Comparing the Electrical Modeling and Thermal Analysis Toolbox Simulation Data to Electrified Aircraft Propulsion Test Hardware Data

Mark E. Bell

HX5, LLC

Santino J. Bianco

Jonathan S. Litt

NASA Glenn Research Center

Problem Statement

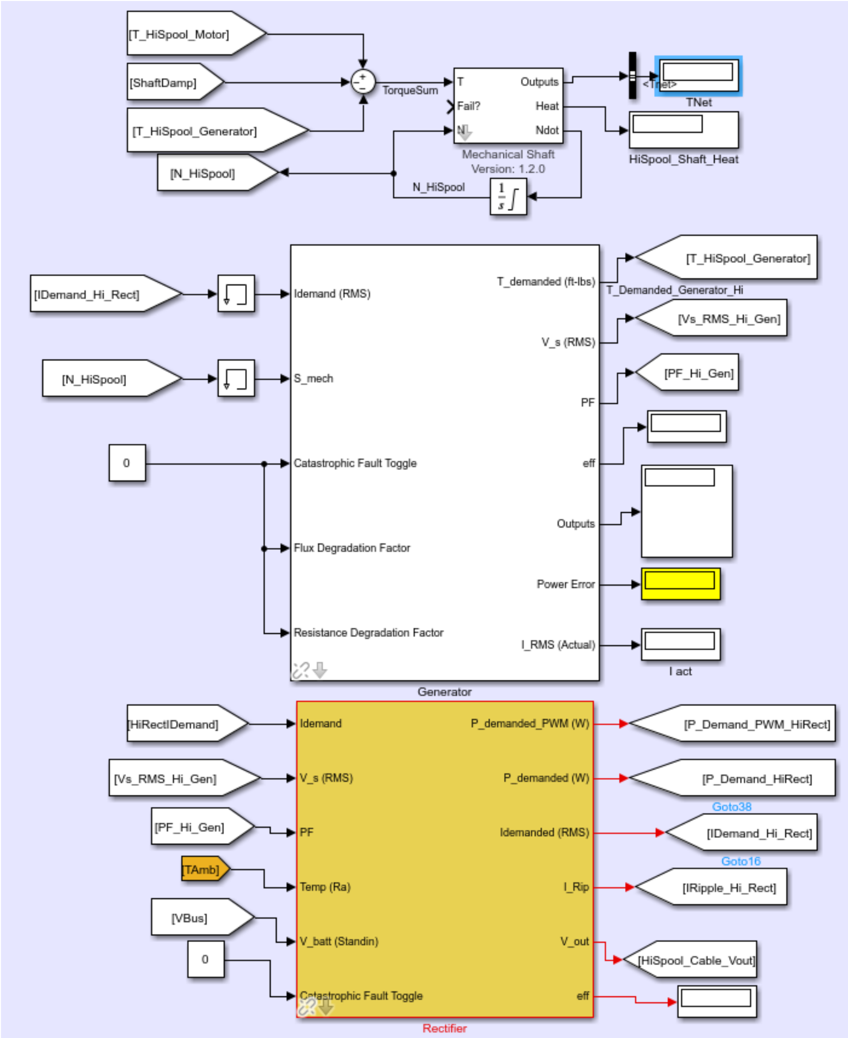
- Electric Aircraft Propulsion (EAP) is an area of research that investigates electrified turbomachinery and all-electric propulsion systems
  - Traditional missions and Urban Air Mobility (UAM) missions
  - Require control design and operational concept analysis through power system simulation as well as whole vehicle simulation
  - Electrical systems coupled with propulsion systems requires each to dynamically affect the other
- These simulations therefore require an electrical simulation toolbox that can run faster than real time (to enable flight simulator testing) and dynamically interact with the mechanical propulsion system

Objectives

- Create a model of an existing EAP test hardware system using the Electrical Modeling and Thermal Analysis Toolbox (EMTAT)
- Compare simulated outputs to hardware data from the Hybrid Propulsion Emulation Rig (HyPER) at NASA Glenn across a range of operating conditions
- Demonstrate the utility of the library by comparing the accuracy of the library models to the performance of real hardware
  - Primary metrics: simulation outputs matching hardware data within 5% of full scale.

