Model Predictive Control Strategies for Turbine Electrified Energy Management

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Agenda

- Motivation and purpose of study
- System overview and background
- Controller design
- Case study results
- Conclusions and acknowledgements

Motivation and Purpose of Study

- Increased focus on electrified aircraft propulsion has encouraged development of various control strategies.
- New strategies developed for hybrid-electric systems manage electric and turbomachinery components; e.g., Turbine Electrified Energy Management (TEEM).
- Model predictive control (MPC) presented as alternative to traditional, decentralized control architectures.
- Study seeks to develop MPC architectures for application to hybrid-electric systems.

System Overview

Electrified Advanced Geared Turbofan 30,000lbf Engine

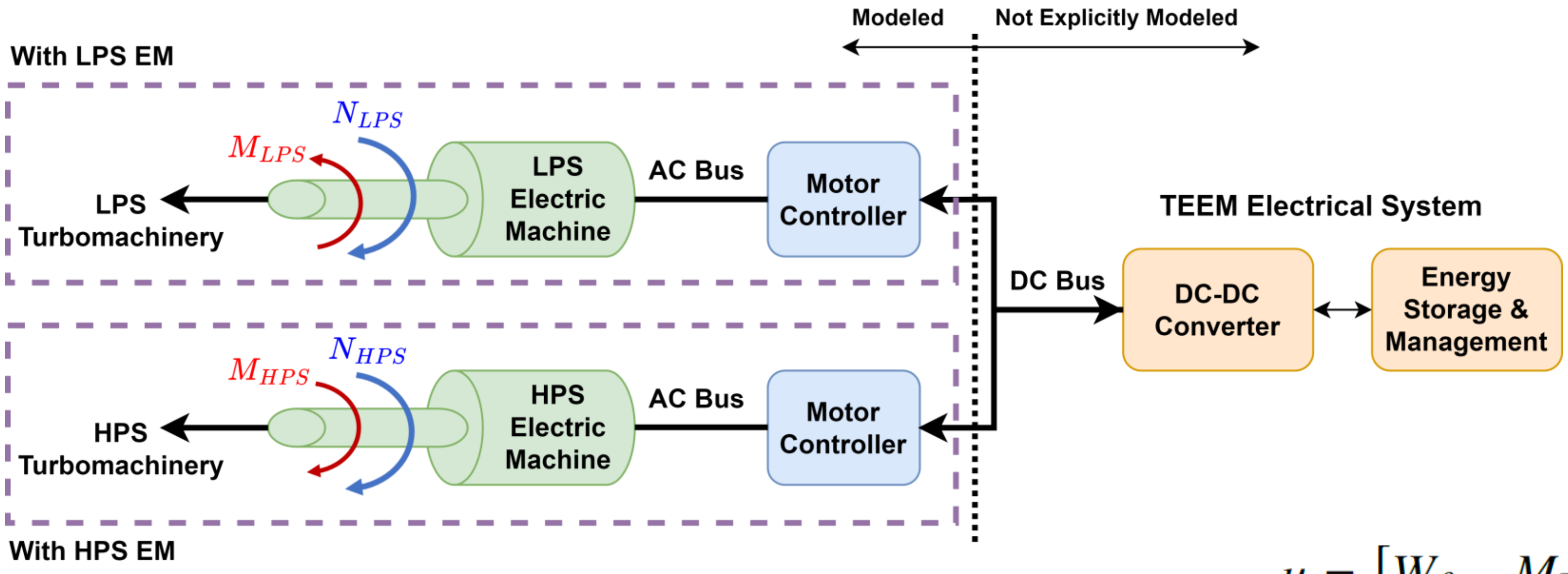


Figure 1: Electrical System Architecture.

$$\delta\dot{x}(t) = A\delta x(t) + B\delta u(t)$$

$$\delta y(t) = C\delta x(t) + D\delta u(t)$$

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

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

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

System Overview (cont.)

