Failure Behavior and Control Based Mitigation for a Parallel Hybrid Propulsion System

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Session: GTE-05, GTE Controls and Operations

Room: Celebration 1

Jonathan Kratz & Donald Simon

NASA Glenn Research Center

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Background/Motivation

- Challenge – maintaining operability throughout a vast operating envelope with consideration of electrified aircraft propulsion (EAP)
  - Various EAP architectures add components
  - Additional components are coupled to and impact the operation of gas turbine engines
  - Increases chance of a failure
  - Concerns how failures in the electrical system will propagate to impact the turbomachinery
  - Desire to mitigate failures with reversionary control logic
- Focus on a parallel hybrid architecture
  - Relevant to regional and single-aisle aircraft
  - Garnered interest in recent years
  - Provides contrast to previously investigate turboelectric concept.
- Goal: Develop a model of a relevant parallel hybrid propulsion system, inject failures into the electrical power system, develop mitigation strategies, and evaluate operability through simulation studies

Artistic depiction of the parallel hybrid Sugar Volt concept vehicle

Parallel Hybrid Engine Model

Based on a Numerical Propulsion System Simulation (NPSS) model developed by the Georgia Institute of Technology under the NASA Electrified Powertrain Flight Demonstration (EPFD) project

Electric Machine = EM = M/G = Motor/Generator

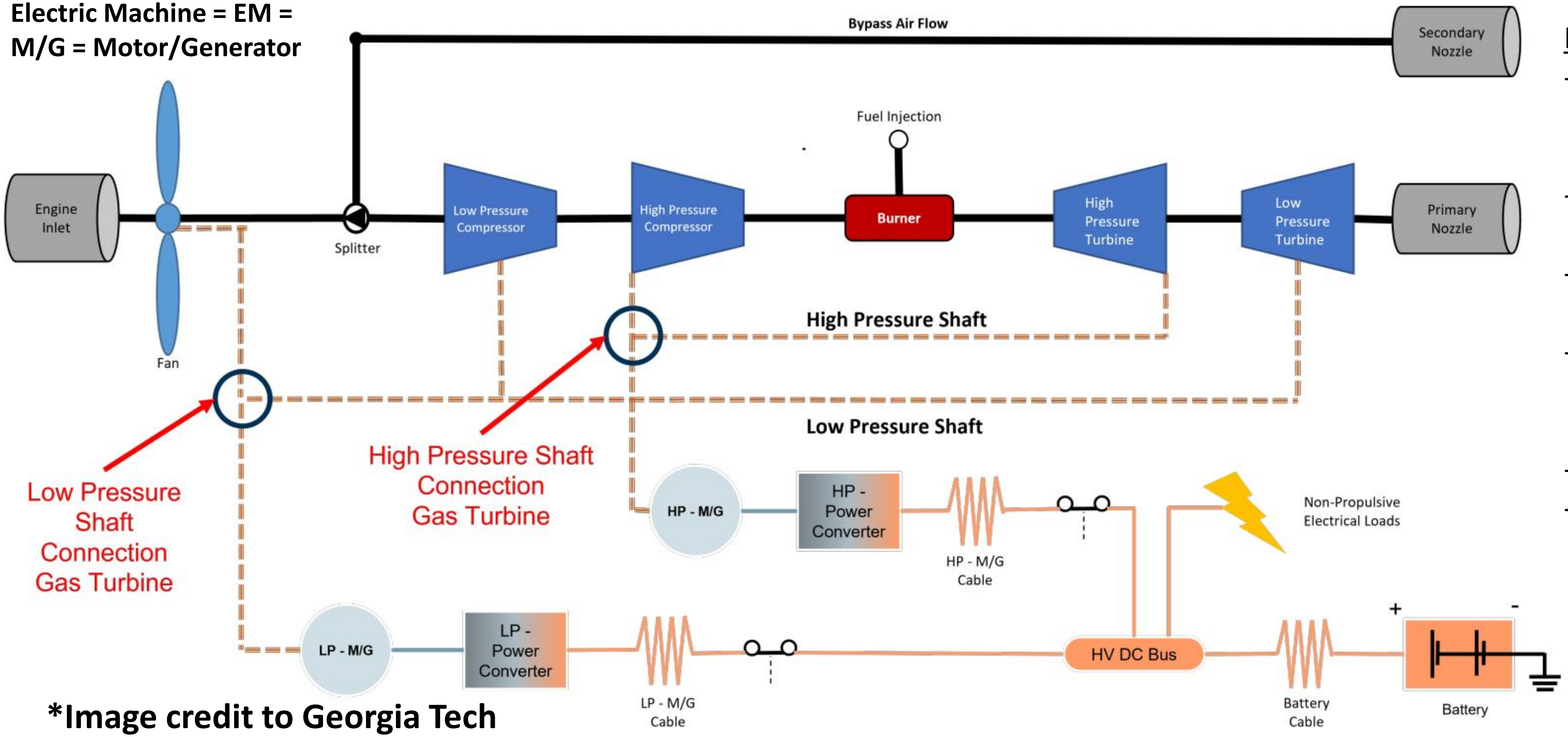


***Image credit to Georgia Tech**

Notable features

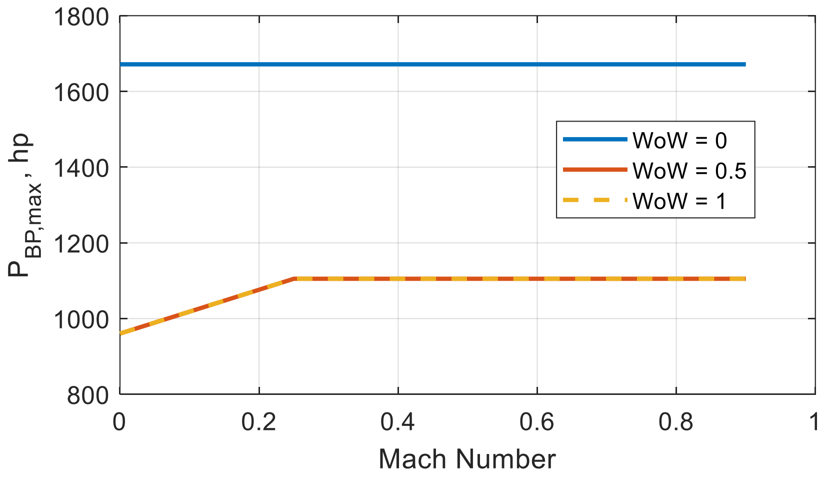
- ~19klb$_f$ of thrust at sea level static conditions
- Mission range: ~1000nmi
- ~1.25MW (~1676hp) available for boost
- Boost envisioned for take-off and start of climb (all on LPS)
- Pre-cooling
- Cooled-cooling