Background - EMTAT

- EMTAT
  - Developed at NASA Glenn
  - MATLAB® - Simulink® based software library
  - Contains blocks to represent a variety of electrical and electronic components for simulation
  - Compatible with the NASA developed Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) software package
  - Equation based simulation
    - No additional solvers required

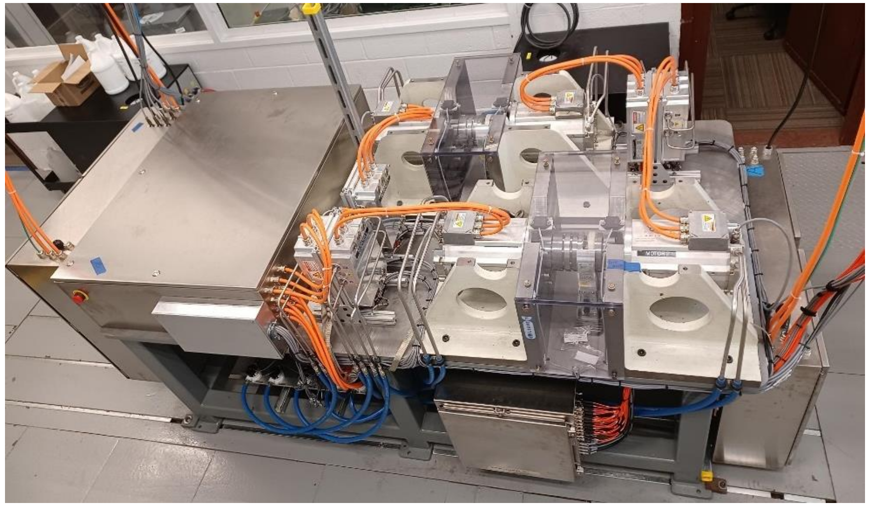


Background - EMTAT

- Turbomachinery simulations focused on shaft dynamics often use a relatively slow time step, on the order of ~15 ms
- Electrical components have significantly higher frequency dynamics, typically on the order of micro- or nanoseconds
- EMTAT assumes that the electrical components have reached a steady state over the course of any given turbomachinery timestep
  - This allows the simulation to capture system level electrical dynamics while speeding up computation, often to 10x real time or more
  - High frequency electrical dynamic losses are captured as efficiency losses
  - Heat generated in the electrical components can be fed to thermal simulation systems, and the operating temperature directly affects component operation