Turbine Electrified Energy Management (TEEM)

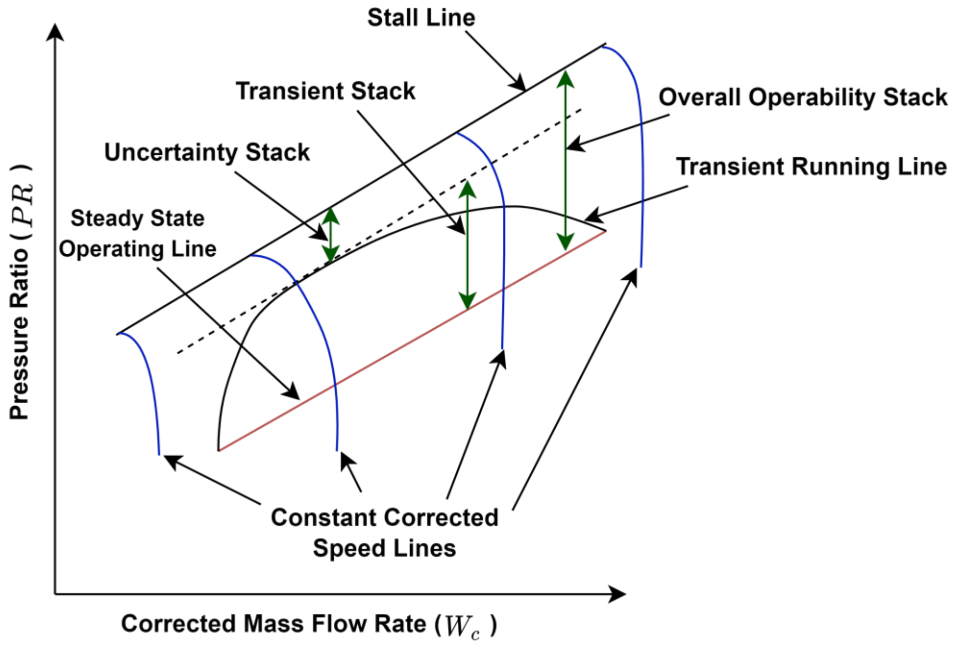


Figure 2: Illustration of TEEM Concept.

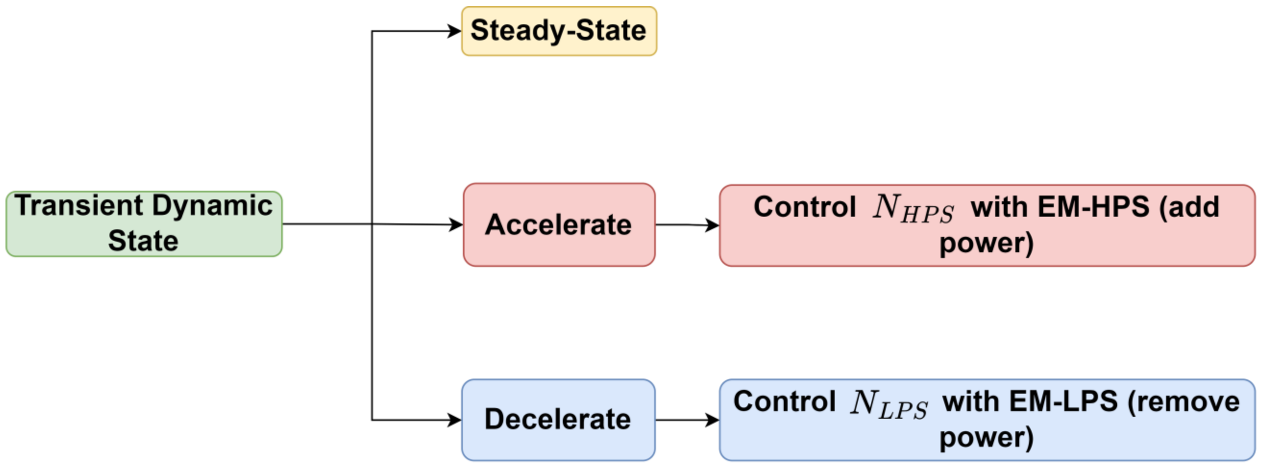
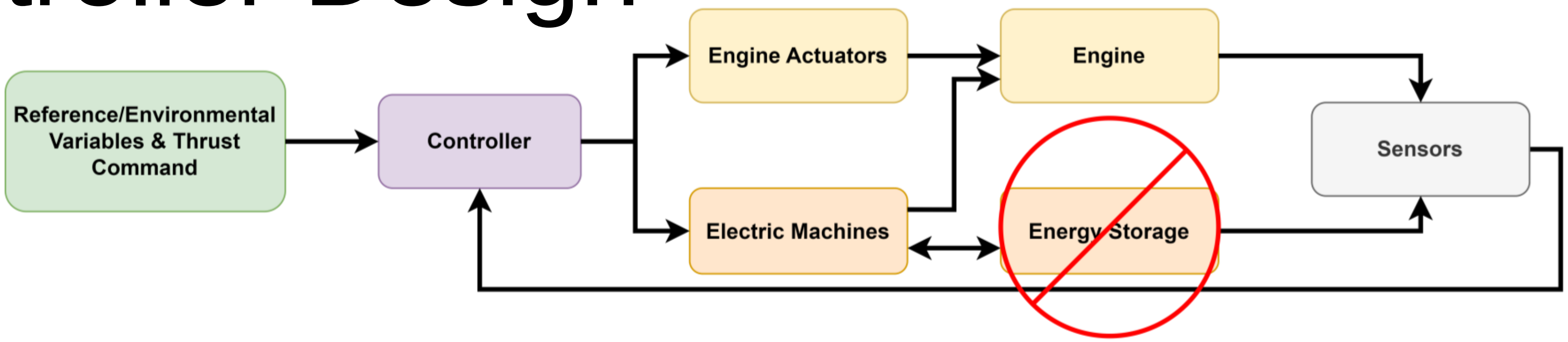


