

Turbine Electrified Energy Management with Model Predictive Control

Elyse D. Hill

Oak Ridge Associated Universities, Oak Ridge, TN, USA

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Agenda

- Motivation
- Background
- System overview and controller design
- Simulation results
- Conclusions and acknowledgements

Motivation



Figure 1: ARMD Implementation Plan.

- Sustainability driving current aeronautics research.
- Strong focus on Electrified Aircraft Propulsion (EAP).
- Benefits of EAP include potential reduction in cost, noise, emissions, and fuel burn.

Background

- Various EAP architectures present many technology challenges that necessitate hardware and software solutions.

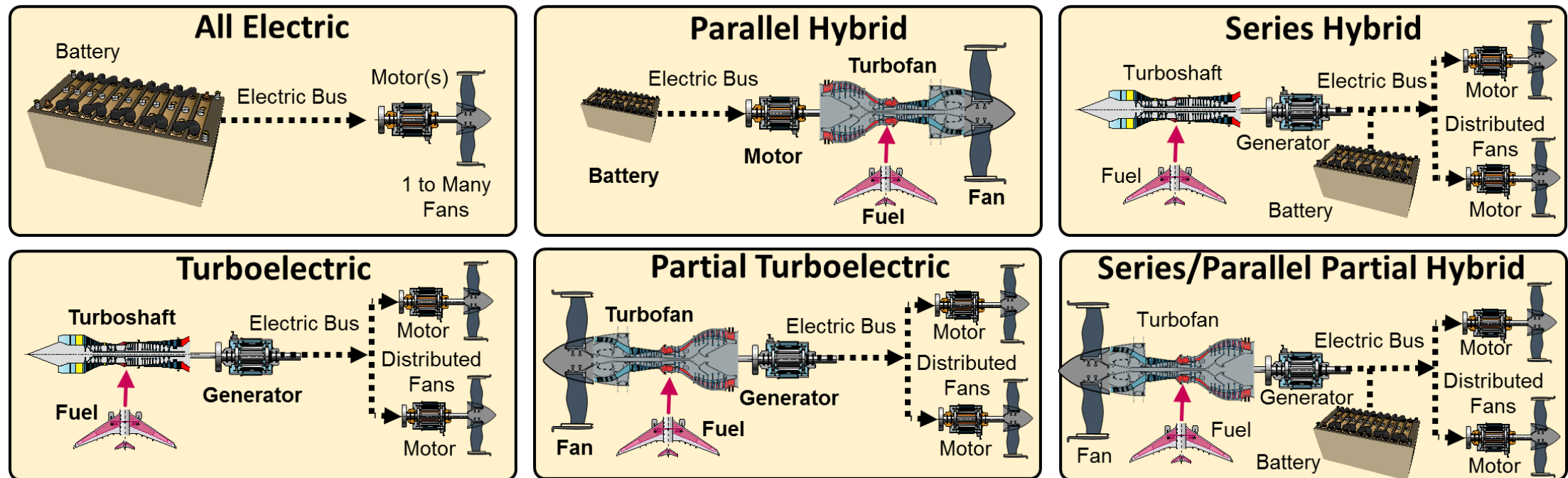


Figure 2: EAP Architecture Options.