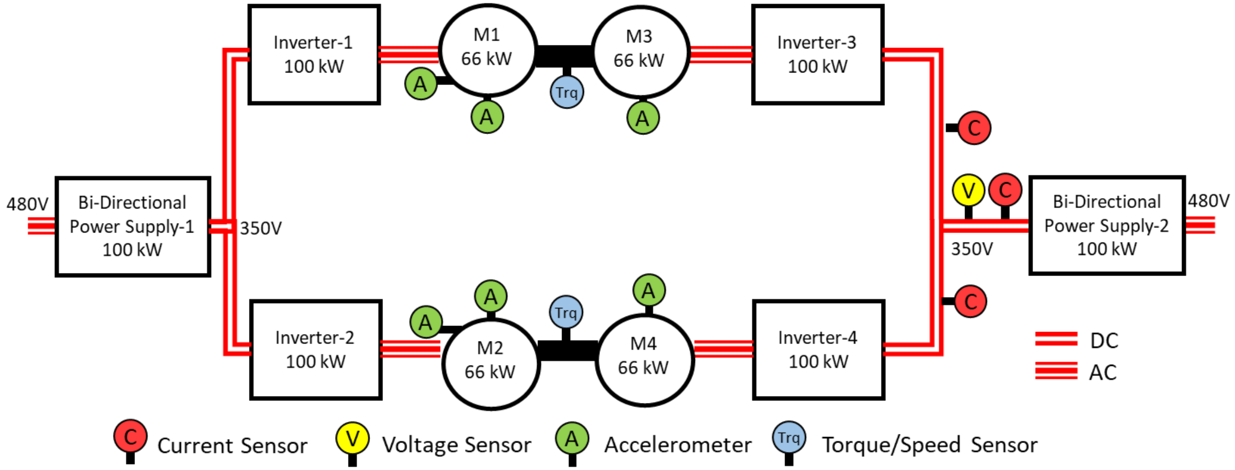
Background - HyPER

- HyPER is a reconfigurable EAP hardware and control lab at NASA Glenn
- Consists of two pairs of 66 kW electric machines
  - Each pair mechanically connected via a shaft
  - Any machine can be run as a motor or generator, switching roles as needed
- These machine pairs can be used to simulate a variety of EAP architectures
  - Gas turbine powering an electrical system
  - Electric machine adding or removing torque from a shaft to increase shaft reaction speed



Background – HyPER

- HyPER was configured for electric machine checkout testing
  - Bi-directional power supplies used to source or sink power as needed
  - Machines moved through a range of shaft speeds and torque demands
  - The data used for these tests comes from the Machine 2 – Machine 4 pair (M2-M4)
  - The system also includes a super capacitor bank with a voltage converter, but was not used in these tests