Figure 3: Dual-Spool TEEM Configuration.

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

Controller Design



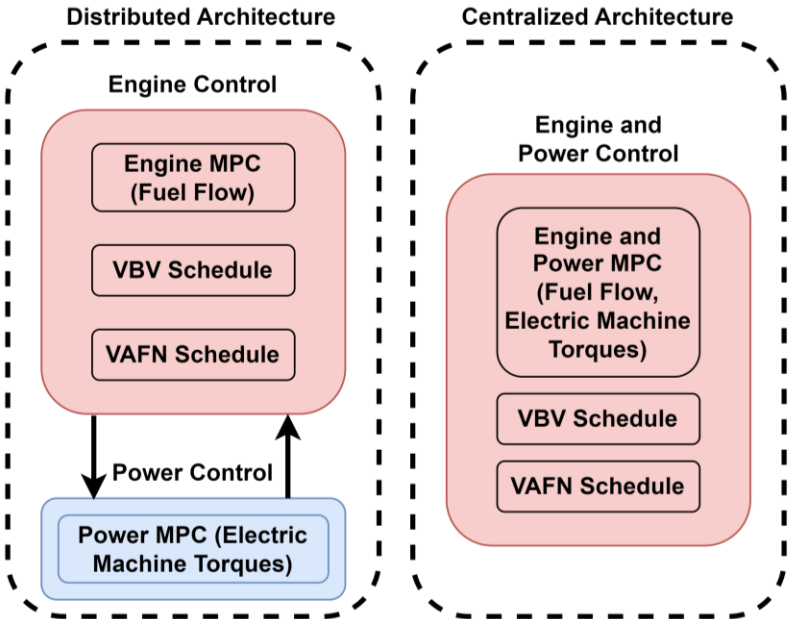


Figure 4: Proposed controller architecture.

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

Controller Design (cont.)

Optimal Control Problem:

$$\min_{u} \quad J(\delta y, \delta u)$$

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

$$\Omega(\tau) = [W_f(\tau) \quad M_{LPS}(\tau) \quad M_{HPS}(\tau) \quad VAFN(t) \quad VBV(t)]$$

CMPC cost function:

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

DMPC cost functions:

$$J_p(\delta y_p, \delta u_p) = \int_t^{t+T} ||\delta\tilde{y}_p(\tau)||_{Q_p}^2 d\tau + \int_t^{t+T_u} (||\Delta u_p(\tau)||_{R_p}^2 + ||\delta u_{washout}(\tau)||_{R_{washout}}^2) d\tau$$

$$J_e(\delta y_e, \delta u_e) = \int_t^{t+T} ||\delta\tilde{y}_e(\tau)||_{Q_e}^2 d\tau + \int_t^{t+T_u} ||\Delta u_e(\tau)||_{R_e}^2 d\tau$$

Controller Design (cont.)

x_{ss} Tracking:

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

Motor activation:

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

Case Study - Setup

- Vetted controllers at Ground and Cruise conditions for burst-chop transient; PLA change of 48°- 80° - 48°.
- MPC motor constraints selected to adhere to dual-spool strategy.
- Compared TEEM and non-TEEM applications of MPC controllers to PI.
- Performance evaluated with compressor map data, minimum stall margin, and the metrics:

$$TSU = \max\left(\frac{PR - PR_{SS}}{PR_{stall} - PR_{SS}}\right) \times 100\% \qquad TEI = \int \left|\frac{PR - PR_{SS}}{PR_{SS}}\right| dW_c$$

Case Study – Ground Scenario

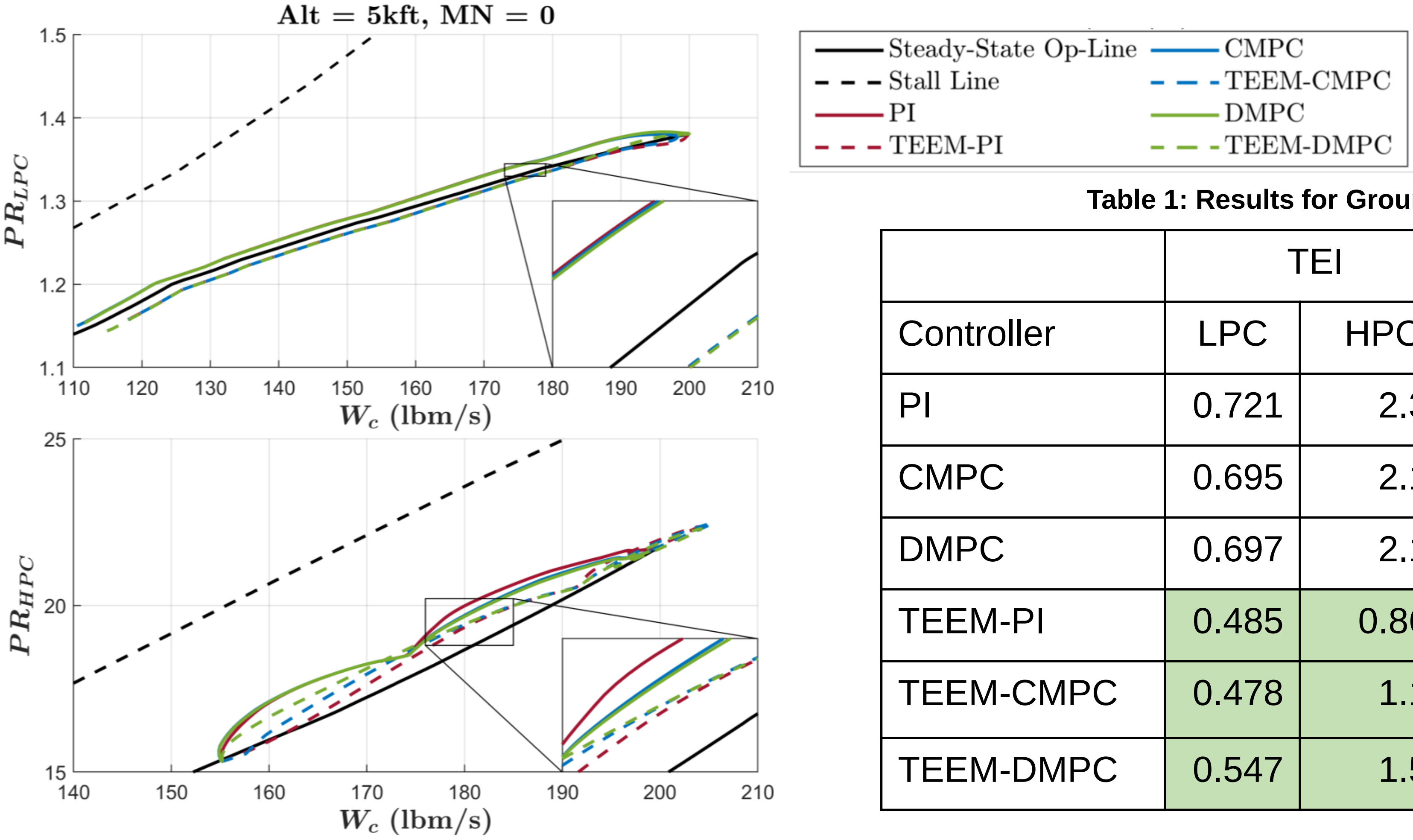
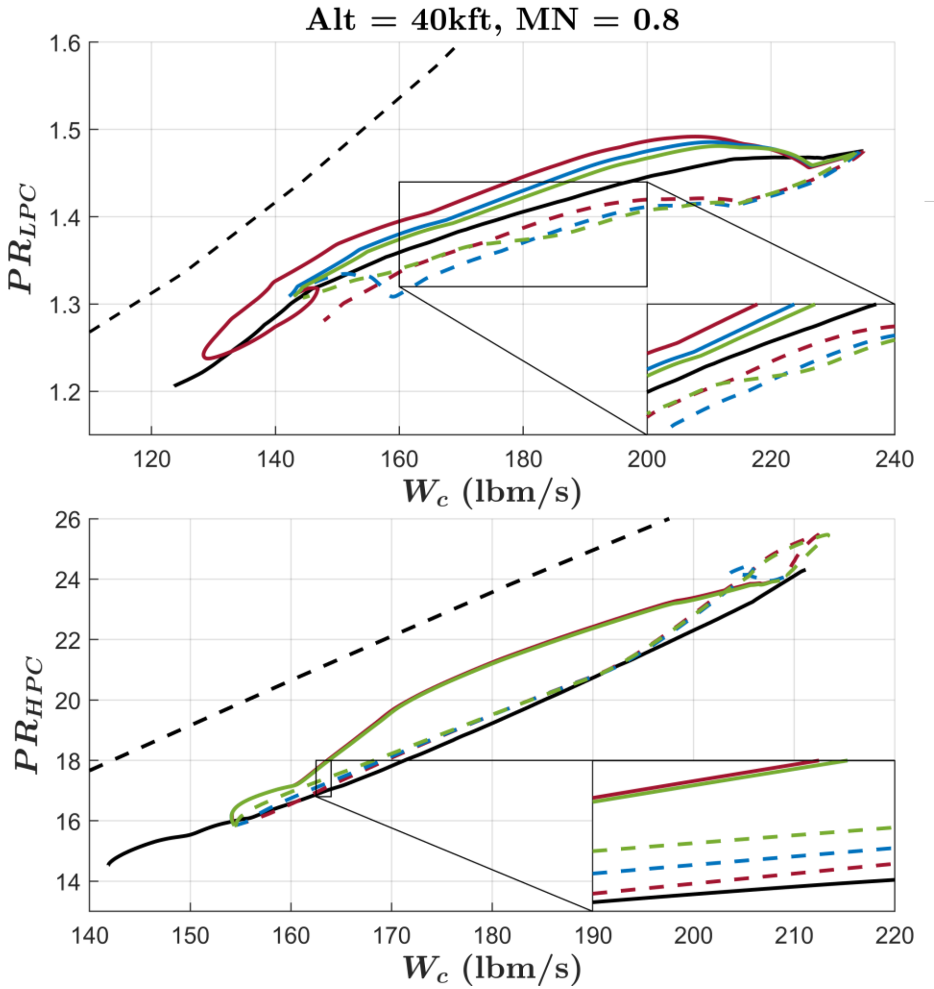