Background

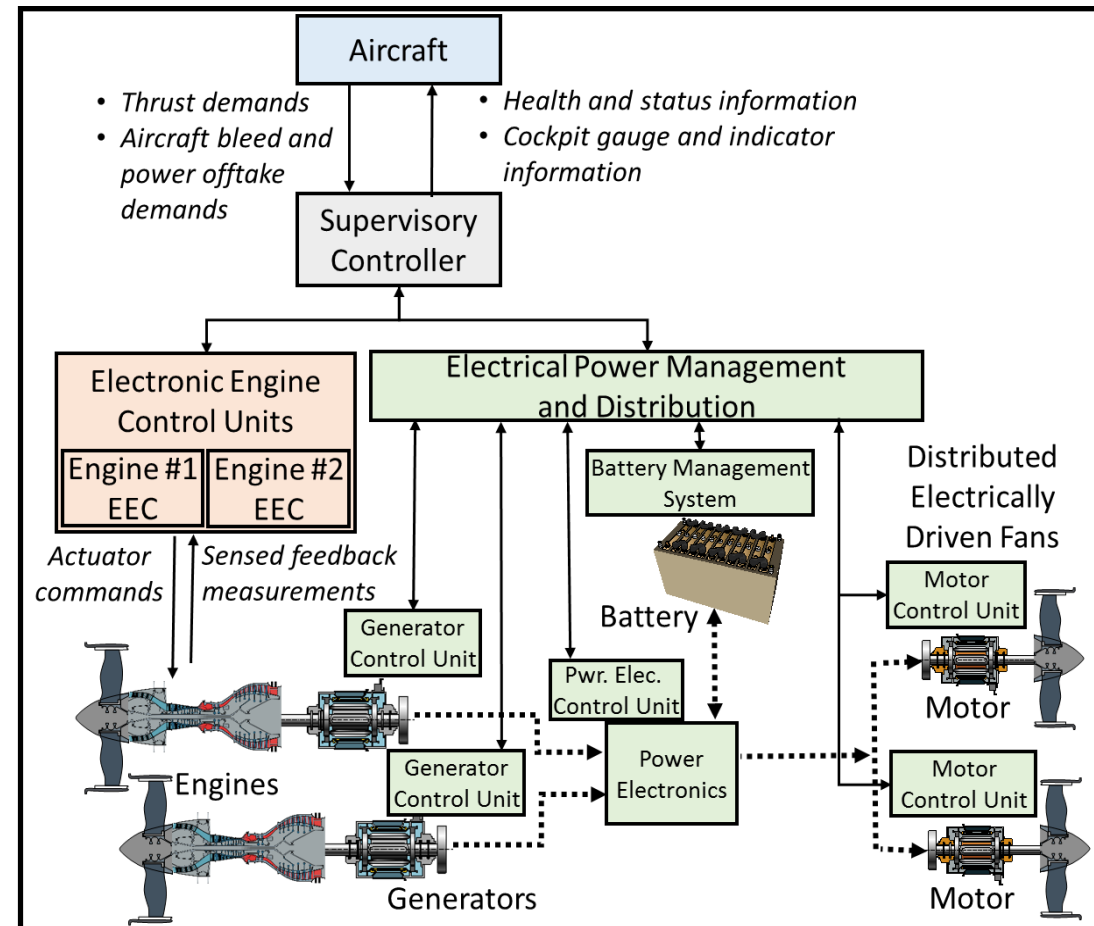
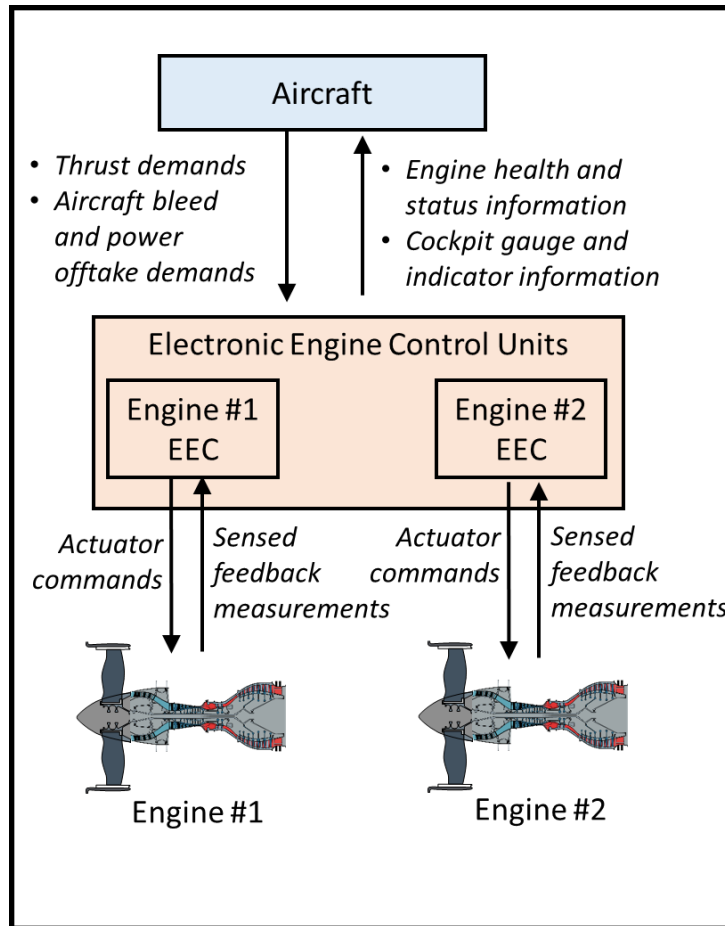


Figure 3: Aircraft Propulsion Control Architectures: Conventional (left) and Electrified (right).

Hybrid-Electric Control

Turbine Electrified Energy Management (TEEM) manages electric and turbomachinery components for hybrid-electric systems.

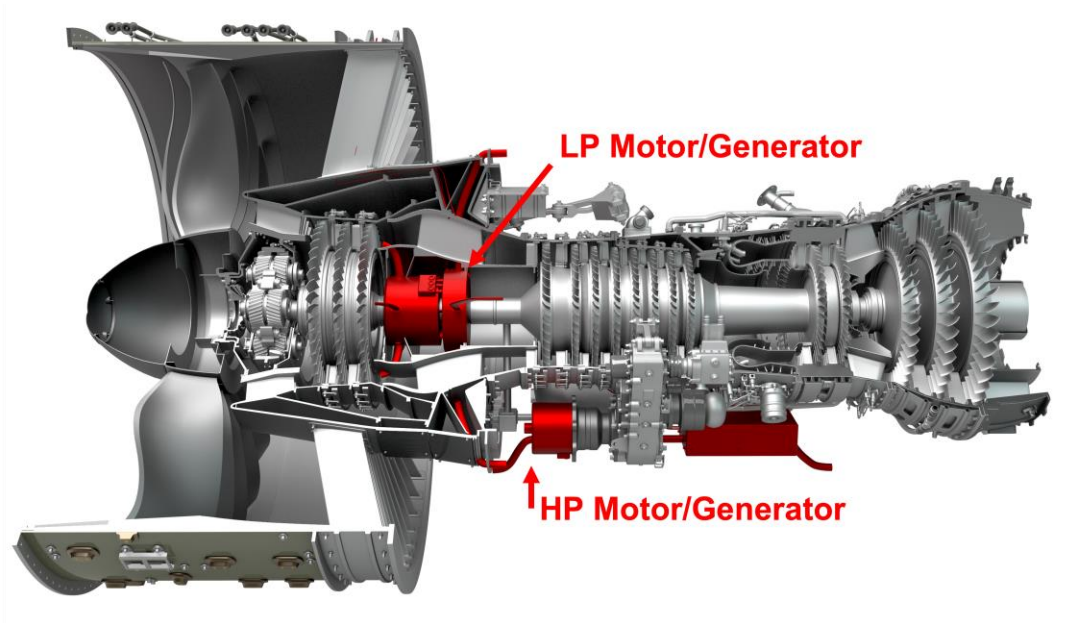


Figure 4: Electrified Turbofan.