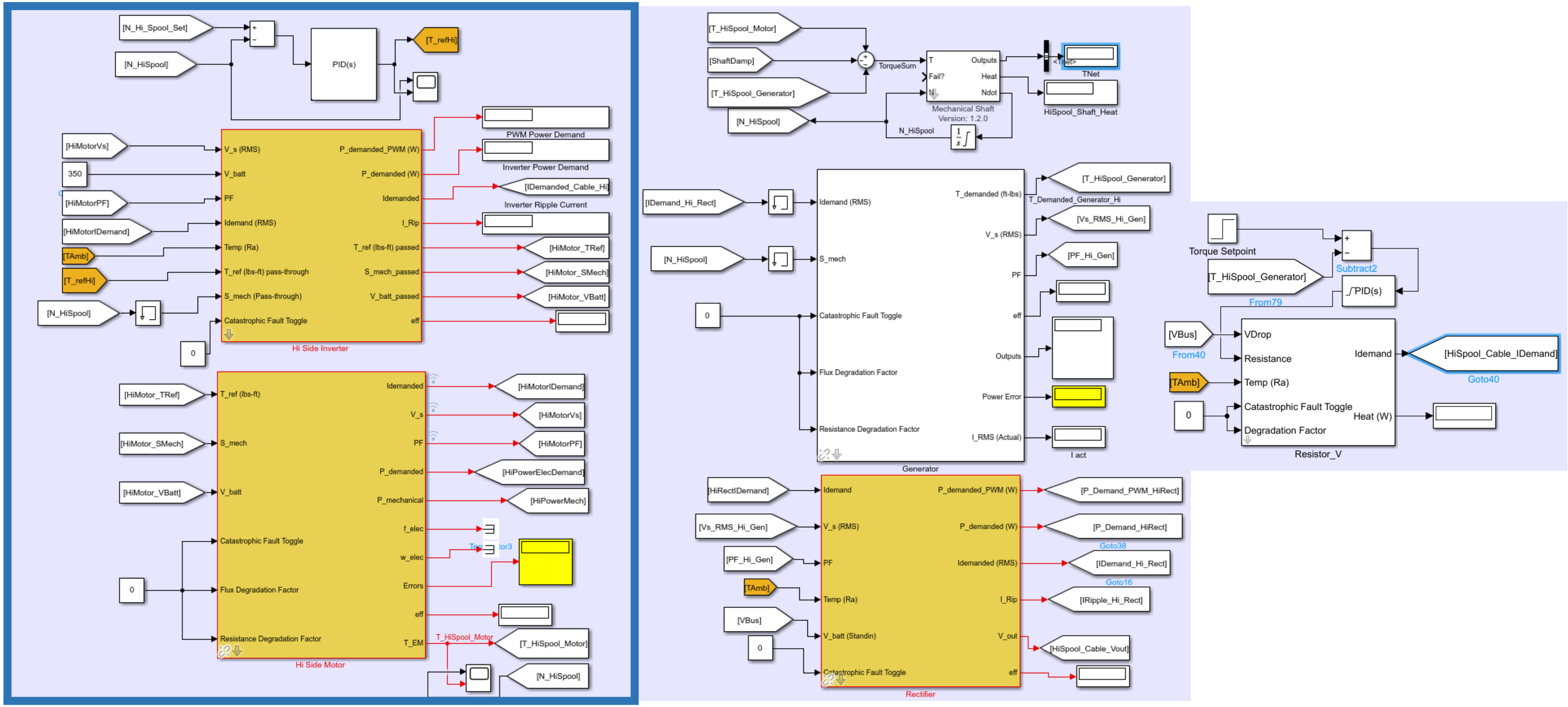
EMTAT Model

- The EMTAT model focused on recreating the HyPER configuration as closely as possible
  - Components laid out in a similar fashion to the physical arrangement of the HyPER machines
  - Datasheet information from the rig hardware informed digital model performance
  - The iDesign tool in EMTAT was used to calculate machine parameters not listed on data sheets, such as
    - Magnetic flux and iron losses in the electric machines
    - Diode and transistor losses in inverters and rectifiers

EMTAT Model

- One machine was configured to run in speed controlled mode
  - Commanding whatever torque necessary to maintain a given shaft speed
- The other was configured to run in torque controlled mode
  - Commanding whatever electrical load necessary to maintain a given torque on the shaft, whether adding or extracting
- Each machine used a separate PID controller to adjust their respective setpoints dynamically
- Mechanical shaft uses sum of torques to determine change in speed