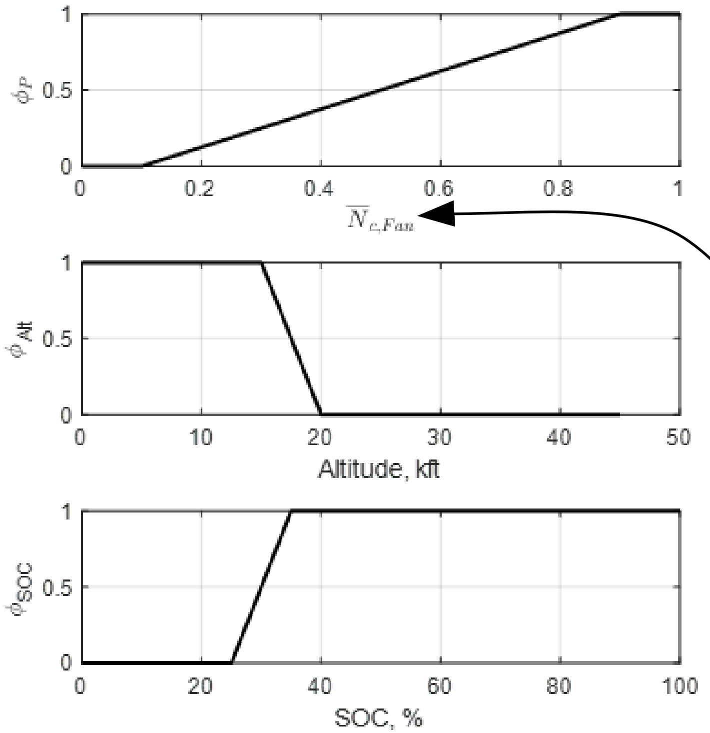
***Modeled in MATLAB/Simulink® with the Toolbox for Modeling and Analysis of Thermodynamic Systems (T-MATS)**

Controller (normal operation)

- Boost power determination:
  $P_{BP} = P_{BP,max}\varphi_P\varphi_{SOC}\varphi_{Alt}\varphi_{TS}$
  φ_{TS} is 1 when the boost command toggle switch is enabled and 0 otherwise. A rate limiter with a 15 s ramp is applied to assure a gradual transition
- Scheduled variable bleed valve (VBV)
- Gain scheduled proportional integral (PI) fuel flow rate controller with limit logic and min-max controller selection logic
- Generic acceleration/deceleration limit logic
- Set-point scheduling adjusts to changes in LPS EM power and boost

