National Aeronautics and Space Administration

Transformational Tools and Technologies (T^3) Project

Energy Management Control for Electrified Gas Turbine Engines

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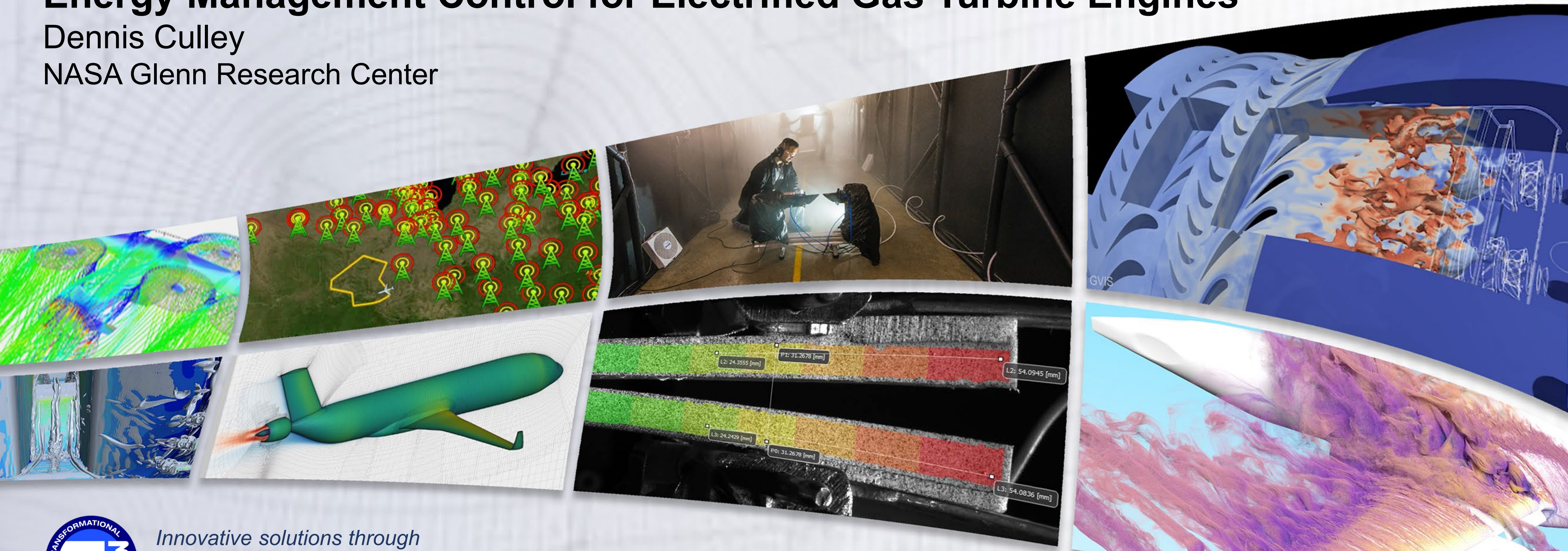

Innovative solutions through foundational research and cross-cutting tools

2024 Turbine Engine Technology Symposium
September 9 - 12, 2024

Outline

- Overview NASA Transformational Tools and Technologies (TTT) Project – Propulsion Controls
- Turbine Electrified Energy Management
- Transient Dynamic Modeling
- Operability Influenced Design
- Integration of Electric Machines with Turbomachinery
- Hybrid Propulsion Emulation Rig
- Tools

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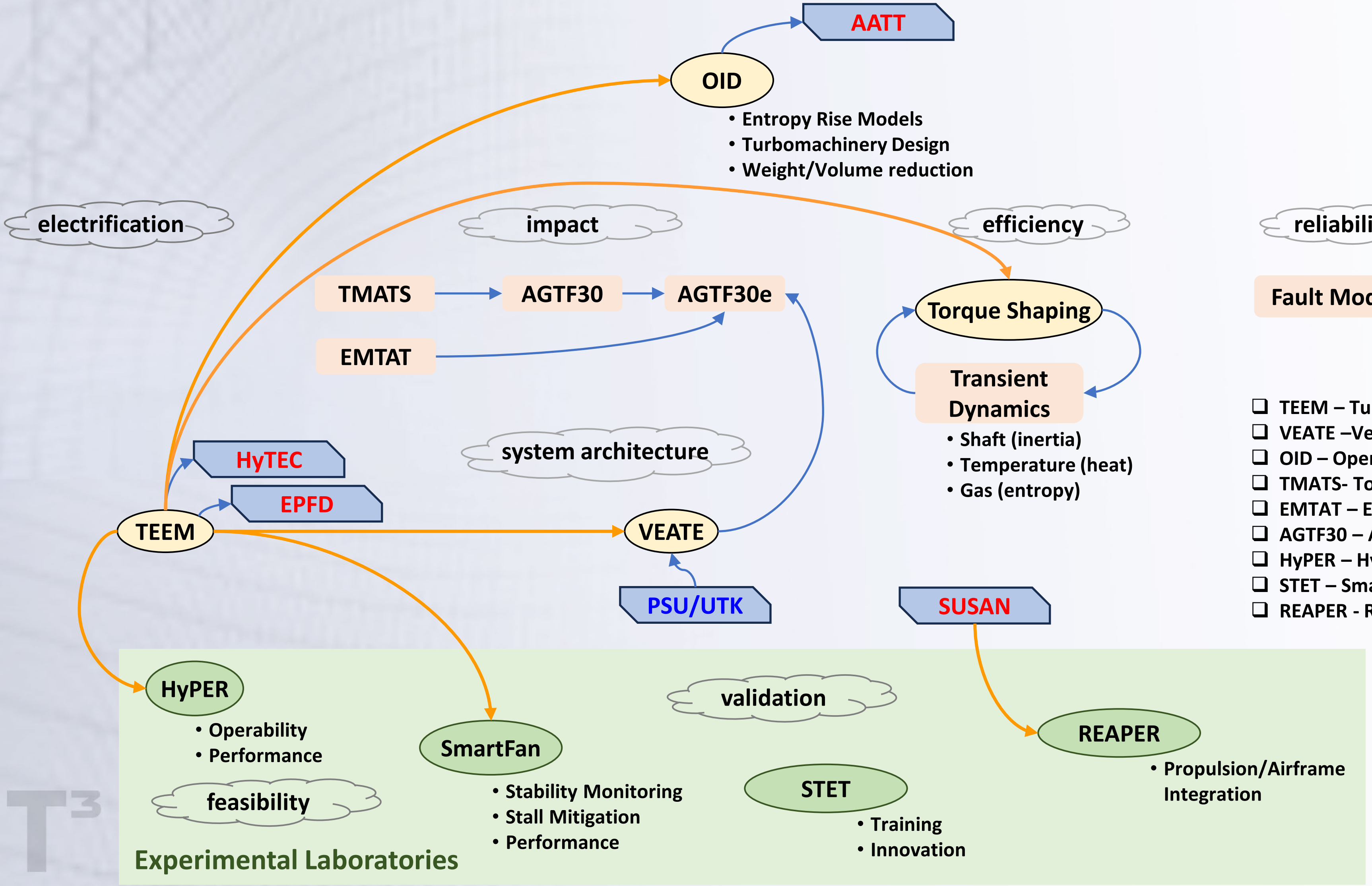
Transformational Tools and Technologies (T³) Propulsion Controls Eco-System



- TEEM – Turbine Electrified Energy Management
- VEATE –Versatile Electrically Augmented turbine Engine
- OID – Operability Influenced Design
- TMATS- Toolbox for the Modelling and Analysis of Thermodynamic Systems
- EMTAT – Electrical Modeling and Thermal Analysis toolbox
- AGTF30 – Advanced Geared Turbofan 30k thrust (e –electrified)
- HyPER – Hybrid Propulsion Emulation Rig
- STET – Small Turbine Engine Testbed
- REAPER - Reconfigurable Aircraft Piloted Evaluation Research lab

- HyTEC – Hybrid Thermally Efficient Core Project
- EPFD – Electrified Powertrain Flight Demonstration Project
- AATT – Advanced Air Transport Technology Project
- SUSAN- Subsonic Single Aft Engine (SUSAN) Aircraft
- RLCC – Reduced Life Cycle Cost Subproject
- iM – Innovative Measurements
- PSU – Pennsylvania State University
- UTK – University of Tennessee Knoxville