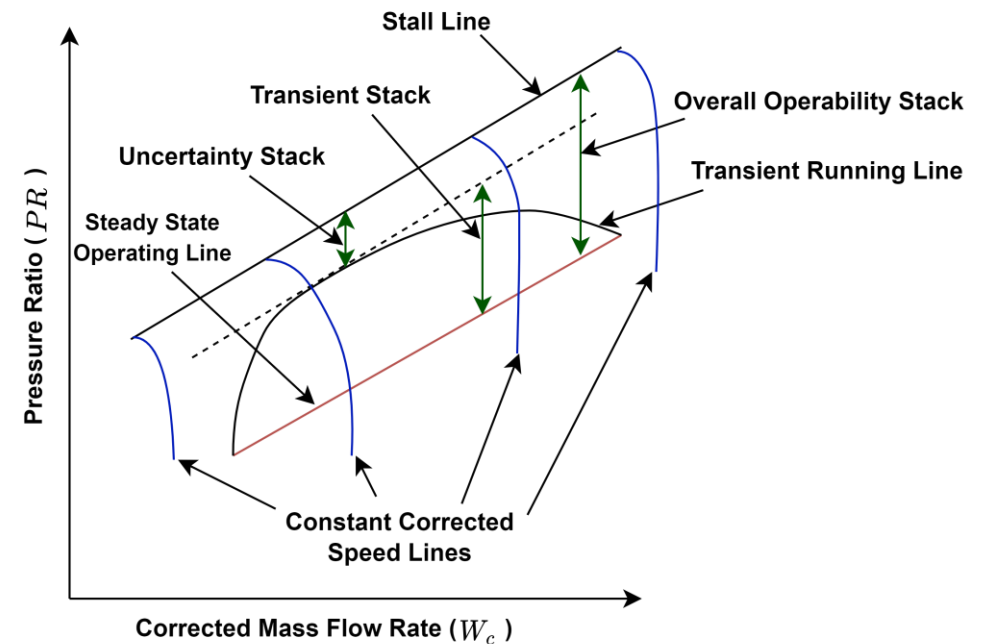


Figure 5: Illustration of TEEM Concept.