*WoW = weight on wheels





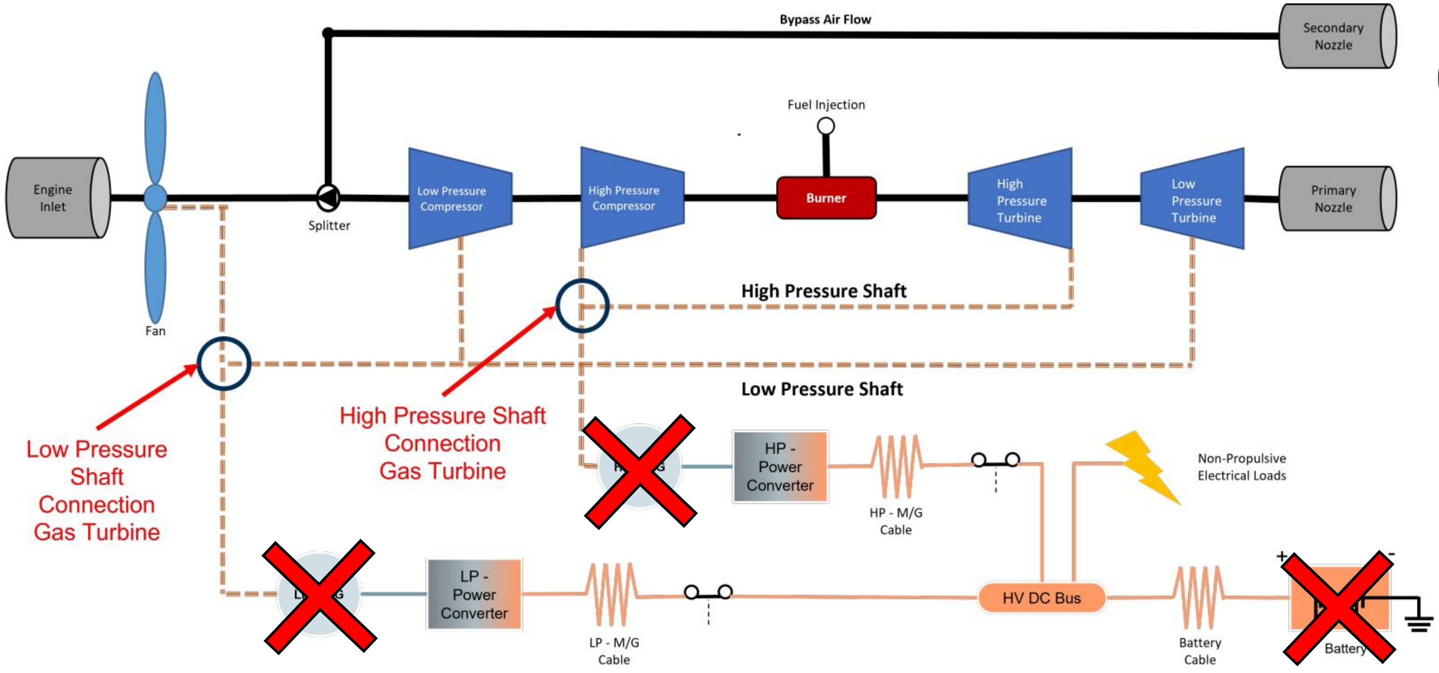
Corrected Fan Speed

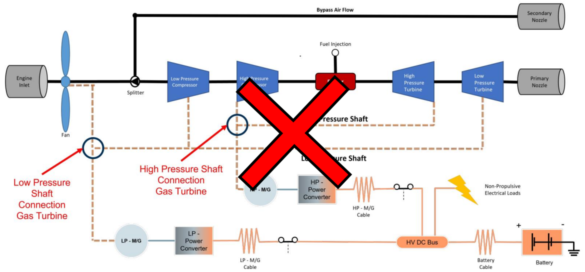
$$\overline{N}_{c,Fan} = \frac{N_{c,Fan} - N_{c,Fan,Min}}{N_{c,Fan,Max} - N_{c,Fan,Min}}$$

***TEEM and charging are addressed in the control design but are not dominant in the analysis**

Controller (reversionary control)

- Types of failures: failure of (1) LPS EM, (2) HPS EM, (3) energy storage system, (4) one of the engines on a 2-engine aircraft (no auxiliary power unit or ram air turbine)
- Failures could be full or partial (ex. 1 of several EMs fail)





Other Engine

Controller (reversionary control)

- Types of failures: failure of (1) LPS EM, (2) HPS EM, (3) energy storage system, (4) one of the engines on a 2-engine aircraft (no auxiliary power unit or ram air turbine)
- Failures could be full or partial (ex. 1 of several EMs fail)

LPS EM Failure

- LPS EM command is limited according to severity of the failure
- Effectively alters the maximum boost power
- Used in determination of actuator inputs, control gains, and the set-point

Energy Storage System

- Accommodated through existing set-point logic (loss in energy storage capacity reduces the SOC → boost is limited for low SOC)

HPS EM Failure

- HPS EM command is limited according to the severity of the failure
- Power extraction unable to be supplied by the HPS EM is provided by the energy storage system accompanied by an adjustment in the LPS EM power command (no additional demands on the power system)

Engine Failure

- Power extraction lost by the failed engine will be picked up by the working engine using the energy storage devices accompanied by reduction in LPS EM power injection.

Failure Analysis Study Overview

Types of failures: LPS EM failure, HPS EM failure, energy storage system failure, failure of the other engine (no auxiliary power unit or ram air turbine)

Failures from a steady-state operating point	
Flight Conditions (Altitude, ft / Mach Number)	0 / 0, 0 / 0.3, 5000 / 0.3, 10000 / 0.4, 15000 / 0.55, 35000 / 0.8
PLA(°)	40, 48, 56, 64, 72, 80
Failure Duration (s)	0.015, 40
Failure Fractions	0.25, 0.33, 0.5, 1
Failure ID Delay (s)	0.015, 1, 3, 5
Boost Option	On, Off
TEEM Option	On, Off
Failures during transients	
Flight Conditions (Altitude, ft / Mach Number)	0 / 0, 0 / 0.2, 5000 / 0.3, 10000 / 0.4, 15000 / 0.55, 35000 / 0.8
PLA changes (°)	40° ↔ 80°, 40° ↔ 60°, 60° ↔ 80°, 50° ↔ 70°
Time of the failure insertion as a fraction of the transient time	0, 0.1, 0.25, 0.5, 0.75, 0.9
Failure Duration (s)	sustained
Failure Fractions	0.25, 0.33, 0.5, 1
Failure ID Delay (s)	0.015, 1, 3, 5
Boost Option	On, Off
TEEM Option	On, Off

Additional Test Cases

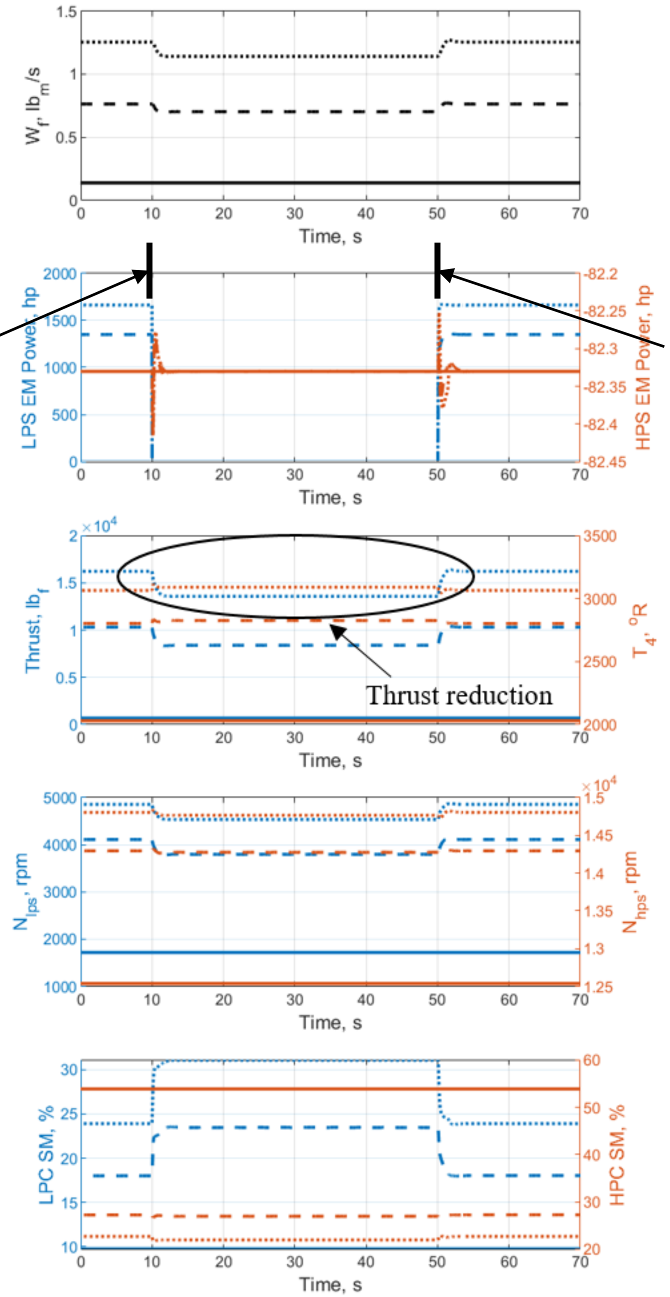
- Take-off: sea level, increasing Mach number profile, decreasing weight on wheels, failures inserted at various times
- Landing: sea level, decreasing Mach number profile, increasing weight on wheels, failures inserted at various times