EMTAT Model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[TAmb]
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V_s (RMS)
V_batt
PF
Idemand (RMS)
Temp (Ra)
T_ref (lbs-ft) pass-through
S_mech (Pass-through)
Catastrophic Fault Toggle
P_demanded_PWM (W)
P_demanded (W)
Idemanded
I_Rip
T_ref (lbs-ft) passed
S_mech_passed
V_batt_passed
eff
Hi Side Inverter
PWM Power Demand
Inverter Power Demand
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Inverter Ripple Current
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P_demanded (W)
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Rectifier
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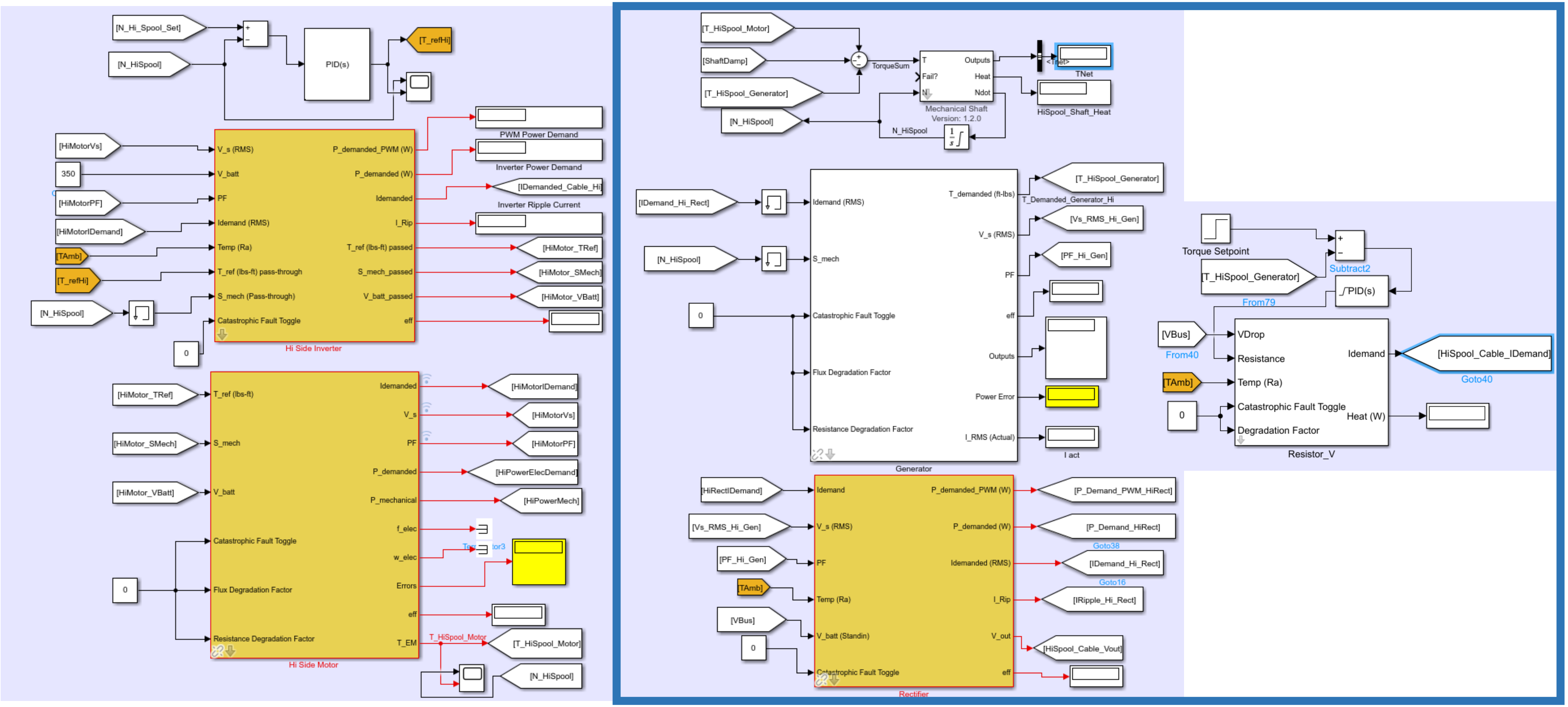
EMTAT Model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Catastrophic Fault Toggle
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PF
P_demanded
P_mechanical
f_elec
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Errors
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[P_Demand_HiRect]
Goto38
[IDemand_Hi_Rect]
Goto16
[IRipple_Hi_Rect]
[HiSpool_Cable_Vout]