System Overview

Electrified Advanced Geared Turbofan 30,000lbf Engine

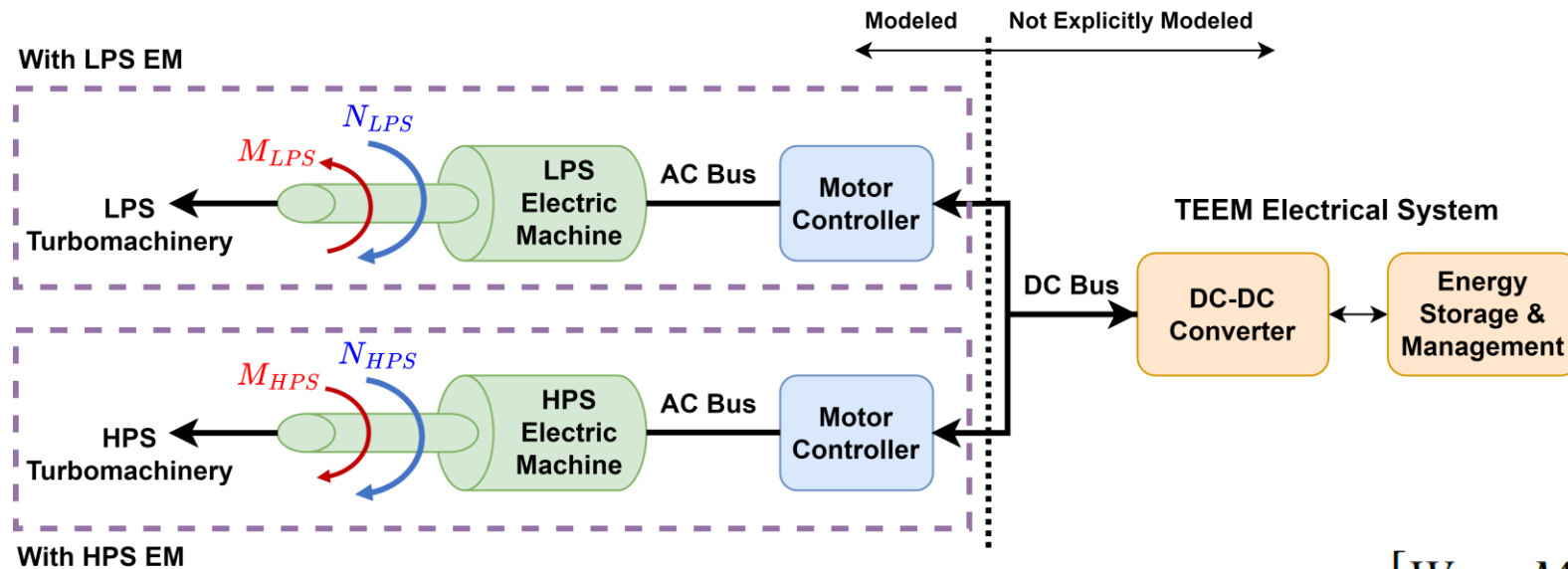


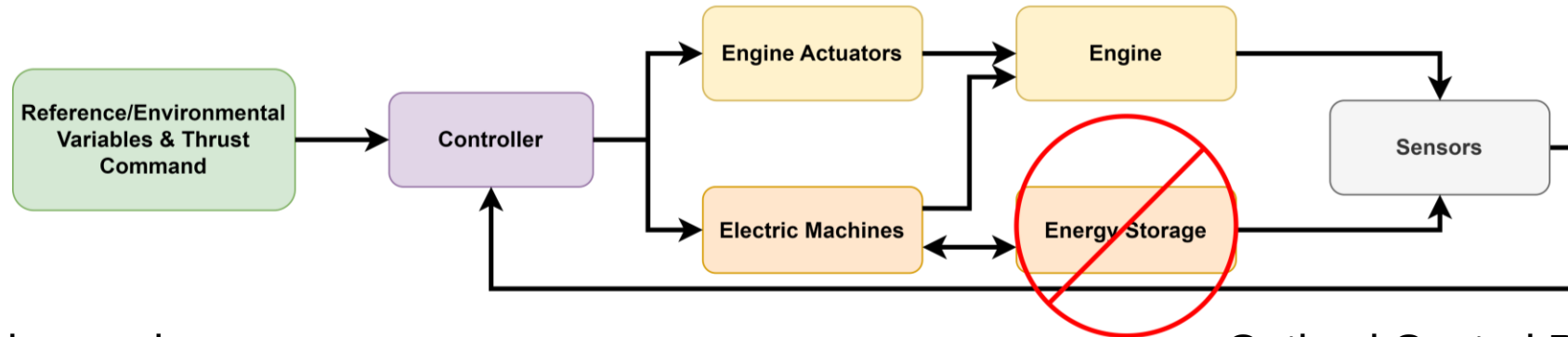
Figure 6: Electrical System Architecture.

$$x = [N_{LPS} \quad N_{HPS}]^T$$

$$u = [W_f \quad M_{LPS} \quad M_{HPS} \quad VAFN \quad VBV]^T$$

$$y = [N_{fan} \quad N_{HPS} \quad SM_{LPC} \quad SM_{HPC}]^T$$

Controller Design



Control design goal:
Replace traditional TEEM controller with MPC.

Control goals:
Track:

$$x_{SS} = [N_{LPS,SS} \quad N_{HPS,SS}]^T$$

Activate motors during transients.

Optimal Control Problem:

$$\min_u J(\delta y, \delta u)$$

subject to

$$\begin{aligned} \delta y(t) &= \delta y_0 \\ \delta \dot{x}(\tau) &= A\delta x(\tau) + B\delta \Omega(\tau), \\ \delta y(\tau) &= C\delta x(\tau) + D\delta \Omega(\tau), \\ \delta x(\tau) &\in \mathcal{X} - x_{trim}, \\ \delta \Omega(\tau) &\in \mathcal{U} - u_{trim}, \\ \delta y(\tau) &\in \mathcal{Y} - y_{trim}, \\ \delta y(t+T) &\in \mathcal{Y}_f - y_{trim}, \\ \tau &\in [t, t+T] \end{aligned}$$

$$\Omega(\tau) = \begin{bmatrix} W_f(\tau) & M_{LPS}(\tau) & M_{HPS}(\tau) \\ & VAFN(t) & VBV(t) \end{bmatrix}$$

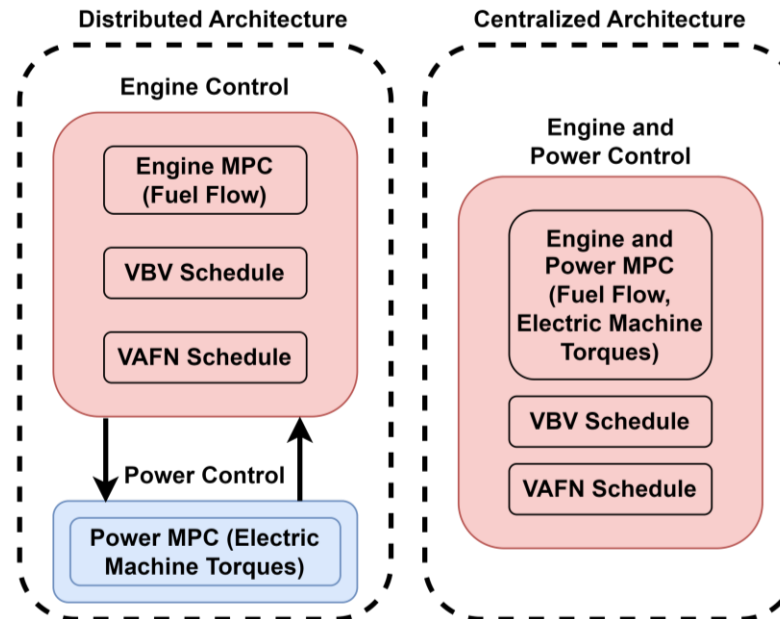


Figure 7: Controller architecture.

Controller Design

Centralized MPC cost function:

$$J(\delta y, \delta u) = \int_t^{t+T} \|\delta \tilde{y}(\tau)\|_Q^2 d\tau + \int_t^{t+T_u} (\|\Delta u(\tau)\|_R^2 + \|\delta u_{washout}(\tau)\|_{R_{washout}}^2) d\tau$$

$$\tilde{y} = [N_{fan} - N_{fan,ref} \quad \tilde{y}_{TEEM}]^T$$

$$\Delta u = \delta u(\tau) - \delta u(\tau - T_s)$$

TEEM goals:

$$\tilde{y}_{TEEM} = \begin{cases} N_{LPS} - N_{LPS,SS} & \text{if } \dot{N}_{fan} < -\phi \\ N_{HPS} - N_{HPS,SS} & \text{if } \dot{N}_{fan} > \phi \end{cases}$$