*PLA = power level angle (throttle)
40° - idle power
80° - max power

Failure Analysis Study Results

Failure of the LPS EM from steady state sea level static (SLS) conditions with instantaneous failure ID and mitigation

- 16% reduction in maximum thrust
- Operability metrics maintain similar values without much disruption



LPS – low pressure shaft
HPS – high pressure shaft
LPC – low pressure compressor
HPC – high pressure compressor

W_f – fuel flow rate
T_4 – turbine inlet temperature
N_{lps} – LPS speed
N_{hps} – HPS speed
SM – stall margin

——— Solid Lines: PLA = 40° (idle)
– – – Dashed Lines: PLA = 64° (intermediate)
········· Dotted Lines: PLA = 80° (max)

Failure Analysis Study Results

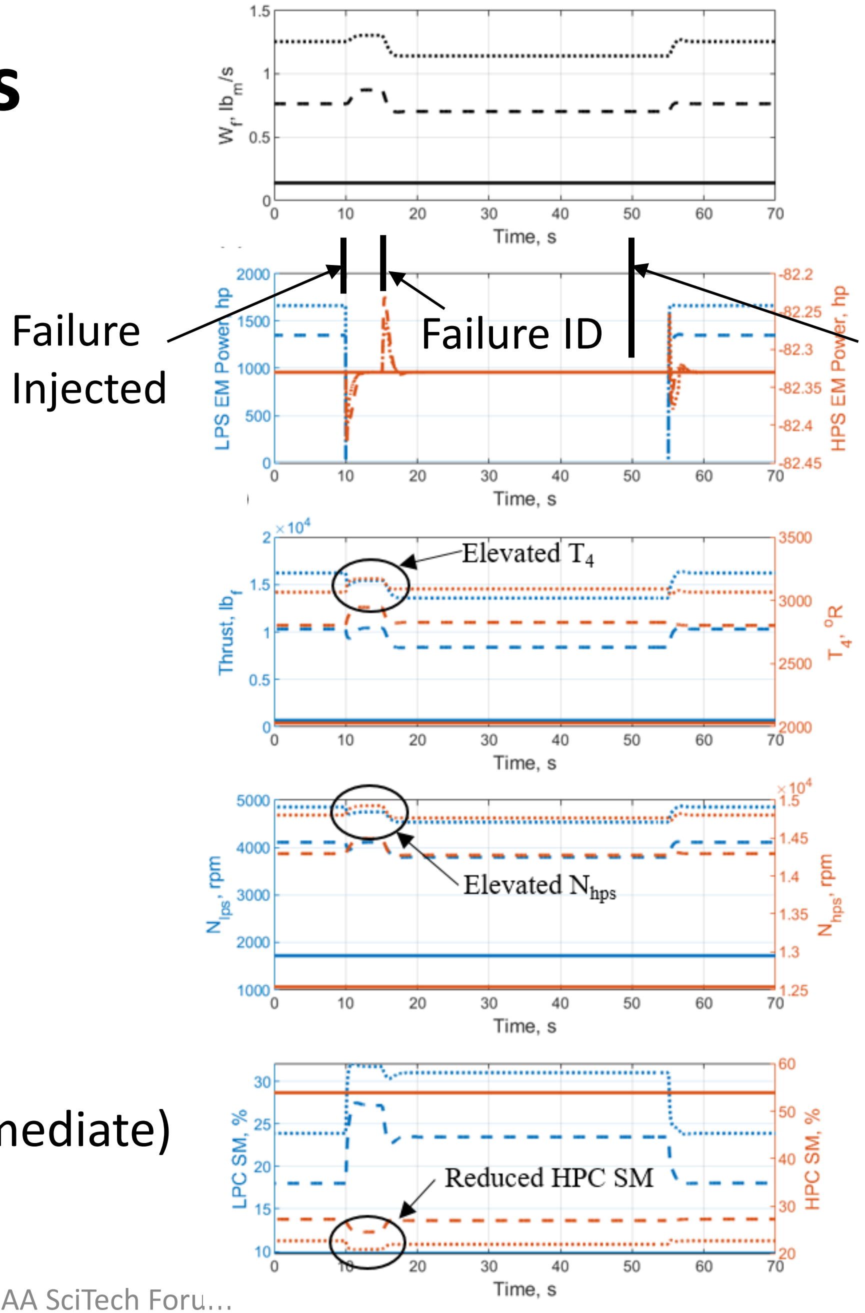
Failure of the LPS EM from steady state sea level static (SLS) conditions with failure ID and mitigation delayed by 5 s

- During delay period:
  - T_4 over-temperature (3%)
  - N_{hps} over-speed (0.85%)
  - HPC SM reduction

Solid Lines: PLA = 40° (idle)

Dashed Lines: PLA = 64° (intermediate)

Dotted Lines: PLA = 80° (max)