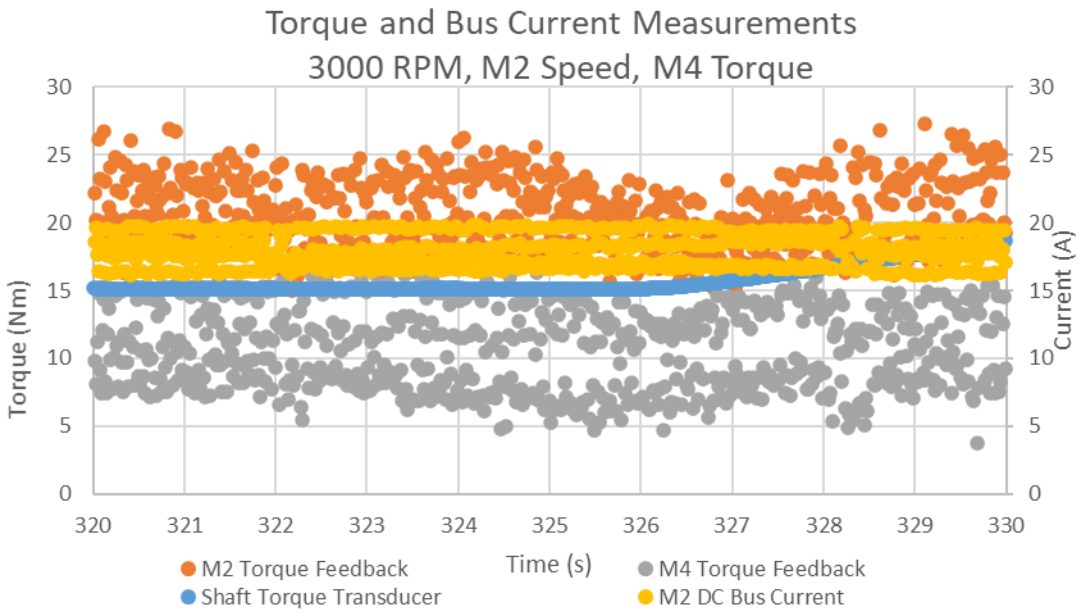
Comparisons

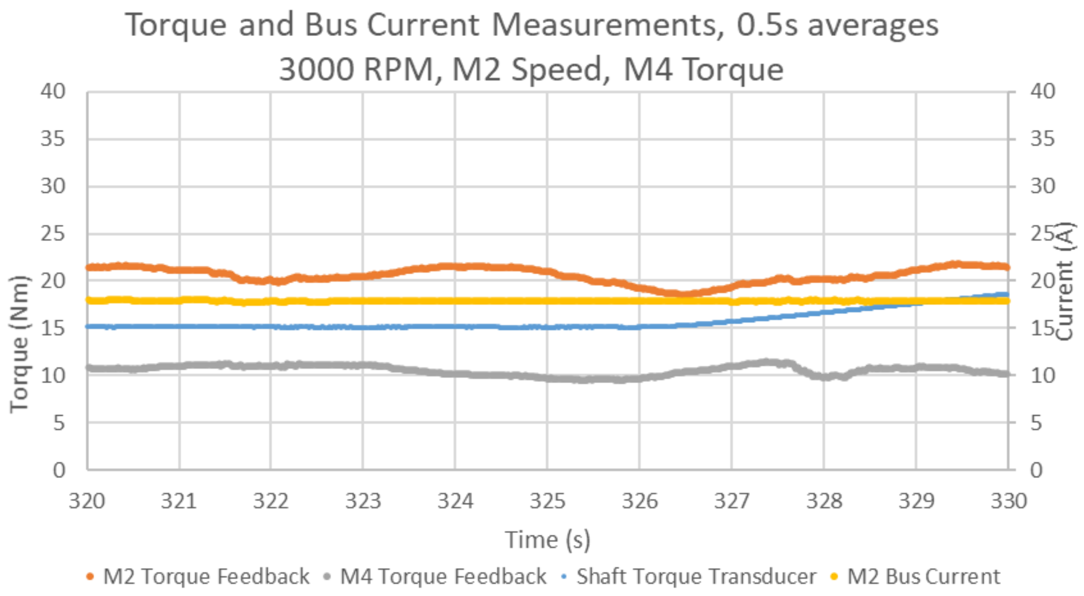
- The HyPER test data was collected at 4 speed setpoints and 10 shaft torque setpoints
- Sign conventions for torque
  - Positive = torque extracted from shaft
  - Negative = torque added to shaft

Speed, RPM	Speed Mode	Torque Mode	Shaft Torque Extraction, Nm									
1000	M2	M4	-130	-90	-50	-30	-10	10	30	50	90	130
2000	M2	M4	-130	-90	-50	-30	-10	10	30	50	90	130
3000	M2	M4	-130	-90	-50	-30	-10	10	30	50	90	130
4000	M2	M4	-130	-90	-50	-30	-10	10	30	50	90	130

Comparisons

- Signal noise from the raw data set made it challenging to determine the actual state of the hardware, and a rolling 0.5s average still exhibited significant variation at any given setpoint
- For comparison to the simulation, the test data at any given setpoint was averaged over the entire setpoint, ~30 seconds per point





Comparisons

- Initial comparisons were largely not within the 5% goal
  - Particularly pronounced with bus currents and M2 torque
  - Example set from 3000 RPM test run

