condition)

3. Revised Tailfan Power Lever Angle (PLA) to Fan Speed Schedule



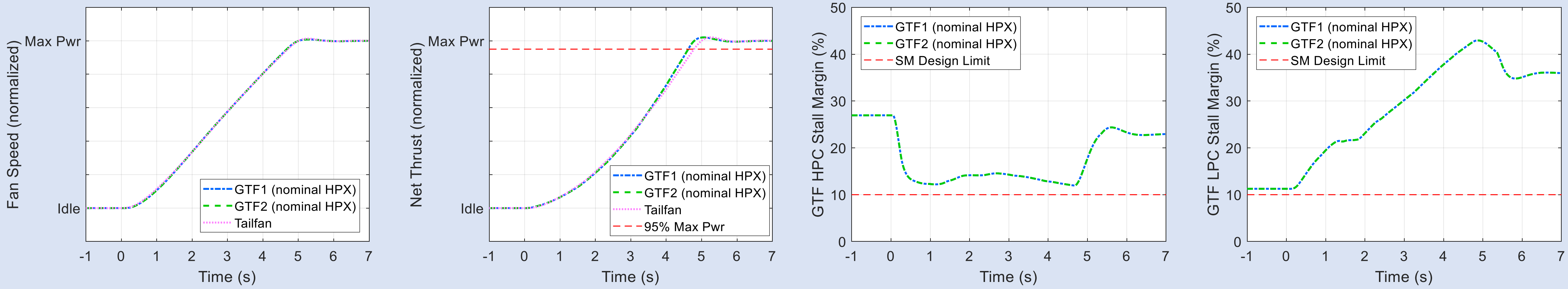
4. Revised GTF and Tailfan Acceleration Schedules



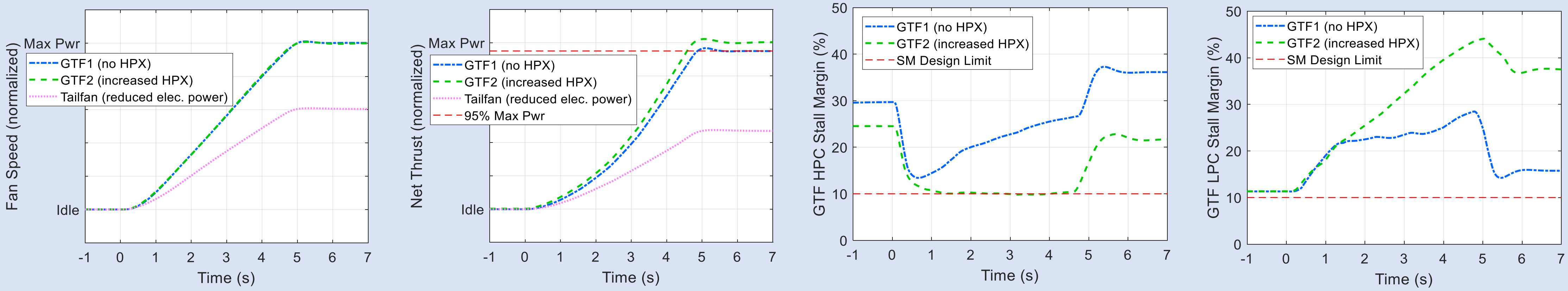
STARC-ABL GTF and Tailfan Acceleration Response: Nominal Response versus Mitigated Failure Response

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

Nominal Response



Mitigated Power System 1 Failure Response



Summary

- Electrified Aircraft Propulsion (EAP) system failure mitigation
  - EAP systems present novel failure modes and hazards beyond those found in conventional propulsion designs
  - Mitigation of these failures requires a system-level approach
  - Turbomachinery controls will play a key role in the mitigation of those failures

- Future steps:
  - Incorporate failure detection logic
  - Extend to cover full envelope transient operation
  - Demonstrate failure mitigation in EAP test facilities

Acknowledgements

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