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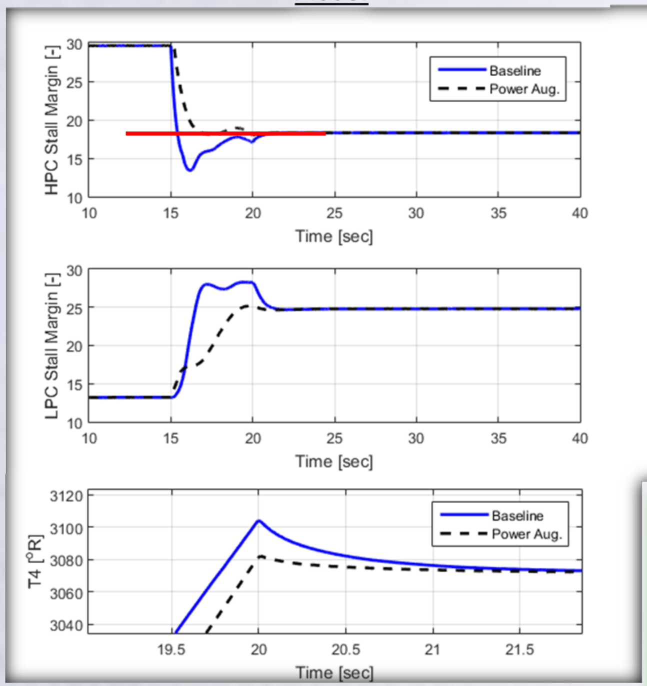
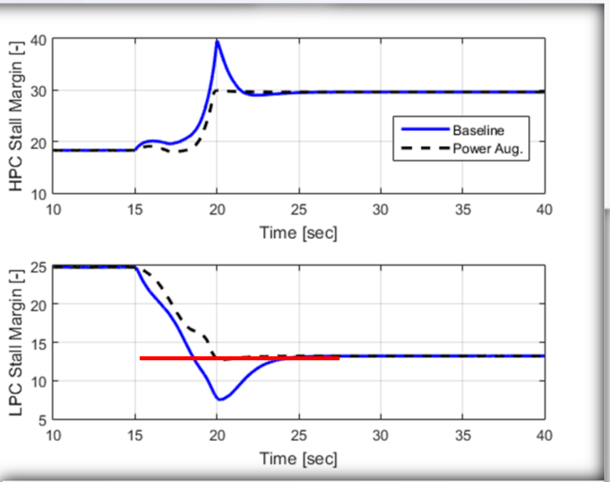
The Impact of Turbine Electrified Energy Management (TEEM)

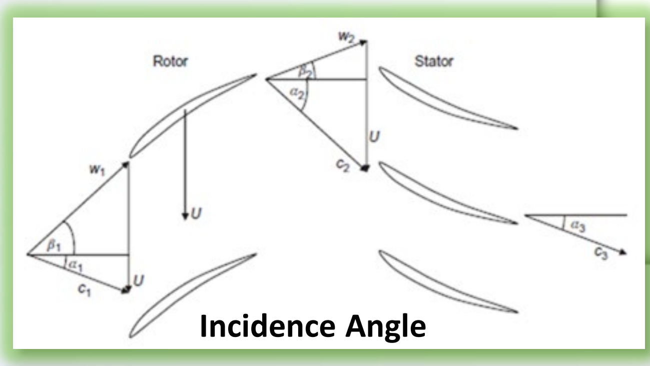
Typically, compressor stability is maintained using limits on fuel flow rate-of-change, scheduled actuation of variable geometry, and compressor bleed. Success is indicated by maintaining proper flow incidence angle across the blading. Fundamentally, it is a state of quasi-equilibrium between energy states involving inertia, gas path, and heat.

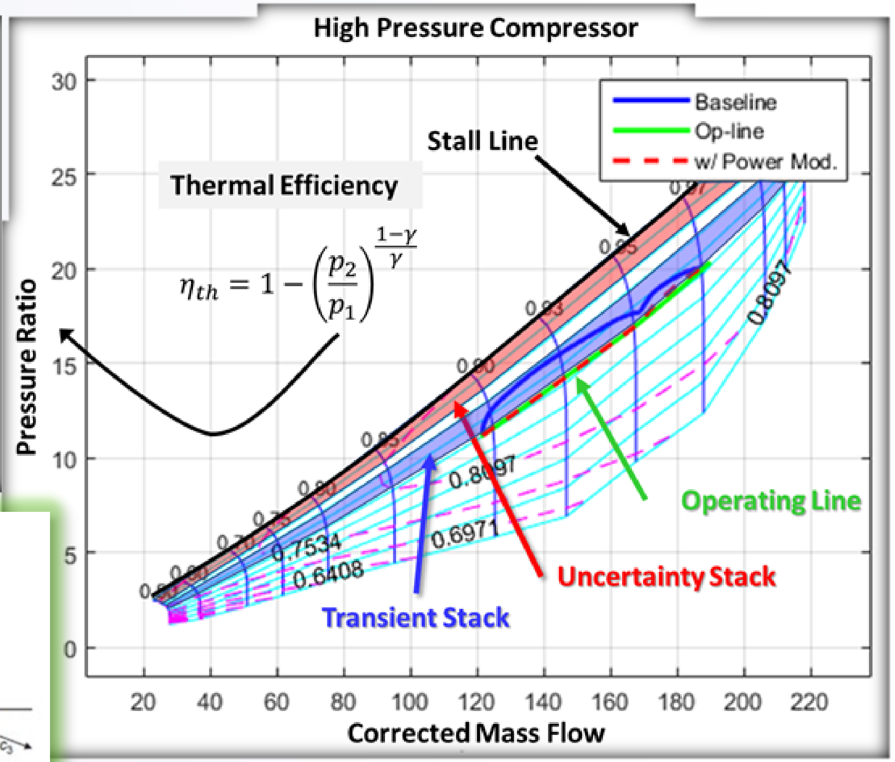
Accel

Decel









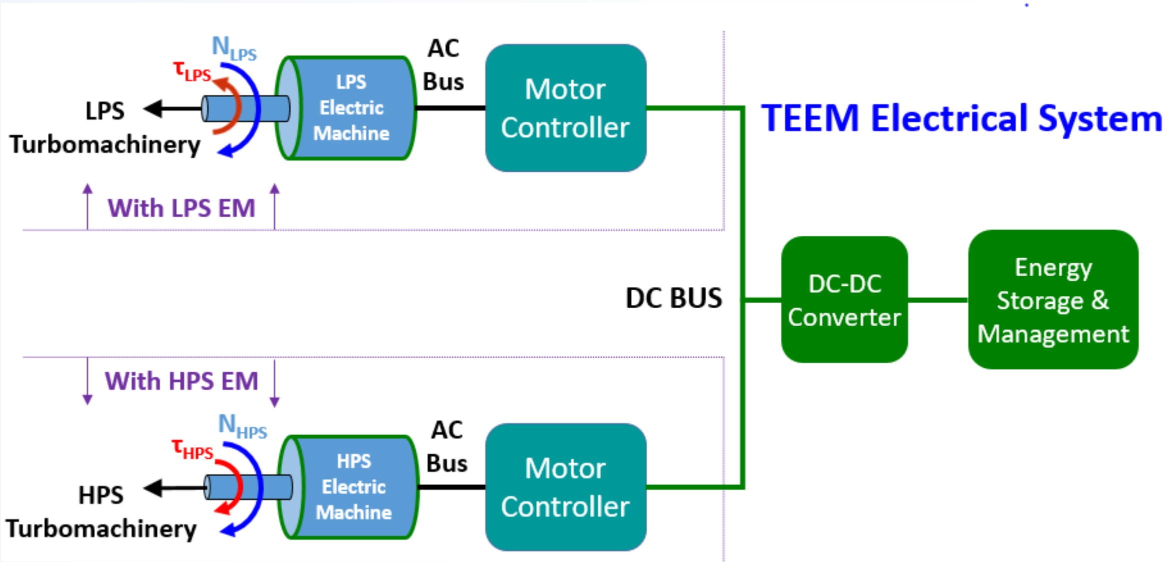
Transient Electric Actuation

Electric machines make very good actuators for turbomachinery stability control, having about 1000x bandwidth of the engine thrust output and bi-directional torque capability. They can force beneficial changes to rotational speed (shaft dynamics) independent of fuel flow control.

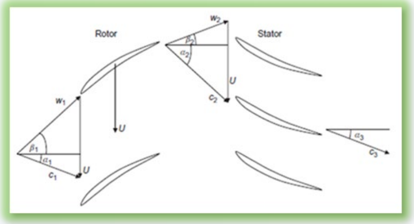
In general

- Torque addition to the HP shaft during acceleration benefits the HP compressor stall margin.
- Constraints are the available energy and the power of the actuator (motor).

- Torque extraction from the LP shaft during deceleration benefits the LP compressor stall margin.
- Constraints are the power of the actuator (generator) and what to do with the extracted energy.
- Power extracted from the LP shaft can be used in the HP shaft to improve low power engine efficiency.