	Shaft Torque Extraction, Nm									
% Difference full scale	-130	-90	-50	-30	-10	10	30	50	90	130
M2 RPM	0.82 %	-0.02 %	-0.02 %	-0.02 %	-0.02 %	-0.01 %	-0.04 %	-0.01 %	-0.01 %	-0.02 %
M2 Bus Current	-6.10 %	-5.21 %	-2.59 %	-2.12 %	-1.58 %	1.66 %	1.38 %	0.79 %	-2.01 %	-2.54 %
M2 Torque	1.71 %	-8.81 %	-8.88 %	-7.28 %	-6.24 %	7.44 %	6.13 %	5.73 %	7.67 %	17.81 %
M4 RPM	-0.83 %	0.02 %	0.02 %	0.02 %	0.01 %	-0.01 %	0.00 %	0.01 %	0.03 %	0.00 %
M4 Bus Current	9.61 %	6.87 %	3.85 %	2.26 %	0.77 %	0.80 %	2.41 %	3.88 %	6.60 %	8.86 %
M4 Torque	0.11 %	-0.77 %	0.90 %	0.03 %	-0.49 %	0.14 %	0.94 %	-0.99 %	0.71 %	1.73 %

Comparisons

- The M2 Torque was the value most consistently out of range
  - Adjusting the shaft physical characteristics (inertia and friction) did not close the gap sufficiently
- To align the simulation outputs with the hardware data, an additional shaft damping torque term was required, but found experimentally at each point
  - Did not scale linearly with shaft speed or torque extraction

Comparisons

- When comparing the electric machine torques, there was an offset of 2-8 Nm at almost every point
  - Did not match well with simulation offsets
  - May not be a significant term in full scale turbomachinery systems

- Following the additional damping torque term, all but one data point was within the 5% full scale range
  - Simulated DC Bus currents remained the largest error terms in the simulation, including the only term outside of 5% matching
  - Nearly 70% of the data was within 1% matching

Comparisons

1000 RPM Test Run

	Shaft Torque Extraction, Nm									
% Difference full scale	-130	-90	-50	-30	-10	10	30	50	90	130
M2 RPM	-0.06 %	0.00 %	-0.03 %	-0.04 %	-0.05 %	-0.05 %	-0.05 %	-0.02 %	-0.04	-0.07 %
M2 Bus Current	-0.53 %	-0.38 %	-0.16 %	-0.10 %	-0.11 %	-0.31 %	-0.36 %	-0.65 %	-1.59 %	-2.75 %
M2 Torque	-0.78 %	0.07 %	-0.19 %	0.28 %	0.00 %	-0.10 %	0.08 %	0.45 %	0.32 %	-0.97 %
M4 RPM	0.06 %	0.03 %	0.06 %	0.04 %	0.03 %	0.06 %	0.07 %	0.04 %	0.03 %	0.05 %
M4 Bus Current	1.54 %	0.93 %	0.52 %	0.33 %	0.06 %	0.11 %	0.50 %	0.55 %	0.92 %	0.97 %
M4 Torque	-0.10 %	0.09 %	-0.23 %	0.11 %	0.12 %	-0.15 %	-0.18 %	-0.10 %	0.14 %	0.00 %
Damping Torque (Nm):	7	7	5	3	5	5	3.5	2	4	5.5

2000 RPM Test Run

	Shaft Torque Extraction, Nm									
% Difference full scale	-130	-90	-50	-30	-10	10	30	50	90	130
M2 RPM	0.08 %	-0.01 %	-0.06 %	-0.01 %	-0.01 %	-0.08 %	-0.07 %	-0.02 %	-0.04 %	0.10 %
M2 Bus Current	-0.66 %	0.03 %	-0.48 %	-0.33 %	-0.34 %	-0.26 %	-0.64 %	-0.63 %	-2.15 %	-3.41 %
M2 Torque	0.44 %	0.05 %	-0.08 %	-0.22 %	0.19 %	0.24 %	0.67 %	0.38 %	0.08 %	-0.12 %
M4 RPM	0.06 %	0.00 %	-0.01 %	0.05 %	0.00 %	-0.05 %	-0.04 %	0.00 %	0.09 %	0.08 %
M4 Bus Current	2.72 %	1.72 %	0.99 %	0.55 %	0.38 %	0.20 %	0.85 %	1.31 %	1.31 %	1.64 %
M4 Torque	0.01 %	0.00 %	0.01 %	0.01 %	-0.03 %	0.01 %	0.03 %	-0.15 %	0.08 %	-0.19 %
Damping Torque (Nm):	10.5	12	6	6	4.5	5.25	7	5	5	5