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

Simulation Results

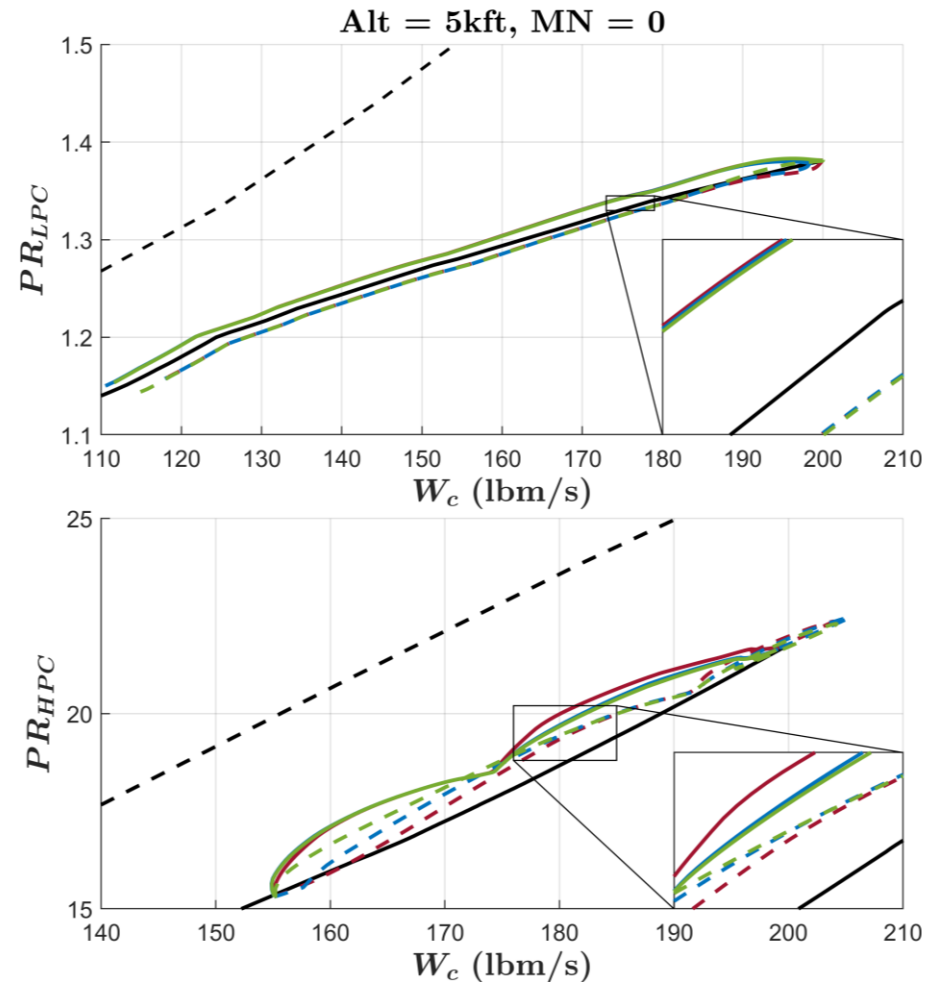


Figure 8: LPC and HPC compressor map data across controllers at Ground condition.

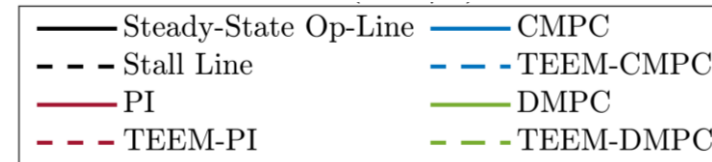


Table 1: Results for Ground Condition

Controller	Minimum SM (%)	
	LPC	HPC
PI	10.0	17.7
CMPC	9.98	18.8
DMPC	10.0	19.1
TEEM-PI	12.2	19.8
TEEM-CMPC	12.2	20.1
TEEM-DMPC	12.2	20.3

Simulation Results (cont.)

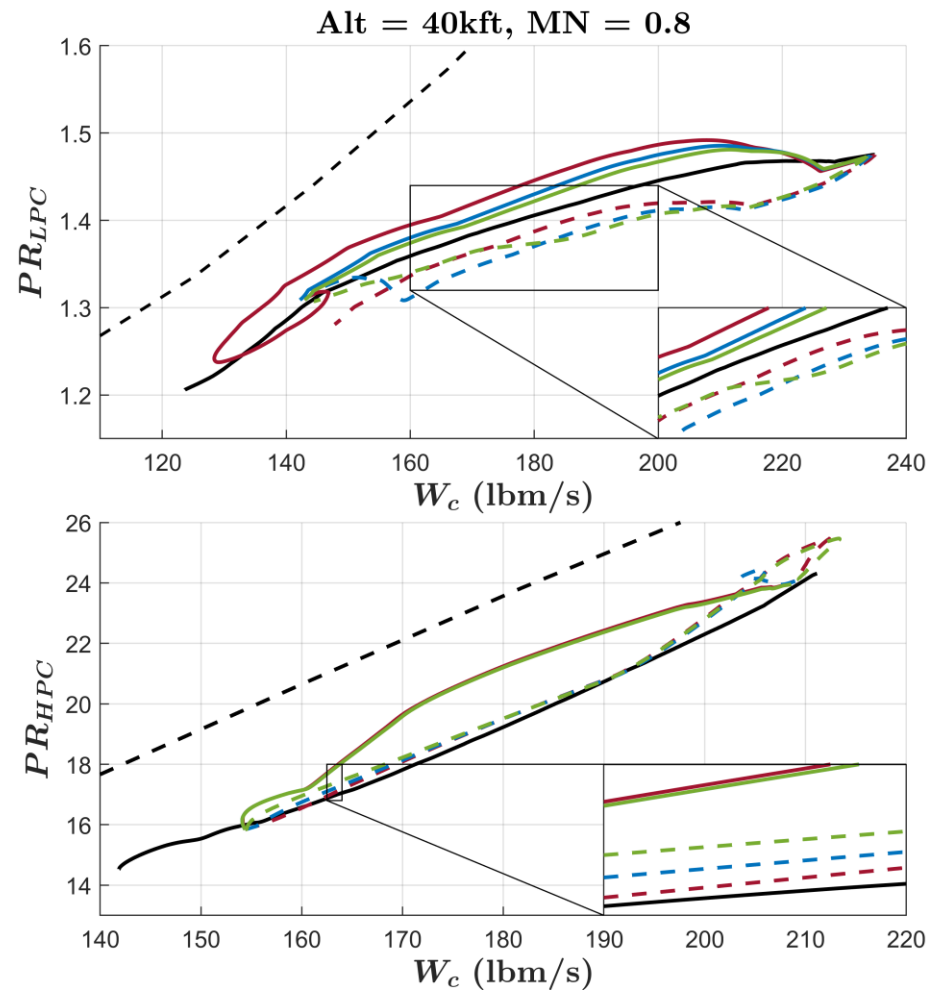


Figure 9: LPC and HPC compressor map data across controllers at Cruise condition.