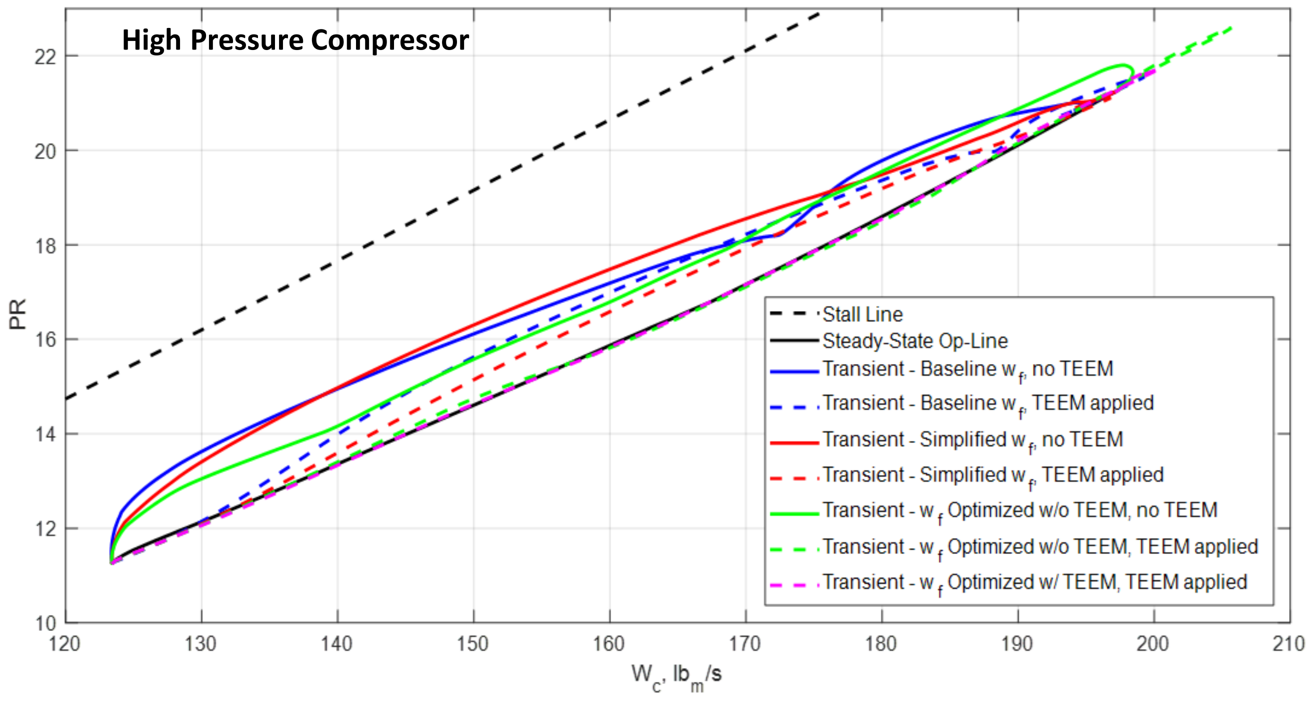


Whereas fuel flow directly affects gas dynamics (and shaft dynamics indirectly), electric actuation directly affects the shaft dynamics (and gas dynamics indirectly). Controlling both helps to minimize the perturbation of the gas dynamics, in essence reducing the entropy rise in the gas path.



Optimization – Torque Shaping

NASA has developed optimizations of the TEEM and fuel flow strategies within the propulsion system trade space using machine learning and genetic algorithms. These results can vary depending on the system architecture and specific system goals.



Results indicate there is significant capability with electric actuation to force the system to respond as if at steady state even while undergoing transient throttle movements.

<u>Trade Space</u>

- Operability, utilization of the transient stack
- Electric Machine power
- Energy storage and power flow
- Thrust response time
- Engine degradation
- Fuel flow
- Peak turbine temperatures and tip clearance

The ability to control engine shaft torque using fuel and electric machines is so significant that we are incorporating engine model improvements to include heat and gas dynamics.

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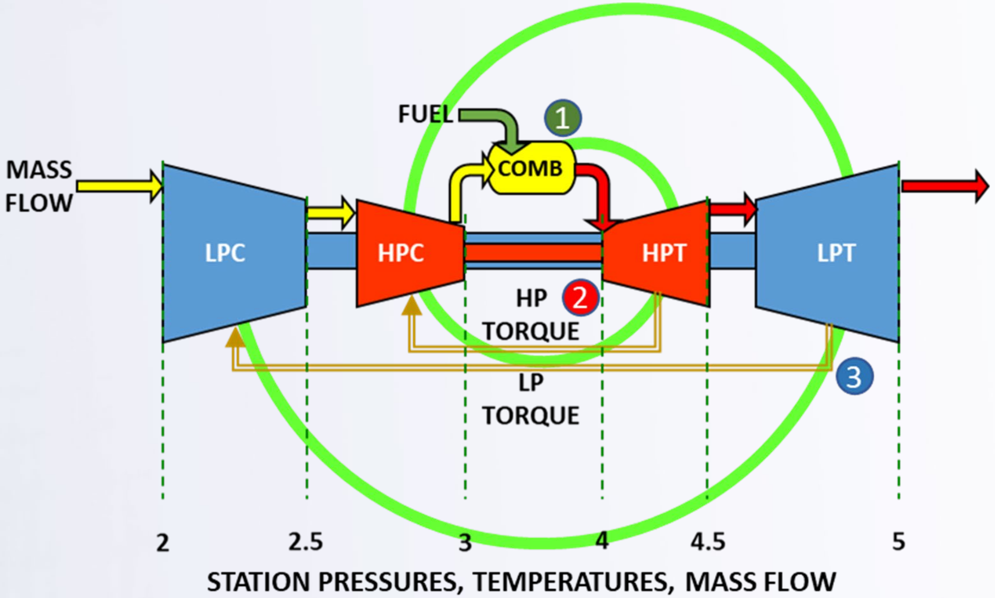
Turbomachinery Transient Dynamics

Significant performance benefits can be achieved by reducing the need for transient stack margin in the compressors. However, the primary objective of control is to avoid instability, therefore the incentive is to develop an improved understanding of the dynamics that cause instability. Our existing quasi-steady engine models rely primarily on the effects of shaft dynamics although we have recently begun to incorporate temperature effects on the gas path.

A lack of empirical data drives the need to develop physics-based models when working with conceptual systems.

Transient dynamics are the result of various forms of energy stored within the system that enter a state of disequilibrium with changes in the system operating point. These dynamics are primarily due to

- ***shaft inertia,***
- ***gas path and***
- ***thermal.***

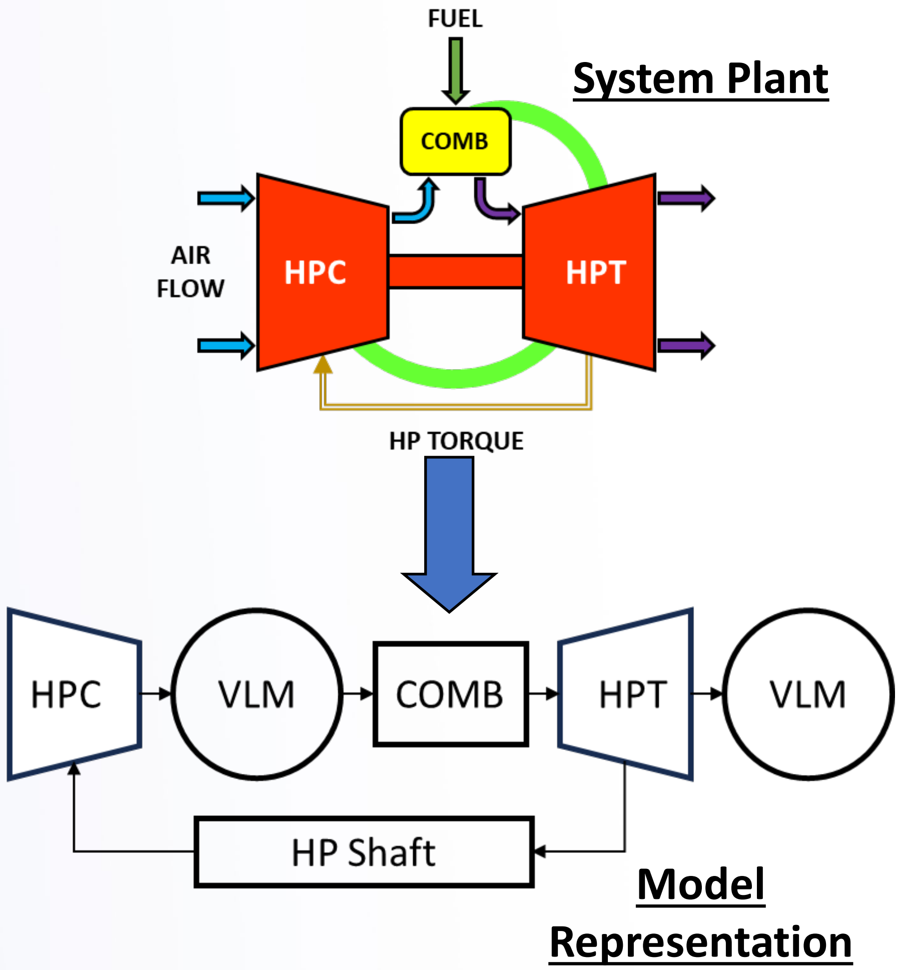


Conceptual view of a 1st principles timeline (green spiral) for equilibrium being re-established in the engine core during transient dynamics

Using electric power to modify shaft dynamics in coordination with fuel flow and gas dynamics allows an approximation of steady-state equilibrium

Transient Gas Dynamics

- Prior to hybridized electrification the control strategy was concerned with operating at points on the compressor map that avoided gas path instability.
- A deeper understanding is focused on the concept of entropy rise, resulting from the interaction of multiple system dynamics.
- The question on whether controls can safely perform with reduced transient stack margin rests on the idea that operability can minimize the disequilibrium caused by multiple energy sources.
- Volume dynamics modeling represents the estimation of gas path energy fluctuations and is not intended to be a detailed multidimensional model.