Comparisons

3000 RPM Test Run

	Shaft Torque Extraction, Nm									
% Difference full scale	-130	-90	-50	-30	-10	10	30	50	90	130
M2 RPM	-0.02 %	-0.02 %	-0.02 %	-0.02 %	-0.02 %	-0.02 %	-0.04 %	-0.01 %	-0.01 %	-0.02 %
M2 Bus Current	-1.58 %	-0.27 %	-0.11 %	-0.20 %	-0.36 %	-0.36 %	-0.53 %	-0.71 %	-2.52 %	-4.06 %
M2 Torque	-0.08 %	-0.05 %	0.06 %	0.94 %	-0.44 %	-0.44 %	0.08 %	0.19 %	-0.30 %	-0.31 %
M4 RPM	0.00 %	0.02 %	0.02 %	0.02 %	0.01 %	0.01 %	0.00 %	0.01 %	0.03 %	0.00 %
M4 Bus Current	3.71 %	2.63 %	1.71 %	0.89 %	0.25 %	0.25 %	1.17 %	1.43 %	2.58 %	3.12 %
M4 Torque	0.11 %	0.00 %	0.13 %	0.03 %	-0.10 %	-0.10 %	0.17 %	-0.22 %	-0.06 %	0.19 %
Damping Torque (Nm):	8.75	11.25	8.5	8.5	8.5	7	7	5	9	9

4000 RPM Test Run

	Shaft Torque Extraction, Nm									
% Difference full scale	-130	-90	-50	-30	-10	10	30	50	90	130
M2 RPM	0.01 %	-0.16 %	-0.01 %	0.10 %	-0.08 %	-0.13 %	-0.12 %	-0.19 %	0.11 %	0.07 %
M2 Bus Current	-1.45 %	-1.48 %	-0.36 %	0.16 %	-0.02 %	-0.40 %	0.13 %	-0.17 %	-2.48 %	-4.87 %
M2 Torque	0.01 %	0.15 %	0.10 %	-0.07 %	0.04 %	-0.01 %	0.12 %	0.20 %	-0.11 %	-0.06 %
M4 RPM	-0.06 %	0.04 %	0.08 %	-0.11 %	-0.06 %	0.18 %	0.17 %	-0.12 %	-0.10 %	0.20 %
M4 Bus Current	5.40 %	3.63 %	1.97 %	0.87 %	0.35 %	-0.12 %	1.24 %	2.29 %	3.77 %	1.94 %
M4 Torque	0.25 %	0.03 %	-0.06 %	-0.01 %	0.03 %	-0.04 %	0.07 %	0.08 %	-0.03 %	0.01 %
Damping Torque (Nm):	7	8	8.25	9.25	7.75	3.25	1	4.5	8.5	3

Summary

- EMTAT can be used to simulate real world EAP hardware
  - Matched or nearly matched HyPER hardware over a range of speeds and power conditions
  - Each simulated machine switched from positive power to negative power and back as needed
  - Simulated faster than real time
- More analysis is needed to better understand remaining errors, particularly DC Bus currents and relationship of model shaft damping terms to hardware shaft damping
- More varied speed data can be collected to better understand shaft damping terms

Contact

- Contact information:
  - Mark E. Bell, HX5, LLC
  - mark.e.bell@nasa.gov

  - Santino J. Bianco, NASA
  - santino.bianco@nasa.gov

  - Jonathan S. Litt, NASA
  - jonathan.s.litt@nasa.gov

- EMTAT publicly available on GitHub: https://github.com/nasa/EMTAT

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