Table 2: Results for Cruise Condition

Controller	Minimum SM (%)	
	LPC	HPC
PI	6.79	10.9
CMPC	8.79	11.2
DMPC	9.21	11.2
TEEM-PI	13.9	9.67
TEEM-CMPC	9.26	10.7
TEEM-DMPC	10.2	10.0

Conclusions

- Designed and validated MPCs incorporating TEEM design strategy.
 - Similar performance to baseline with and without TEEM.
- Easily include sustainability goals with MPC.
 - Fuel consumption, emissions reductions, net energy use, etc.
- Prior knowledge of mission profile could improve outcomes.

Acknowledgements

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Paper Reference

- **E. Hill**, A. Amthor, D. Soloway, D. L. Simon, J. Connolly, *Model Predictive Control Strategies for Turbine Electrified Energy Management (TEEM)*, Proceedings of the ASME Turbo Expo 2023. GT2023-101735. Boston, Massachusetts, June 25-30, 2023.

Questions?

Backup Slides

Case Study – Ground Scenario

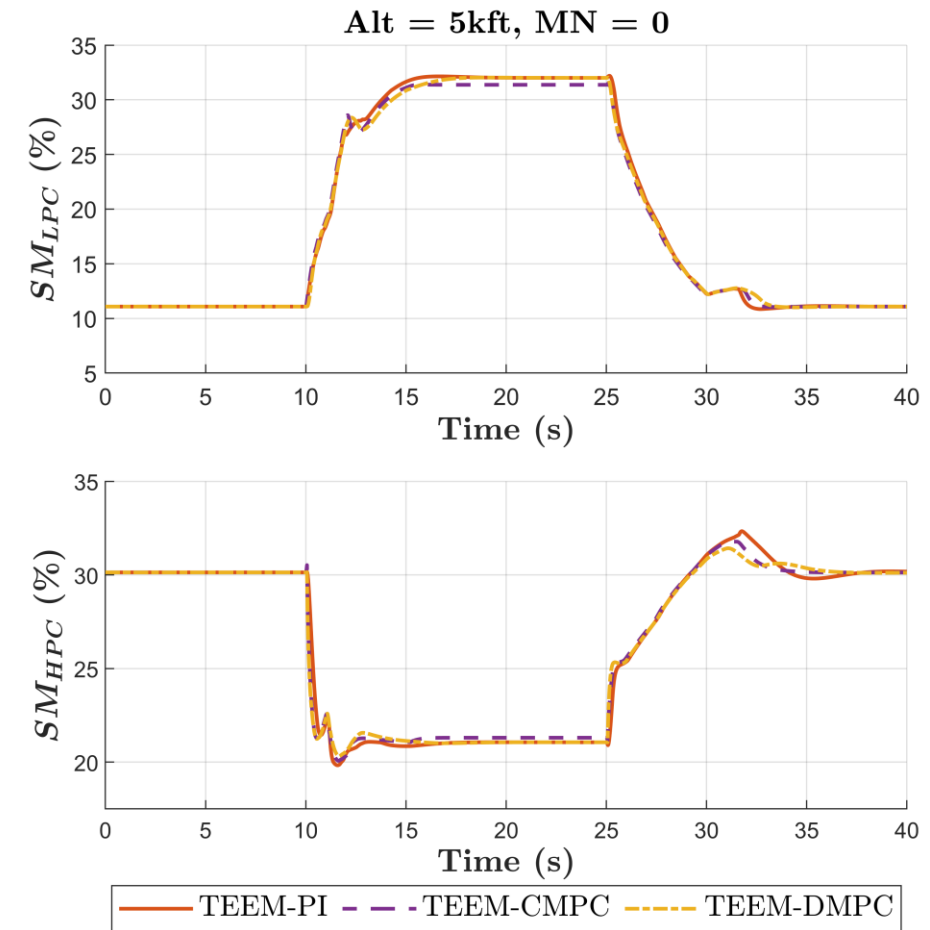
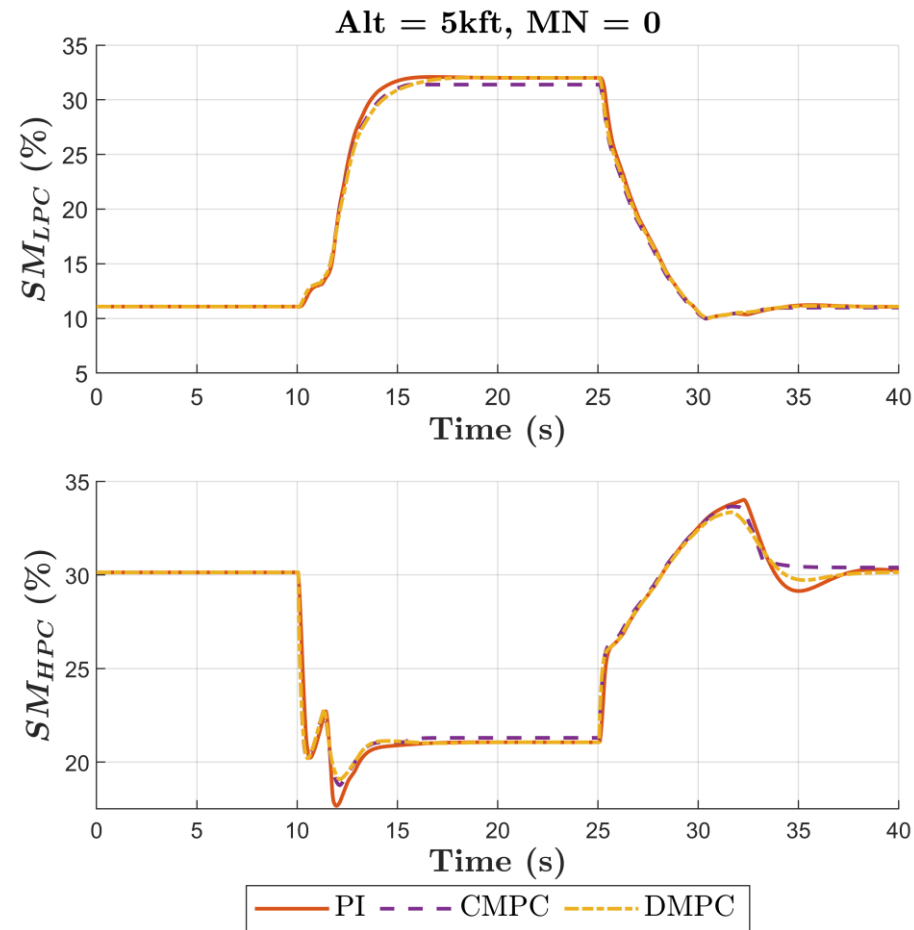