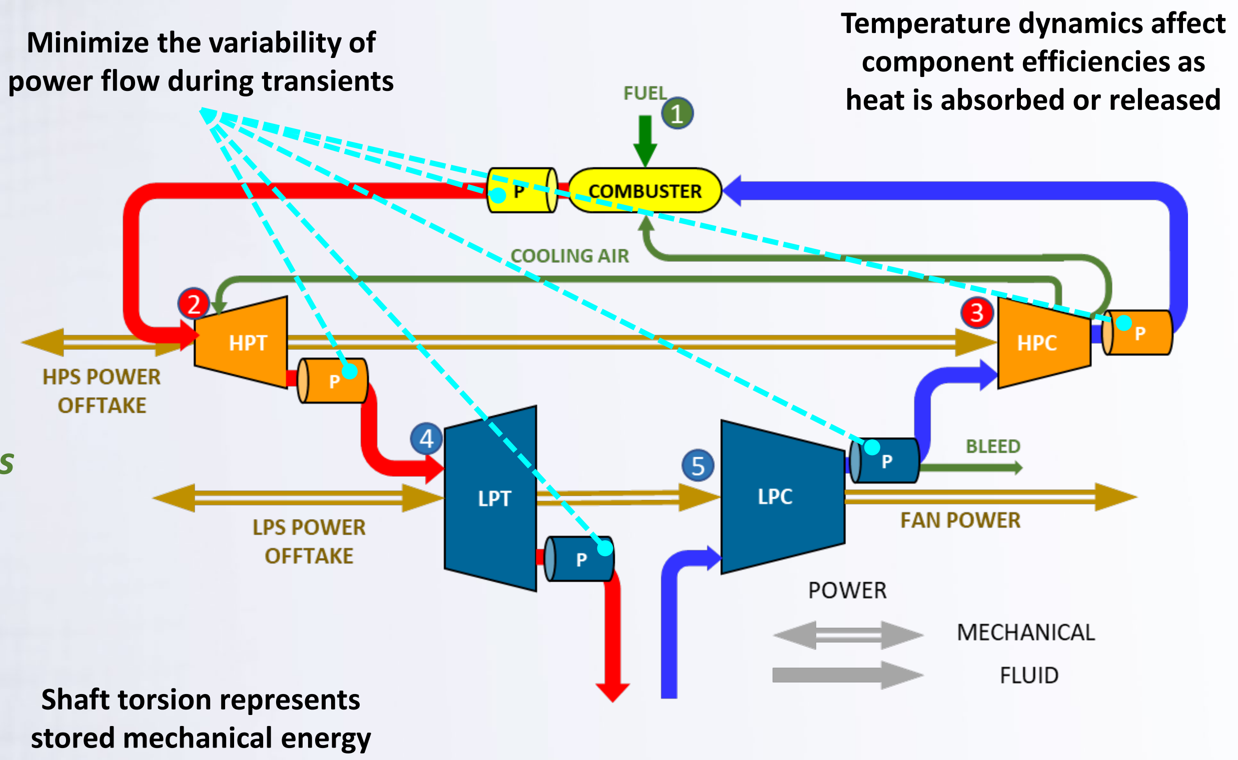
Improved understanding of the transient dynamics that cause transient off-design operation and engine instability is required to make a step change in turbomachinery performance.

System Transient Dynamics

FY25 L2 Goal: Physics-based predictive understanding of transient dynamics

In quasi-steady modeling the convergence criteria requires constant mass flow through the gas path, but this is only true during steady-state operation.

Adding the volume block removes the restriction on constant mass flow and allows the component's stored energy to vary, also affecting the component's efficiency.



Power Flow diagram with Plenum (volume) blocks for energy storage. Components are generally power conversion blocks for mechanical and fluid power.

During steady-state operation the mass flow is constant, representing equilibrium. This also delineates the beginning and end of transient operation and a method to verify the model.

The control, therefore, seeks to minimize the unsteady power variation as a means of optimization.

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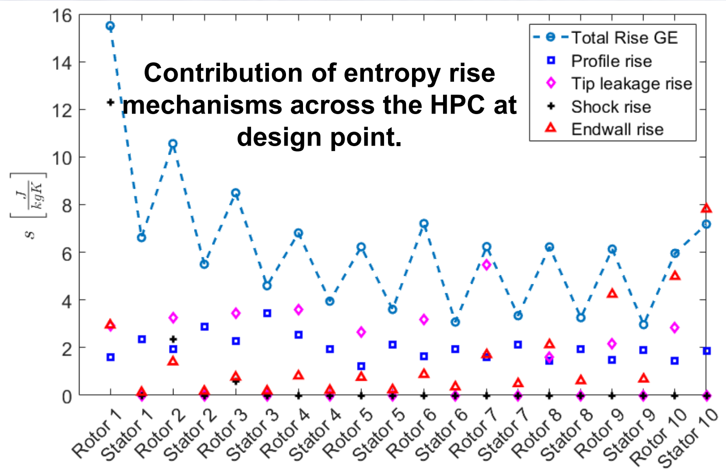
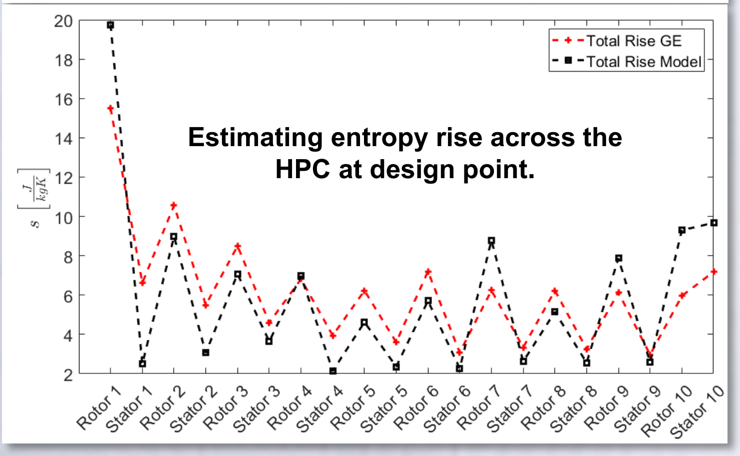
Operability Influenced Design (OID)
A New Design Approach Based on Entropy Rise Models



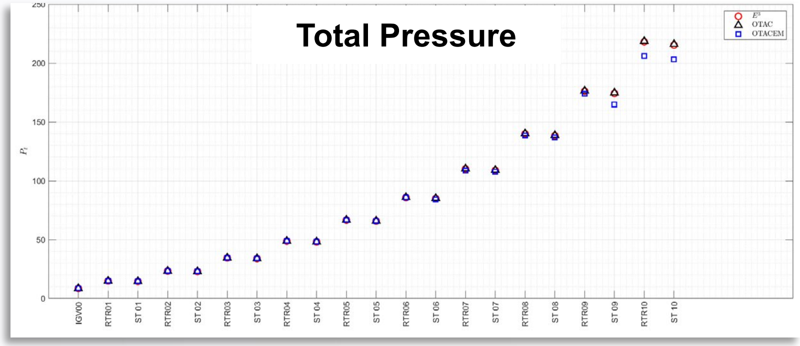


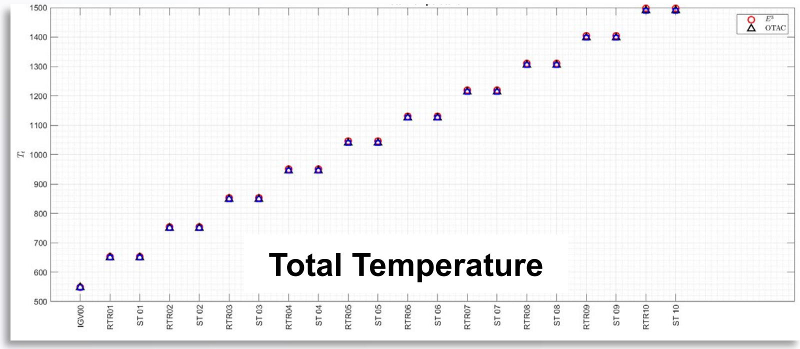
Entropy Rise models were developed by simplifying the physics of loss mechanisms (blade profile, end-wall flows, shock, and tip leakage) instead of being based on empirical data, offering a more meaningful conceptual design approach.

These improvements were implemented in the Object-oriented Turbomachinery Analysis Code (OTAC).