Figure 5: LPC and HPC compressor map data across controllers at Ground condition.

Table 1: Results for Ground Condition

	TEI		TSU (%)	
Controller	LPC	HPC	LPC	HPC
PI	0.721	2.37	9.31	26.9
CMPC	0.695	2.19	9.48	25.6
DMPC	0.697	2.14	9.38	25.6
TEEM-PI	0.485	0.861	0.153	13.7
TEEM-CMPC	0.478	1.17	0.0929	16.1
TEEM-DMPC	0.547	1.52	1.12	17.9

Case Study – Cruise Scenario



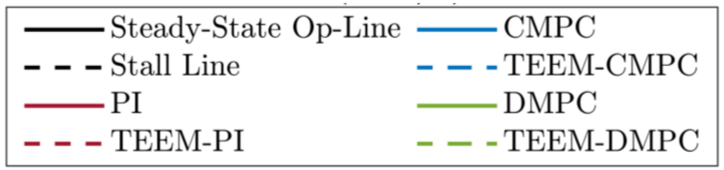


Figure 6: LPC and HPC compressor map data across controllers at Cruise condition.

Table 2: Results for Cruise Condition

	TEI		TSU (%)	
Controller	LPC	HPC	LPC	HPC
PI	2.32	3.83	31.3	46.9
CMPC	1.30	3.72	14.0	46.1
DMPC	0.929	3.72	9.73	46.1
TEEM-PI	1.60	0.867	0.00	31.2
TEEM-CMPC	2.06	0.734	6.73	33.7
TEEM-DMPC	1.80	1.12	0.00	29.1

Case Study – Motor Results

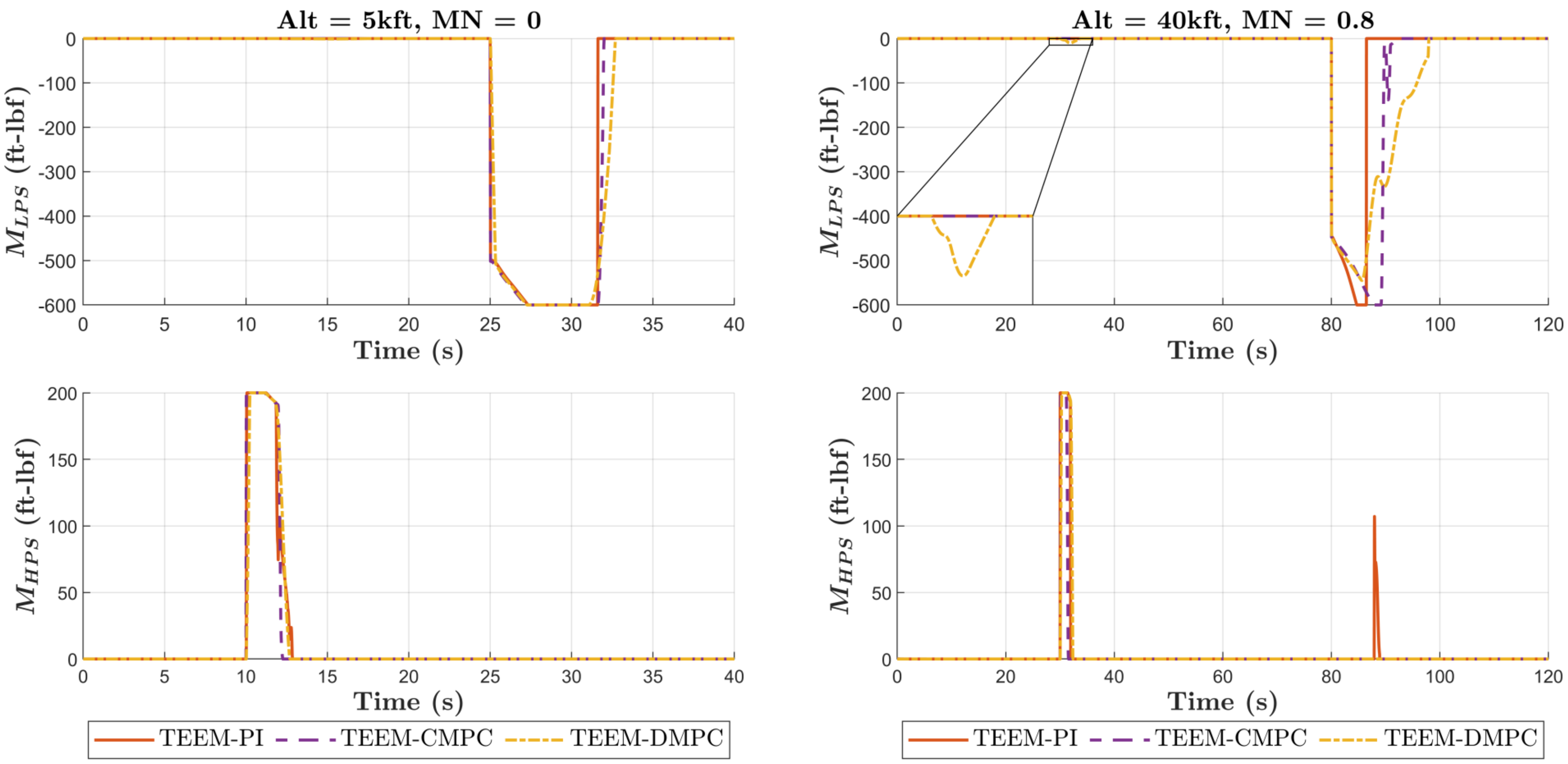


Figure 7: Resultant motor torque trajectories across controllers for Ground (left) and Cruise (right) scenarios.