Figure A1: Resultant stall margin trajectories across controllers without TEEM applied (left) and with TEEM applied (right)..

Case Study – Cruise Scenario

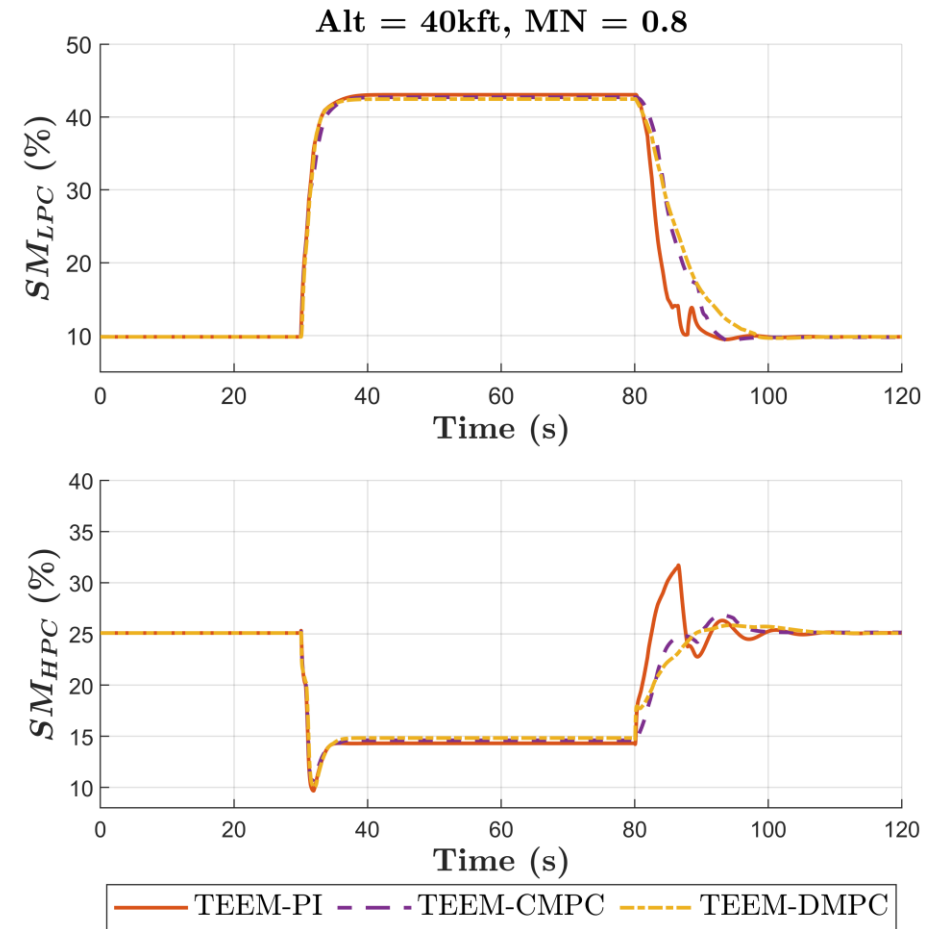
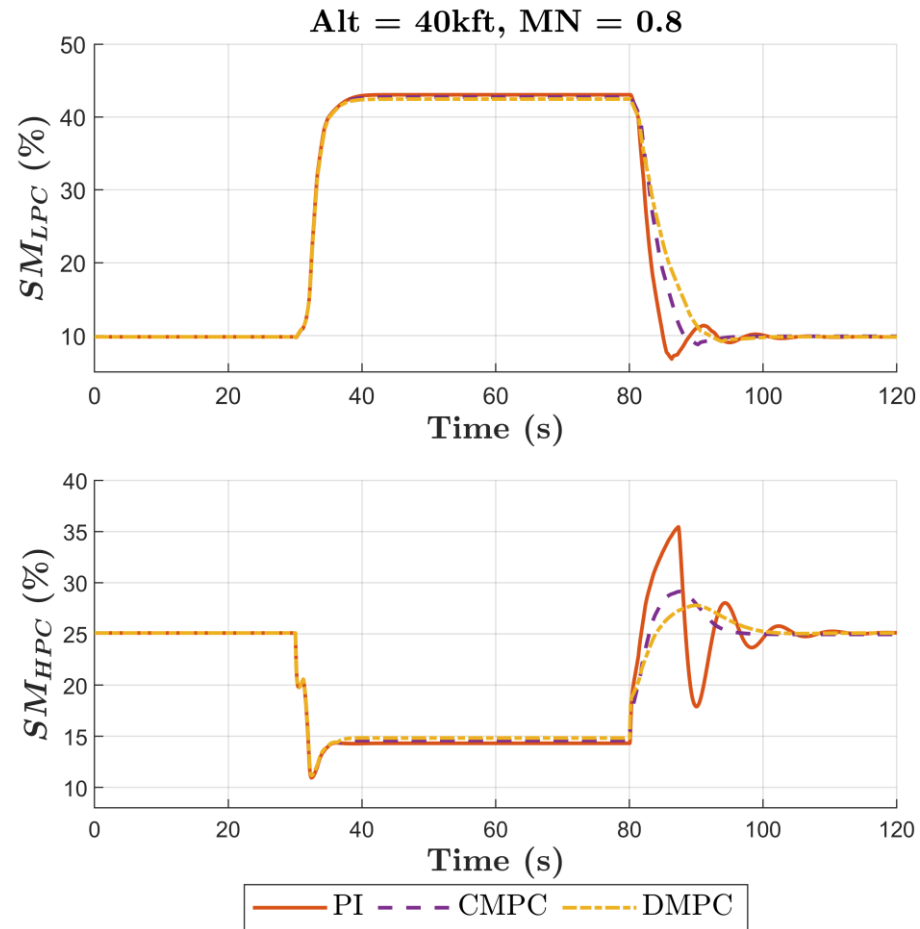