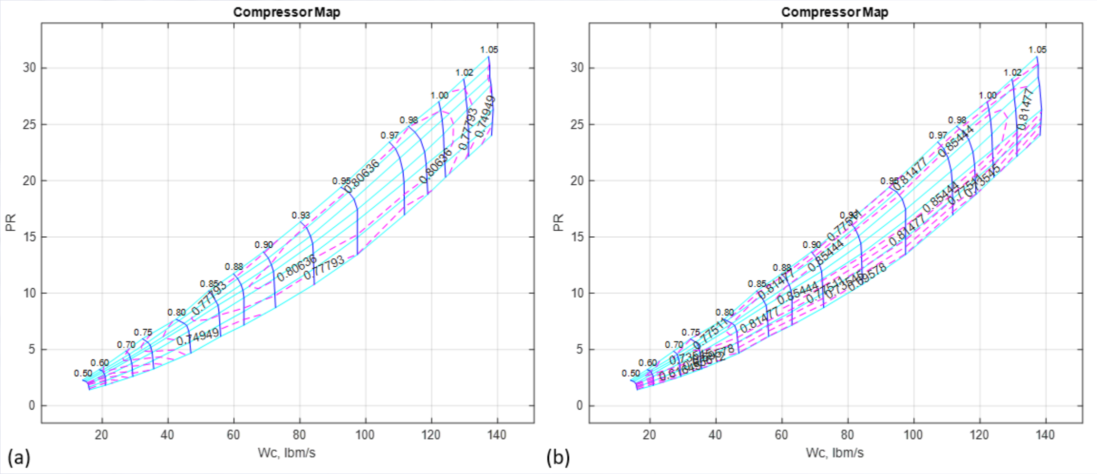
The objective is to minimize entropy rise (based on operability improvements), thereby reducing losses throughout the machine and enhancing the compressor's efficiency.

OTAC's performance in modelling the total pressure and temperature rise across the HPC.

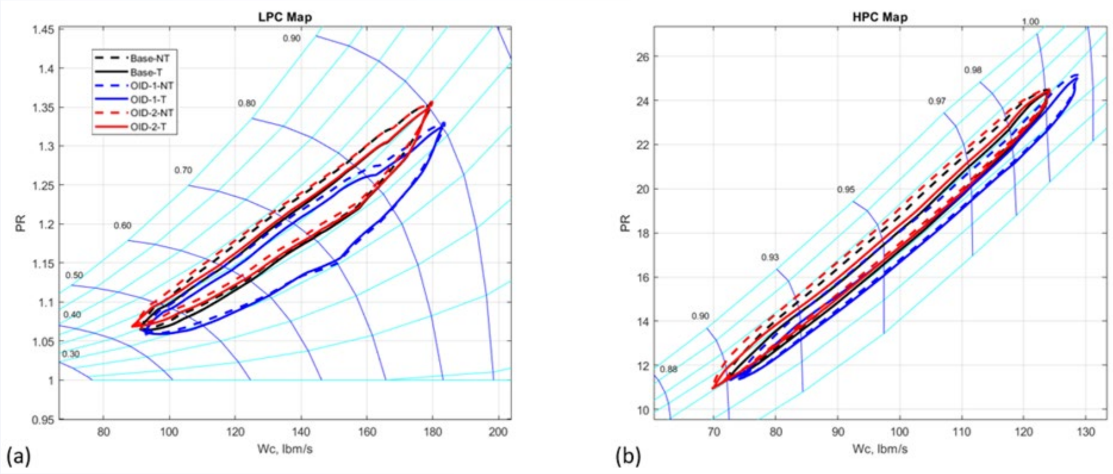


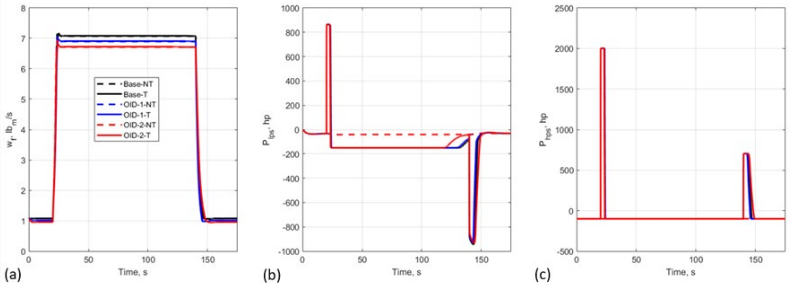


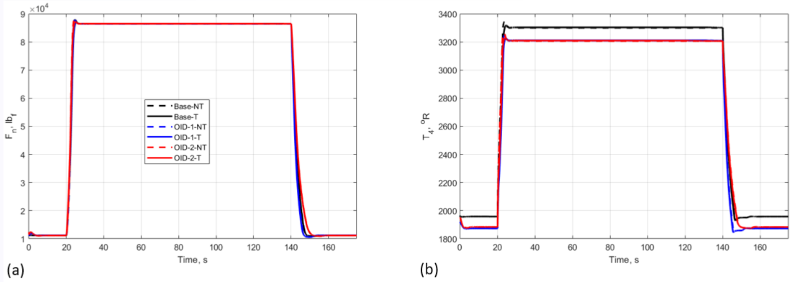
Operability Influenced Design (OID)
Preliminary Analysis of Entropy Rise Model Design



. Map comparison: (a) original unscaled HPC map and (b) improved unscaled HPC map







Entropy Rise models were applied to the rich **NASA E³** design database to produce an OID High Pressure Compressor (HPC) design. An **E³ engine model** was analyzed with the OID and baseline compressor maps without any further optimization.

These preliminary results demonstrated greater than 4% fuel burn reduction and T4 temperature reduction of 100 °R

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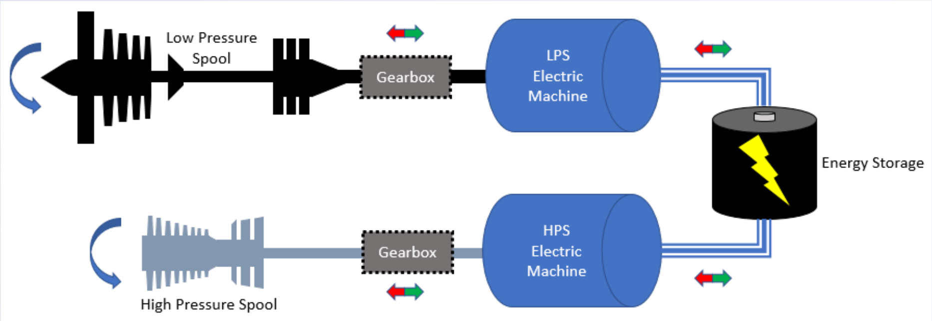
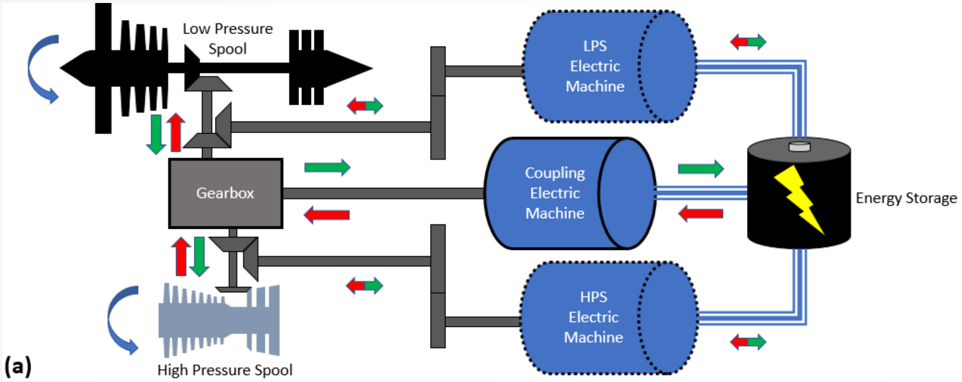
Versatile Electrically Augmented Turbine Engine (VEATE) Gearbox

The **VEATE** gearbox is a NASA innovation for the integration of electric machines in hybridized turbine-based propulsion architectures. The idea transforms the common accessory gearbox, that is presently used on aircraft for electric power off-take and to start the engine, into an active, performance-enhancing capability. This is a collaboration with **Penn State and the University of Tennessee Knoxville** to develop the concept for feasibility.

In a recent analysis, the technology was used to look at performance and weight impacts for several hybrid operating modes; Thrust Boost, Large Power Extraction, and a bidirectional mode that provides transient control and bleedless operation under low engine power. In each case, there was significant weight reduction in the electrical power system with the same or improved performance relative to the baseline engine system that uses dedicated electric machines connected via a passive accessory gear box.



Baseline configuration with dedicated electric machines independently connected through an Accessory gearbox to both engine spools.