Conclusions

- Designed two MPCs incorporating TEEM design strategy.
- TEEM goals included in cost function via:
  - Piecewise tracking logic and thresholding.
  - Washout filter to restrict motor response.
- MPCs performed comparably to PI with and without TEEM.
- Data highlighted efficacy of washout filter and importance of holistic data analysis.
- Future work can take many avenues.

Acknowledgements

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Questions?

Backup Slides

Case Study – Ground Scenario

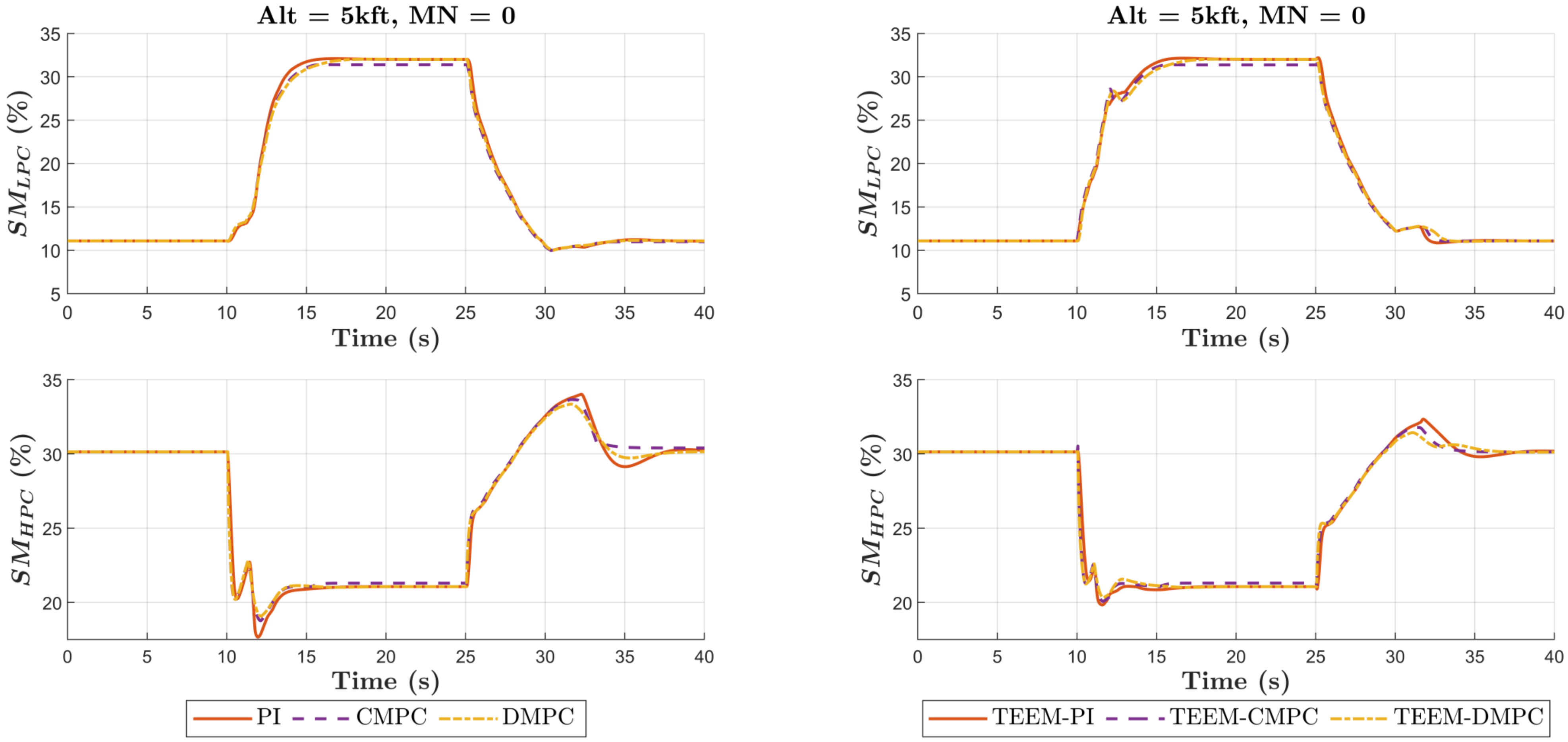

Figure A1: Resultant stall margin trajectories across controllers without TEEM applied (left) and with TEEM applied (right)..