Figure A2: Resultant stall margin trajectories across controllers without TEEM applied (left) and with TEEM applied (right)..

Case Study – Motor Results

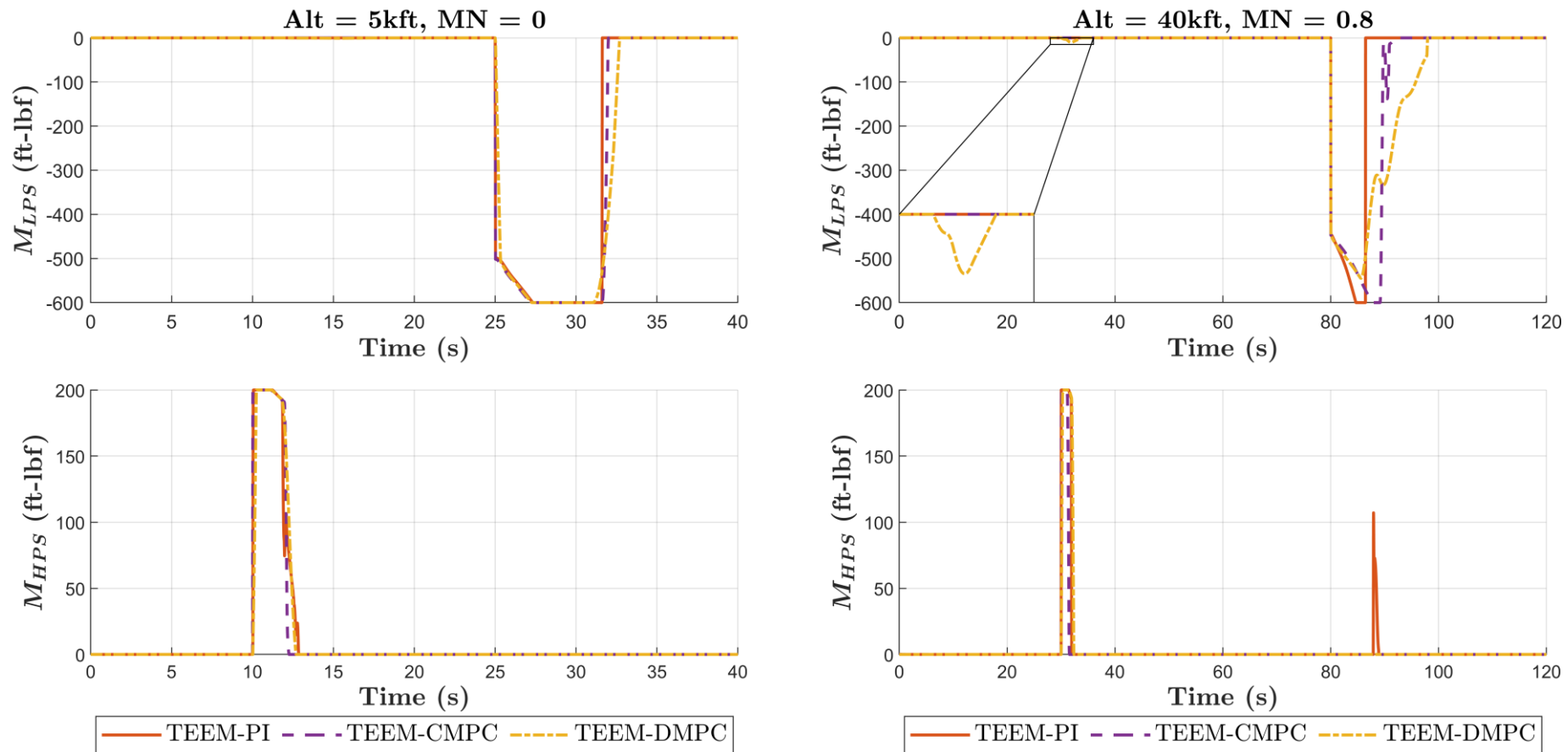


Figure A3: Resultant motor torque trajectories across controllers for Ground (left) and Cruise (right) scenarios.