VEATE configuration with smaller electric machines connected through a multi-input/multi-output planetary gearbox to both engine spools

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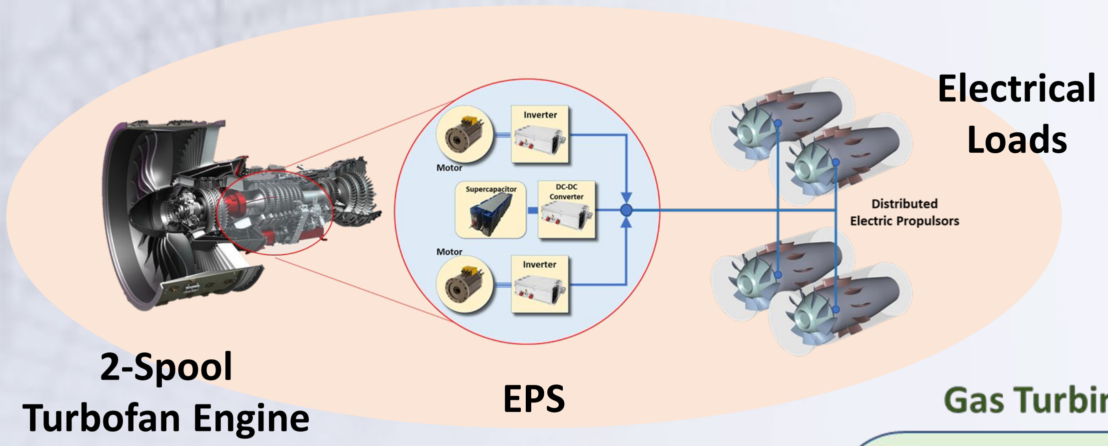
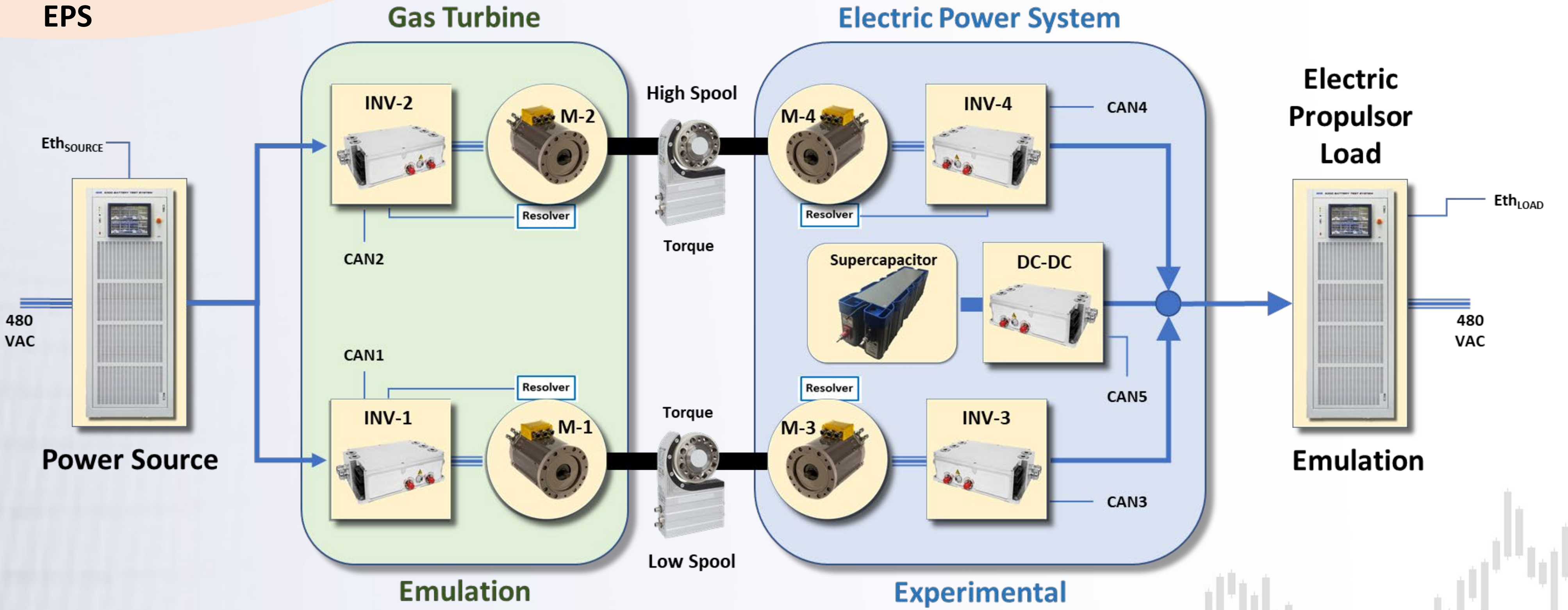
Hybrid Propulsion Emulation Rig (HyPER)



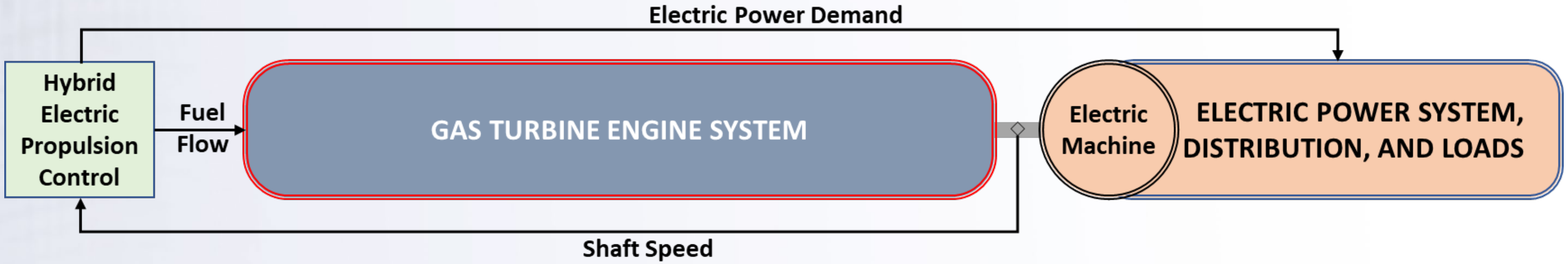
HyPER is an agile, low-cost, reconfigurable Hardware-in-the Loop test bed with a specific focus on the dynamics of Turbine Engine – Electric Power System interactions,
Without the turbomachinery

Two-Spool Power Extraction with TEEM Control



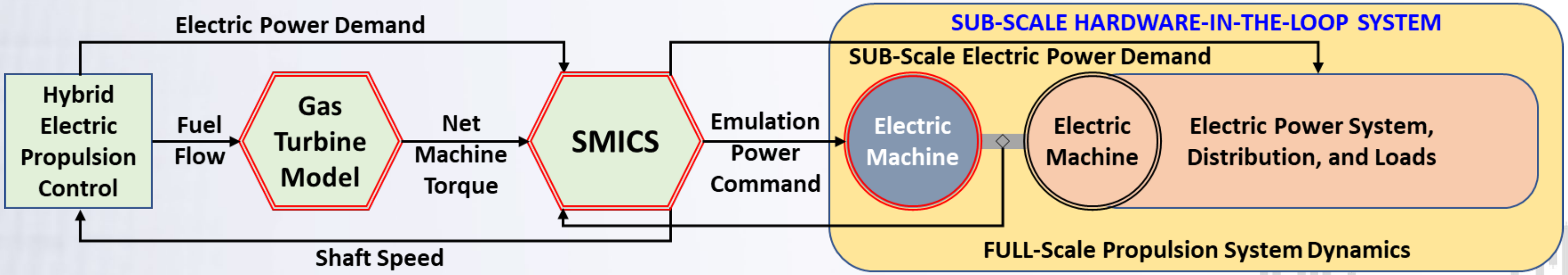
Adaptive Sliding Mode Impedance Controller with Scaling (ASMICS)
A Solution for Scaling Full Size Systems to Sub-scale Hardware