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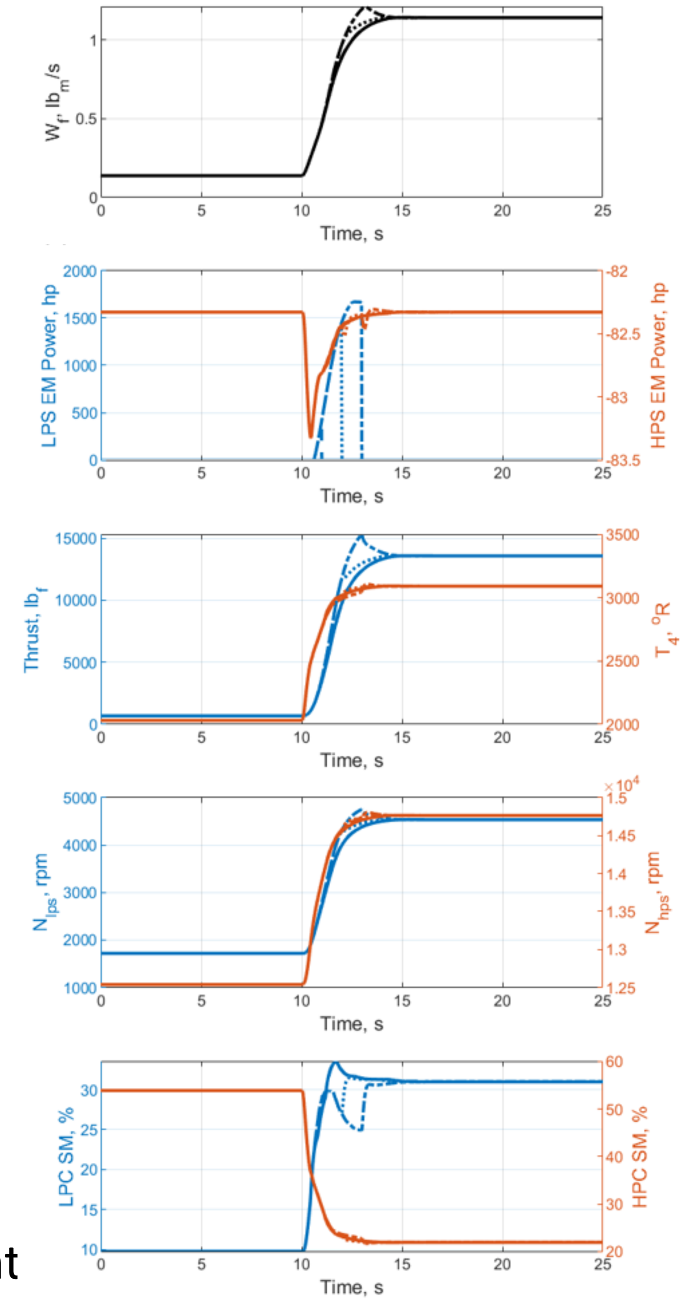
W_f – fuel flow rate
T_4 – turbine inlet temperature
N_{lps} – LPS speed
N_{hps} – HPS speed
SM – stall margin

Failure Analysis Study Results

Failure of the LPS EM during an acceleration at sea level static (SLS) conditions with instantaneous failure ID and mitigation

- No significant degradation to operability
  - No limit violations
  - No reduction in HPC SM



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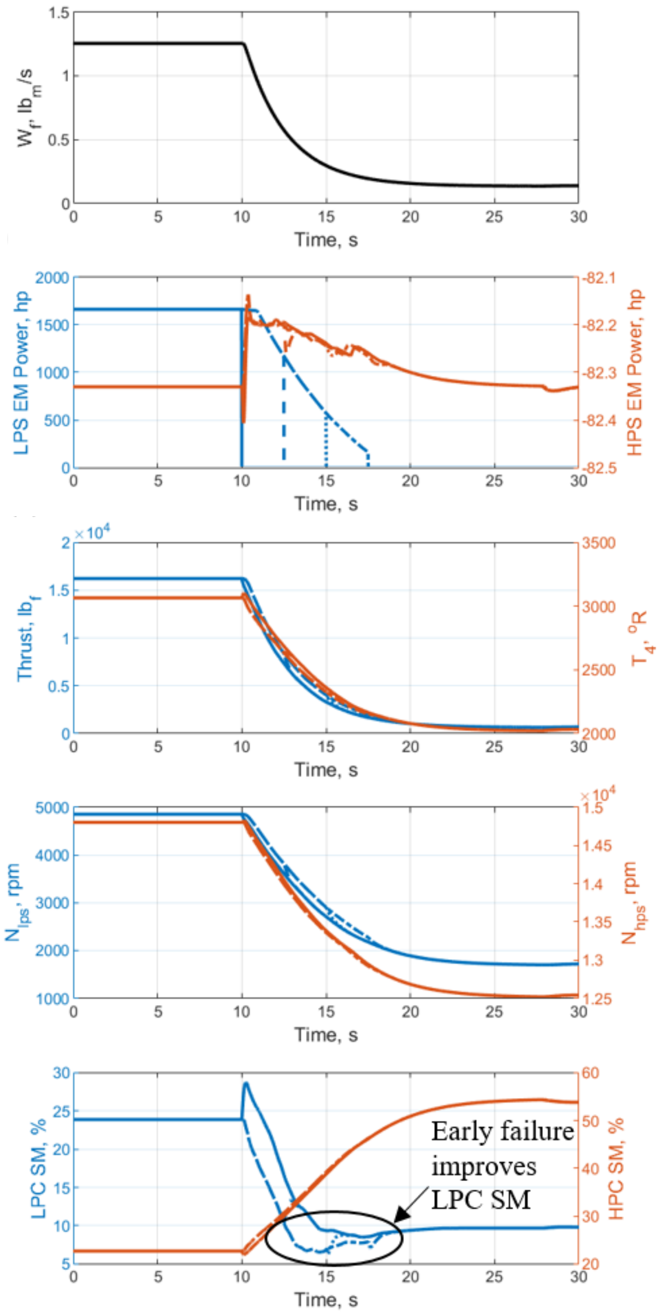
W_f – fuel flow rate
T_4 – turbine inlet temperature
N_{lps} – LPS speed
N_{hps} – HPS speed
SM – stall margin