Case Study – Cruise Scenario

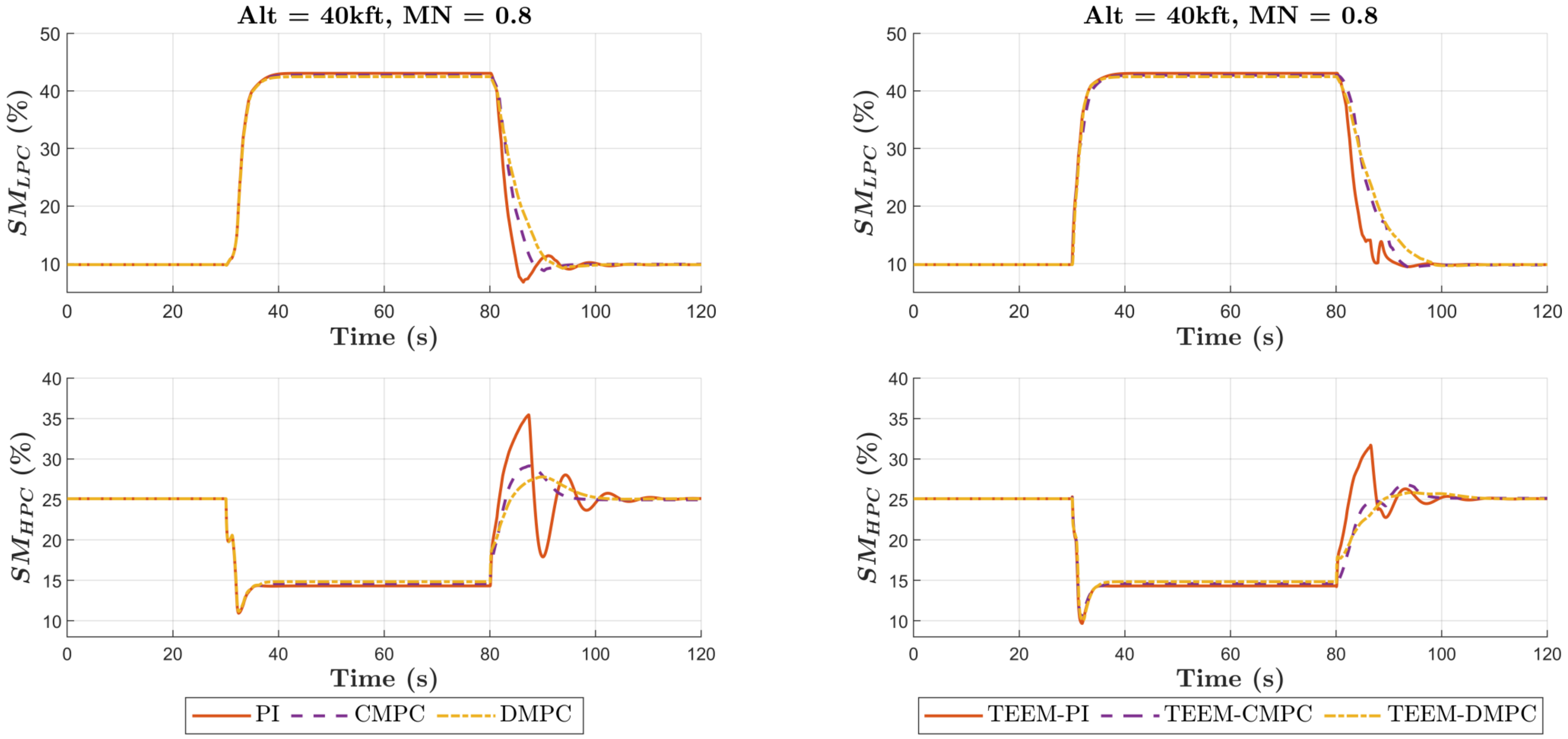

Figure A2: Resultant stall margin trajectories across controllers without TEEM applied (left) and with TEEM applied (right)..