Full-Size Propulsion System

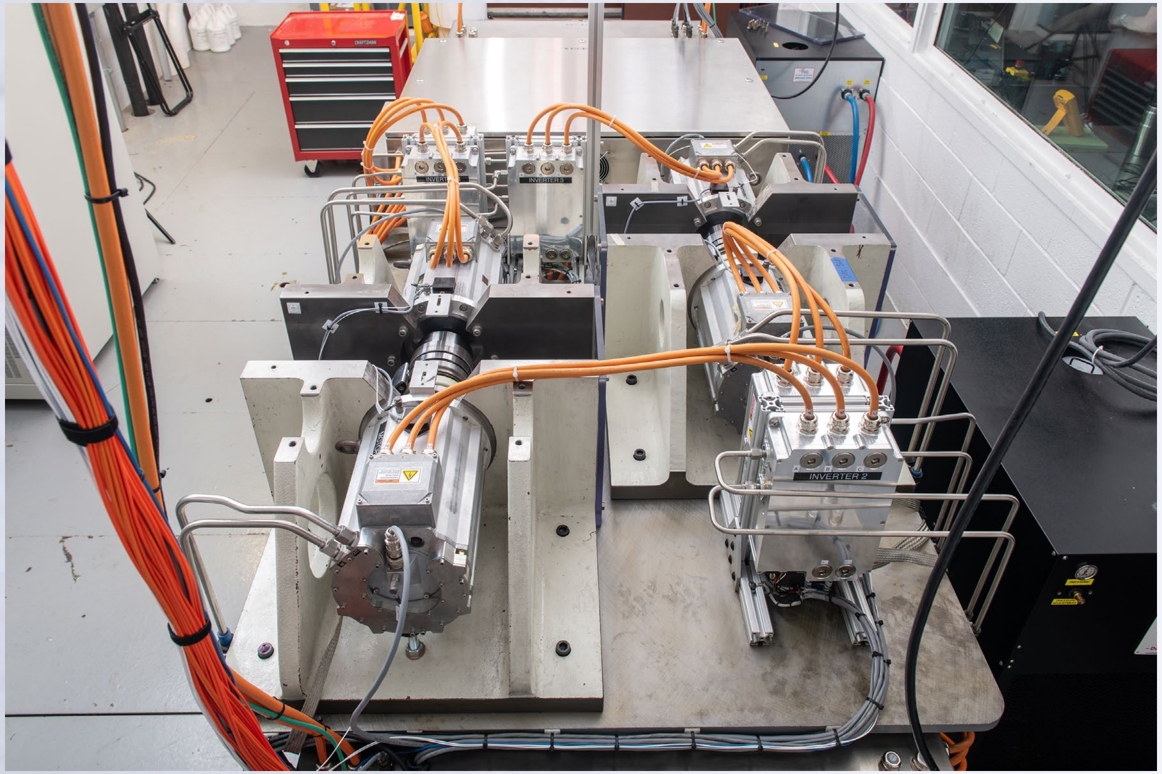


- The Propulsion Control is built for the Full-Scale Propulsion System
- The Electric Power System, Distribution, and Loads are replaced by Sub-Scale Hardware-in-the-Loop components
- The Turbine Engine is replaced by a Full-Scale Engine Model and SMICS
  1. The Engine Model provides a NET Torque, i.e., aero loads on the turbines are nulled out to emphasize the power transfer between the Engine and the Electrical Power System
  2. SMICS scales the engine shaft Torque and Speed (Power) to the capability of the subscale HIL hardware while preserving the Full-Scale system dynamics
  3. Signals returned from the Sub-Scale HIL are scaled back up to Full-Scale

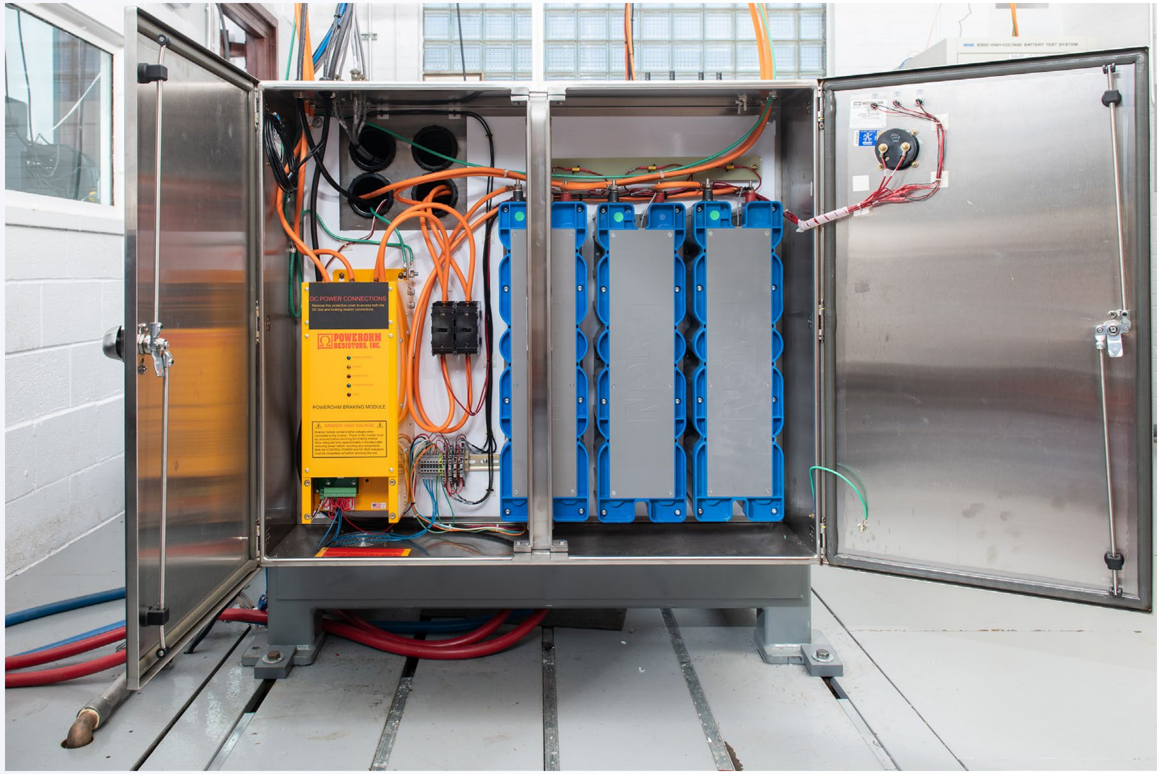
Sub-Scale Emulation of Full-Size Propulsion System



Hybrid Propulsion Emulation Rig (HyPER)



Motor Spool Assemblies with Inverters.
Inverter and Motor Chillers are on the right.



Supercapacitors and backup discharge circuits.

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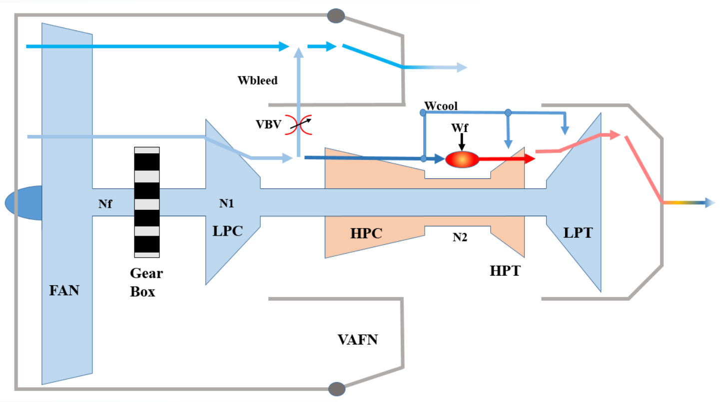
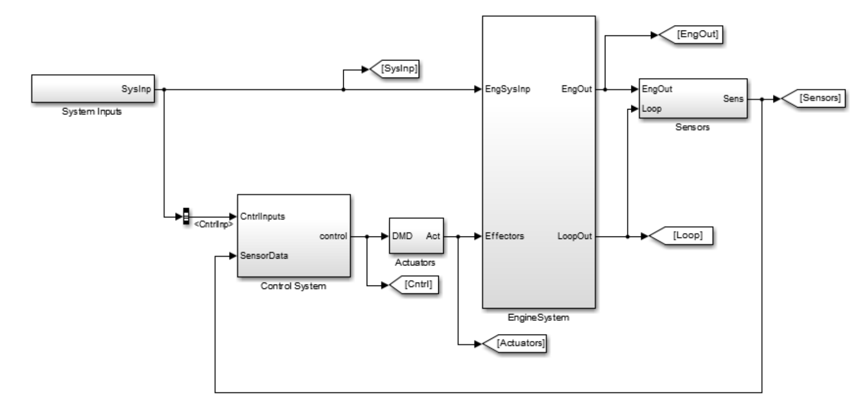
Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS)