Solid Lines: failure 0% through transient
Dashed Lines: PLA = failure 25% through transient
Dotted Lines: PLA = failure 50% through transient
Dashed-Dotted Lines: failure 75% through transient

Failure Analysis Study Results

Failure of the LPS EM during a deceleration at sea level static (SLS) conditions with instantaneous failure ID and mitigation

- No significant degradation to operability
  - Failure boosts LPC SM



LPS – low pressure shaft
HPS – high pressure shaft
LPC – low pressure compressor
HPC – high pressure compressor

W_f – fuel flow rate
T_4 – turbine inlet temperature
N_{lps} – LPS speed
N_{hps} – HPS speed
SM – stall margin

Solid Lines: failure 0% through transient
Dashed Lines: PLA = failure 25% through transient
Dotted Lines: PLA = failure 50% through transient
Dashed-Dotted Lines: failure 75% through transient

Parallel Hybrid vs. Turboelectric Comparison

- Parallel hybrid options have a few potential advantages over turboelectric:
  - Arguably less complex (no additional propulsors, less components)
  - No coupling of propulsors through the electric powertrain and no (or at least less need) for supervisory control logic to perform coordination.
    - Less consideration needed for failure propagation
  - Typically focuses on adding power to the LPS while power extraction could involve both shafts to a significant degree.
  - It is inherent with the boost feature that power injection variability must be designed into the controller.
    - Turboelectric concepts are envisioned to adhere to a power schedule at all times. Significant variations in power extraction would not be addressed in the nominal control design process but should be addressed separately through reversionary control development that is only applicable in the rare case of failure scenarios.

Summary & Conclusions

- A transient parallel hybrid propulsion system model was created.
- Control strategies were developed to operate the system under normal operating conditions.
- The control logic was appended to address failures within the electrical power system.
- Simulation results …
  - demonstrated the success of the reversionary control modes
  - displayed the potential importance of quickly identifying failures and employing reversionary control logic (prevent over-temperature, over-speed, reduced stall margins)
- Parallel hybrid architectures could pose fewer challenges with respect to failure modes and mitigation than turboelectric concepts.

Acknowledgments

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Questions/Discussion

Contact Information

Jonathan Kratz – jonathan.kratz@nasa.gov

Donald Simon – donald.l.simon@nasa.gov

EXTRA CHARTS

Failure Analysis Study Results

Failure of the LPS EM during an acceleration at sea level static (SLS) conditions failure ID and mitigation delayed by 5 s

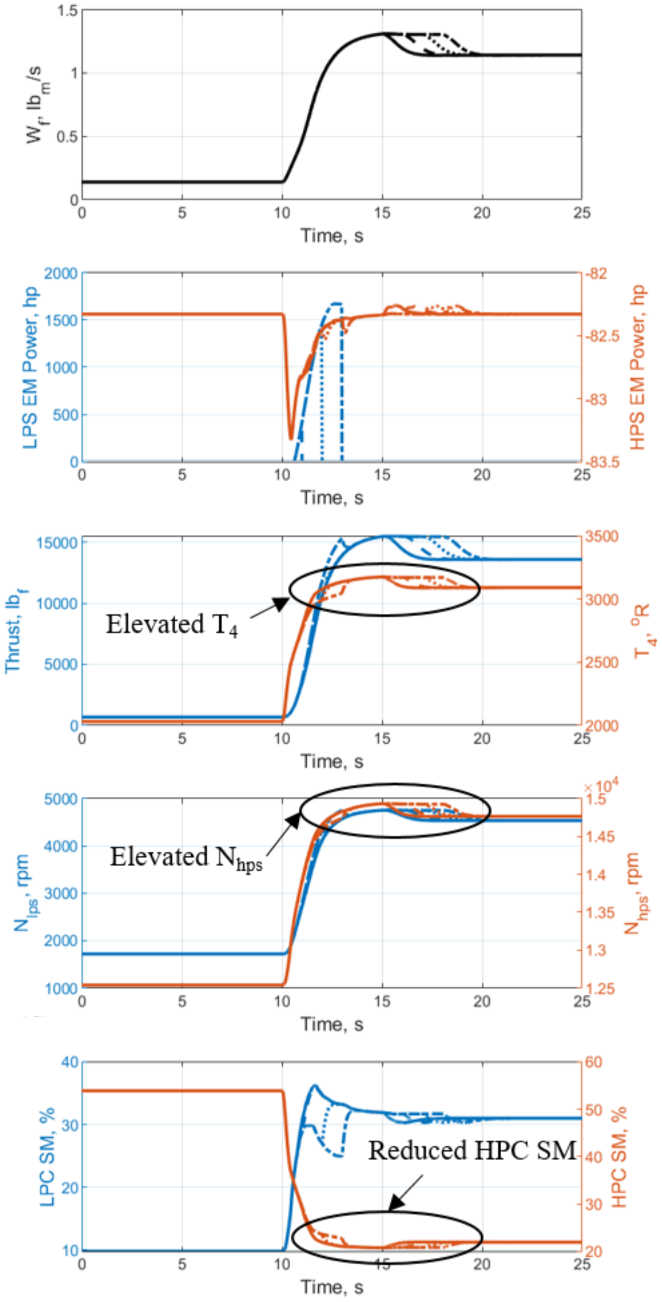
- Same trends as with the steady-state failure simulations
  - T_4 over-temperature
  - N_{hps} over-speed
  - HPC SM reduction