- Modular thermodynamic modeling framework for building dynamic simulations
- Designed for easy creation of custom Component Level Models (CLM) of jet engines
- Includes convenient tool to convert Numerical Propulsion System Simulation (NPSS) cycle design code steady state models to T-MATS dynamic models
- Although originally intended to simulate turbomachinery, it has been used for other applications, such as fuel cell modeling
- Continually upgraded with enhancements planned
- Used under all NASA ARMD Programs and externally
- User Guide cited over 100 times, many by external users

https://github.com/nasa/T-MATS

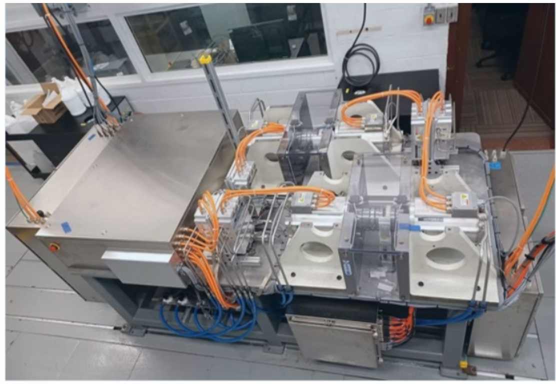


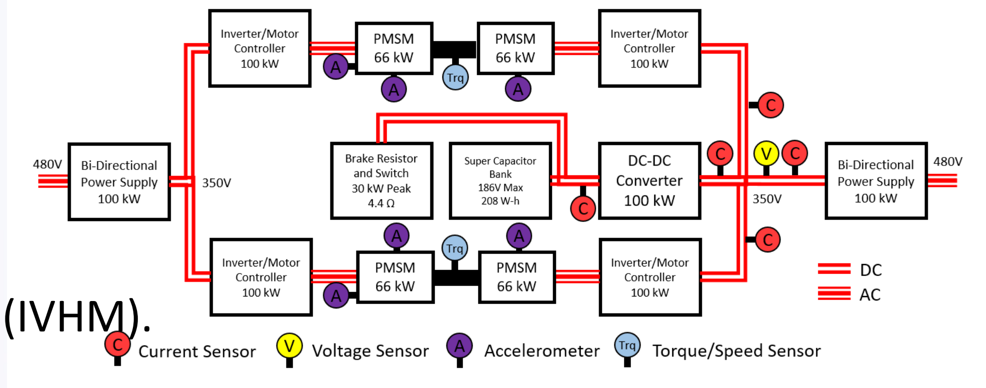


Advanced Geared TurboFan 30k (AGTF30)

Electrical Modeling and Thermal Analysis Toolbox (EMTAT)

- Modular electrical system dynamical modeling toolbox that models electrical system components at mechanical time steps (15-20 msec)
- Facilitates the construction of dynamical electrical models of electrified aircraft propulsion systems that integrate easily with T-MATS
- Used in planning of HyPER; provided insight that pointed out a non-intuitive design flaw. Prevented a potential safety hazard and enabled redesign before buildup, saving time and money
- Helped isolate an unaccounted-for damping torque during HyPER characterization
- Capabilities:
  - Two libraries model electrical components based on power flow and physics-based modeling techniques.
  - Calculates power/heat loss of components.
  - Calculates component temperature changes as a result of heat loss.
  - Contains toggle-able faults (electrical/mechanical) for each component (IVHM).





https://github.com/nasa/EMTAT

Advanced Geared Turbofan 30k_{lbf} Thrust Electrified – (AGTF30-e)

Objectives: Develop and publicly release an updated version of the AGTF30 Advanced Geared Turbofan 30,000lbf engine model that incorporates hybridization options that have relevancy to future aviation, primarily electrified aircraft propulsion (EAP).

Result: The AGTF30-electrified (AGT30-e) – a transient engine model with user selectable hybridized architecture

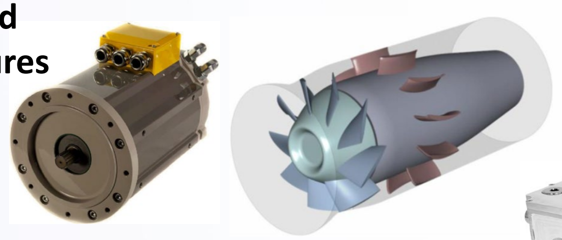
- __Primary electrification options__: standard/conventional engine, boost (enables electric power ***injection*** to augment engine fan thrust), or power extraction (large electric power ***extraction*** for distributed electric thrust production)
- __Secondary electrification options__: bi-directional electric power transfer (transfer power between multiple engine shafts and/or energy storage devices) to support advanced features like turbine transient operability, bleedless low power operation, and in-flight (battery) charging
- __Hybrid integration options__: offers passive and actively controlled options for integrating EMs with the turbine engines.

Significance:

- Provides a virtual testbed for simulating various EAP technologies
- Provides a means of interacting with the greater aerospace community through providing a useful tool and a foundation for collaboration

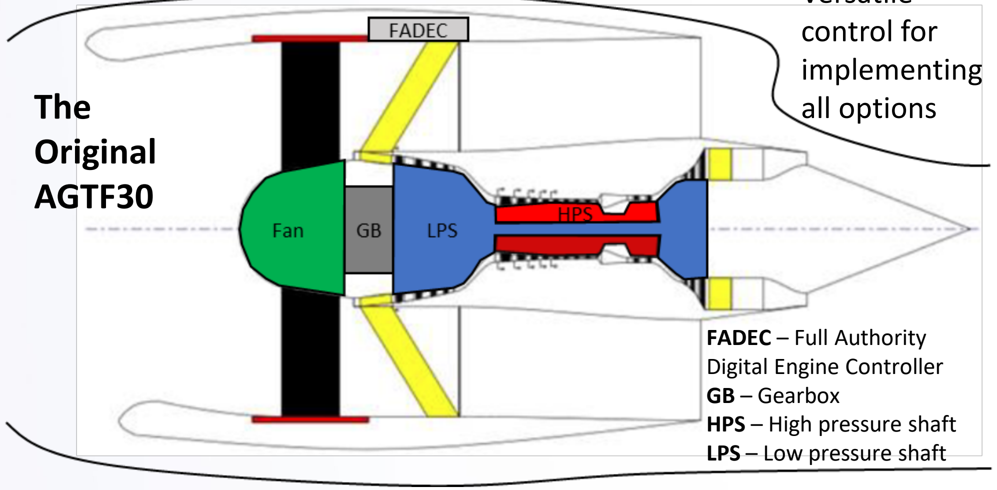
https://github.com/nasa/AGTF30-e

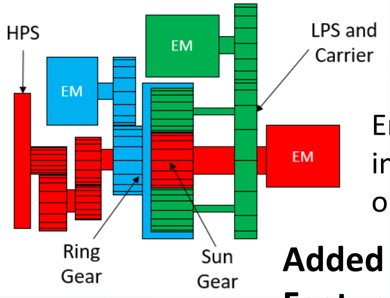
Added Features



Power consumption representative of external propsulors

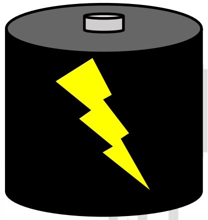
EMs for various uses (boost, power extraction, etc.)





Engine-EM integration options

Energy storage for boost and TEEM



Added Features

Publications

2018 - 2022

- Culley, D., et al, “Turbine Electrified Energy Management (TEEM) For Enabling More Efficient Engine Designs,” AIAA Propulsion & Energy Forum, Cincinnati, OH. 2018.
- Kratz, J., et al, “A Control Strategy for Turbine Electrified Energy Management,” AIAA Propulsion & Energy Forum, Indianapolis, IN. 2019.
- Kratz, J., et al, “Evaluation of Electrical System Requirements for Implementing Turbine Electrified Energy Management,” AIAA Propulsion & Energy Forum, Indianapolis, IN, 2019.
- Kratz, J., and Culley, D., “Enhancement of a Conceptual Hybrid Electric Tilt-Wing Propulsion System through Application of the Turbine Electrified Energy Management Concept,” AIAA 2021-0875, AIAA SciTech Forum, Virtual Conference, 2021.
- Kratz, J., and Simon, D., “Failure Modes and Mitigation Strategies for a Turboelectric Aircraft Concept with Turbine Electrified Energy Management,” AIAA SciTech Forum, San Diego, CA. 2022.
- Kratz, J., et al., “Turbine Electrified Energy Management for Single Aisle Aircraft,” IEEE/AIAA Electric Aircraft Technologies Symposium, Anaheim, CA. 2022.

2023

- Kratz, J. L. "Transient Optimization of a Gas Turbine Engine." *AIAA SCITECH 2023 Forum*. 2023
- *Kratz, J. L., et al. "Transient Optimization for the Betterment of Turbine Electrified Energy Management." AIAA SCITECH 2023 Forum. 2023*
- *Buescher, H. E., et al. "Hybrid-Electric Aero-Propulsion Controls Testbed: Overview and Capability." AIAA SCITECH 2023 Forum. 2023*
- *Litt, J. S., et al. "Control Architecture for a Concept Aircraft with a Series/Parallel Partial Hybrid Powertrain and Distributed Electric Propulsion." AIAA SCITECH 2023 Forum. 2023.*
- Litt, J. S., et al, *“Flight Simulator Demonstration and Certification Implications of Powertrain Failure Mitigation in a Partial Turboelectric Aircraft,”* AIAA Aviation Forum/IEEE Electric Aircraft Technology Symposium
- Connolly, J. W., et al, *“Electrified Aircraft Propulsion Controls Hardware Testing,”* AIAA Aviation Forum/IEEE Electric Aircraft Technology Symposium, 2023
- Bianco, S. J., et al, *“Hybrid-Electric Aero-Propulsion Controls Testbed Results with Energy Storage,”* AIAA Aviation Forum/IEEE Electric Aircraft Technology Symposium, 2023
- Bell, M. E., et al, *“Comparison of the Electrical Modeling and Thermal Analysis Toolbox Physics Based Model Blocks to Electrified Aircraft Propulsion Motor Test Hardware,”* AIAA Aviation Forum/IEEE Electric Aircraft Technology Symposium, 2023

Publications

2024

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