——— Solid Lines: failure 0% through transient

– – – – Dashed Lines: PLA = failure 25% through transient

············ Dotted Lines: PLA = failure 50% through transient

– · – · – Dashed-Dotted Lines: failure 75% through transient



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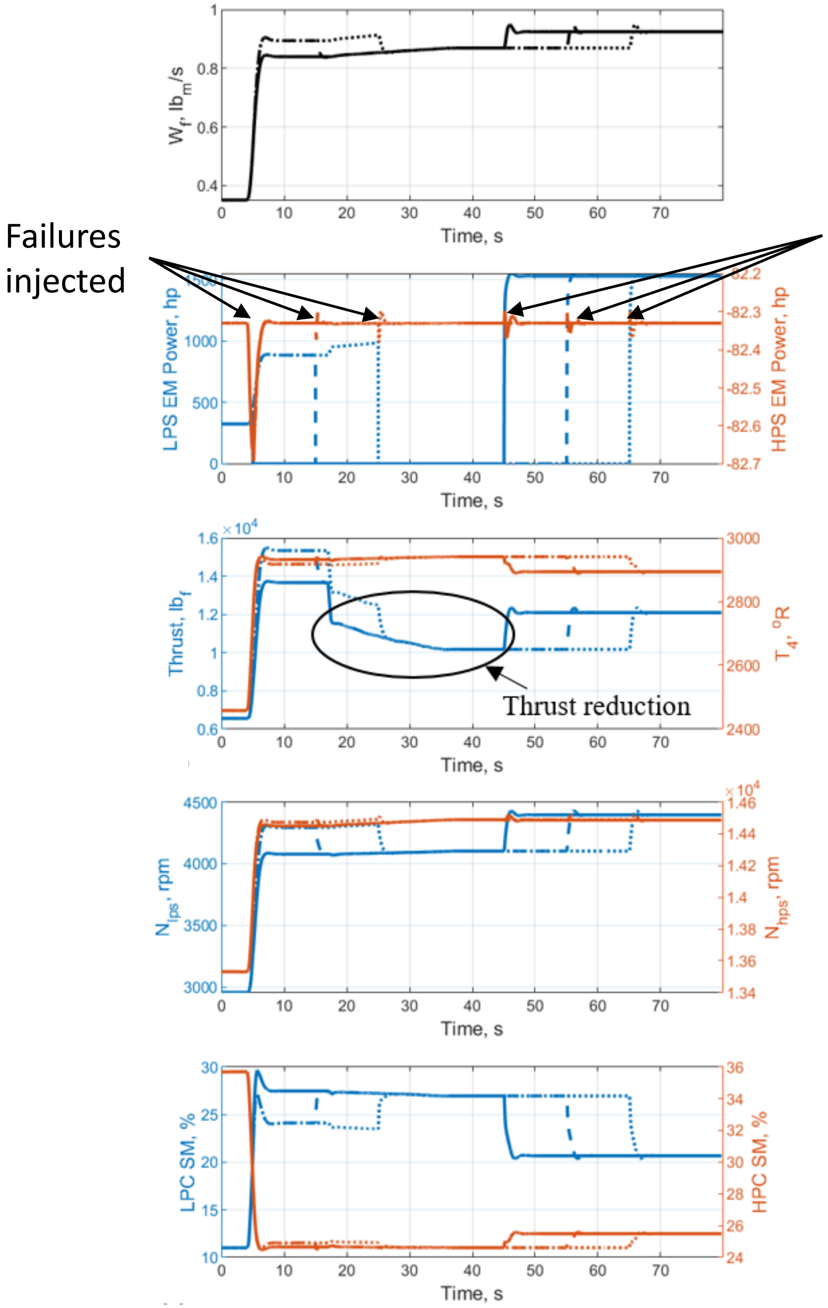
HPS – high pressure shaft
LPC – low pressure compressor
HPC – high pressure compressor

W_f – fuel flow rate
T_4 – turbine inlet temperature
N_{lps} – LPS speed
N_{hps} – HPS speed
SM – stall margin

Failure Analysis Study Results

Failure of the LPS EM during a take-off scenario with instantaneous failure ID and mitigation

- No significant degradation to operability
- Reduction in thrust (not significant for driving design decisions)



——— Solid Lines: failure @ 5s

– – – – Dashed Lines: failure @ 15s (

………… Dotted Lines: PLA = failure @ 25s

LPS – low pressure shaft
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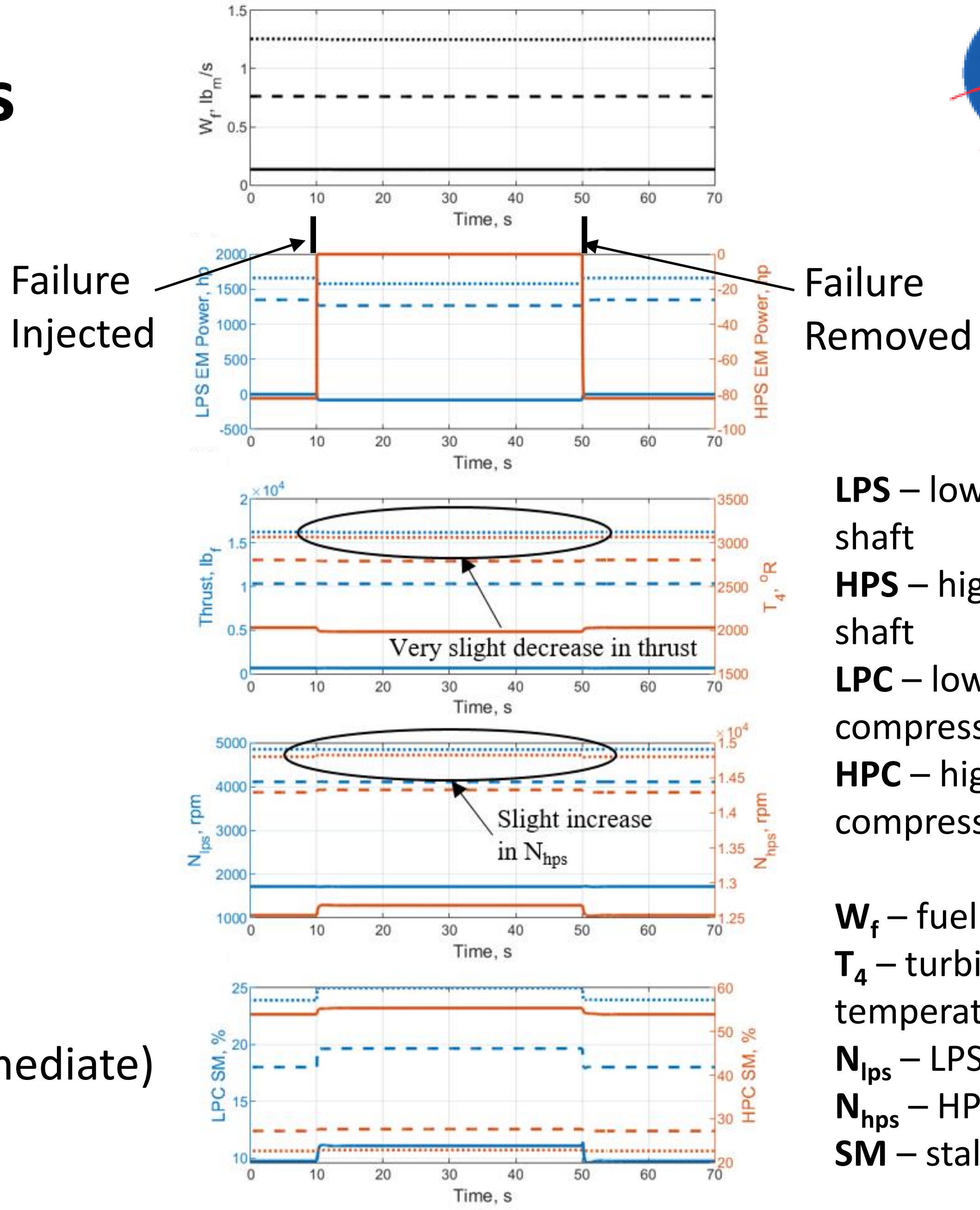
LPC – low pressure compressor
HPC – high pressure compressor

$\mathbf{W_f}$ – fuel flow rate
$\mathbf{T_4}$ – turbine inlet temperature
$\mathbf{N_{lps}}$ – LPS speed
$\mathbf{N_{hps}}$ – HPS speed
SM – stall margin

Failure Analysis Study Results

Failure of the HPS EM from steady state sea level static (SLS) conditions with instantaneous failure ID and mitigation

- Insignificant impact of performance and operability



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HPS – high pressure shaft
LPC – low pressure compressor
HPC – high pressure compressor

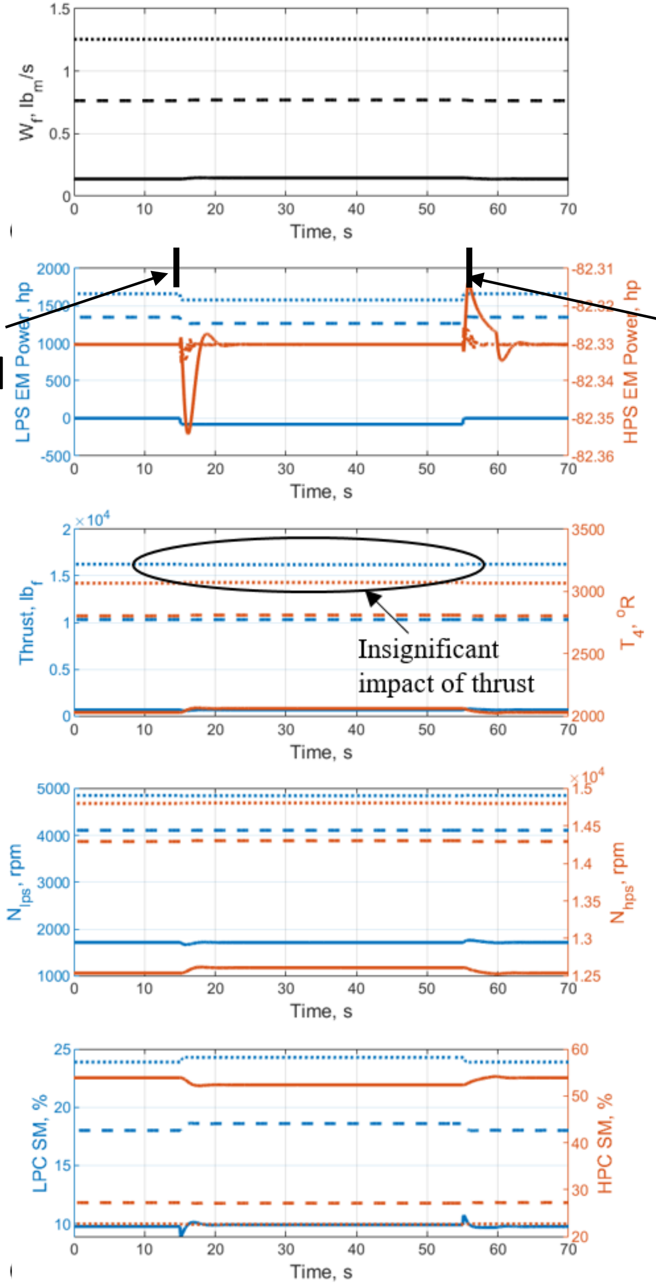
W_f – fuel flow rate
T_4 – turbine inlet temperature
N_{lps} – LPS speed
N_{hps} – HPS speed
SM – stall margin

——— Solid Lines: PLA = 40° (idle)
– – – Dashed Lines: PLA = 64° (intermediate)
········ Dotted Lines: PLA = 80° (max)

Failure Analysis Study Results

Failure of the other engine from steady state sea level static (SLS) conditions with instantaneous failure ID and mitigation

- Insignificant impact of performance and operability



LPS – low pressure shaft
HPS – high pressure shaft
LPC – low pressure compressor
HPC – high pressure compressor

$\mathbf{W_f}$ – fuel flow rate
$\mathbf{T_4}$ – turbine inlet temperature
$\mathbf{N_{lps}}$ – LPS speed
$\mathbf{N_{hps}}$ – HPS speed
SM – stall margin

Solid Lines: PLA = 40° (idle)
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