

SUBsonic Single Aft eNginE (SUSAN) Power/Propulsion System Hardware-in-the- Loop Test Results

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Electrified Aircraft Propulsion (EAP) technology offers a promising path forward for reducing greenhouse gas emissions and other negative environmental effects from the commercial aviation sector. EAP systems can reduce fuel burn and improve performance over state-of-the-art designs, however the increased complexity and highly coupled nature of these systems present challenges that require new control approaches. The SUBsonic Single Aft eNginE (SUSAN) Electrofan is a concept aircraft developed by NASA as a reference design for a commercial transport aircraft with a highly integrated hybrid-electric powertrain. This paper summarizes the results of a Hardware-in-the-Loop (HIL) test of a control architecture developed for the SUSAN power/propulsion system (PPS). The test was performed in the Hybrid Propulsion Emulation Rig (HyPER) facility at the NASA Glenn Research Center (GRC) and involved a real-time reference model of the SUSAN PPS and control system running with a sub-scale electro-mechanical system replacing one of the PPS subsystems. A side-by-side comparison of the simulated and real systems in the HIL test results shows that the control architecture functions well in both the simulation and the real-time HIL environment. In both cases the controller is able to simultaneously deliver the required thrust response and balance power levels between the electrical and turbomachinery subsystems.

I. Introduction

Reducing greenhouse gas emissions and minimizing impact on the global environment is of critical importance to the commercial aviation industry [1]. However, decarbonization of commercial transport aircraft presents unique engineering challenges that have become a focus of the National Aeronautics and Space Administration's (NASA) Aeronautics Research Mission Directorate (ARMD), along with its partners in government, academia, and industry [2, 3, 4]. A promising path towards decarbonization is offered by Electrified Aircraft Propulsion (EAP) technology. EAP systems, specifically hybrid-electric propulsion, show particular promise for the single-aisle and regional transport markets where all-electric designs are not yet viable due to their high power and specific energy requirements [5, 6]. Hybrid-electric aircraft can achieve significantly reduced fuel burn compared to state-of-the-art aircraft through close integration of the propulsion system and airframe along with the optimal use of energy from fuel cells, batteries, capacitors, or combustion of fuel. However, these novel propulsion systems are complex and include multiple interconnected subsystems with different dynamic behaviors, requiring new control approaches [7, 8]. System modeling, simulation, and hardware-in-the-loop (HIL) testing are important tools that can be used to improve confidence in and reduce risk associated with developing and testing EAP control systems.

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Figure 1. Artist renderings of the SUSAN Electrofan concept aircraft.

This paper presents results from a HIL test of the control system for a conceptual single-aisle transport aircraft with a multi-MW class hybrid EAP system. The SUBsonic Single Aft eNginE (SUSAN) Electrofan is a concept for a hybrid-electric regional airliner developed by NASA ARMD's Convergent Aeronautics Solutions (CAS) project as a reference design for a single-aisle airliner with a highly integrated 20 MW hybrid-electric powertrain [9, 10]. The test described in this paper was performed in the Hybrid Propulsion Emulation Rig (HyPER) at the NASA Glenn Research Center (GRC). The test involved running a real-time model of the SUSAN power/propulsion system (PPS) with one of the electro-mechanical subsystems replaced with real, sub-scale hardware. The results of the test allow the performance of the SUSAN PPS control system to be validated by comparing the performance of the controller in the model environment with its performance in real-time on a system that includes real sensors and actuators. This demonstration builds confidence in the control architecture and reduces risk associated with additional testing and development of the SUSAN PPS. In addition, representing the SUSAN PPS in HyPER demonstrates the reconfigurability of the facility for representing new and complex EAP system architectures.

The remainder of this paper is organized as follows. An overview of the SUSAN concept aircraft is presented in Section II. The SUSAN Power/Propulsion System and control architecture are described in Section III. Section IV discusses the HyPER lab and the implementation of the SUSAN PPS model and controller. Section V presents the results of the testing and discusses the performance of the controller in both HyPER and the pure simulation environment. Section VI presents a summary and conclusions.

II. SUSAN Electrofan Concept Vehicle

The SUSAN Electrofan (shown in Fig. 1) is an advanced NASA concept for a single-aisle transport class airliner designed to match the capabilities of modern large regional jets. The concept leverages boundary layer ingestion (BLI), propulsion-airframe integration (PAI), and distributed electric propulsion (DEP) technologies along with a series/parallel partial hybrid-electric propulsion system to reduce emissions by up to 50% per passenger mile when compared to modern airliners [11]. A diagram of the power/propulsion subsystems is shown in Fig. 2. The propulsion system consists of an aft mounted, BLI geared turbofan (GTF) that both produces thrust and provides up to 20 MW of mechanical offtake power to drive a series of motor/generators (M/Gs) attached to the low-pressure (LP) and high-pressure (HP) spools. These M/Gs provide power to a series of 16 contra-rotating electric ducted fans (also referred to as wingfans), with eight mounted under each wing in a mail-slot configuration. The system is designed so that at constant throttle, 1/3 of the thrust comes from the GTF, and 1/3 comes from the wingfans on each wing. Each wingfan and its associated electro-mechanical hardware is referred to as an electric engine, (EE). The engines are numbered 01 through 17 from left to right from the pilot's perspective (with 09 being the GTF).

In order to maximize safety through redundancy, each of the 16 EEs has an independent electrical power system (EPS). Each EPS consists of an M/G on the LP shaft, a main generator converter (MGC), a common DC bus, two electric engine motor controllers (EEMCs), and two electric engine motors (EEMs). Also connected to each DC bus is a DC-DC converter and a secondary (rechargeable) battery (SB). The SB is used to provide a power reservoir to the M/Gs and EEMs in order to decouple their operation. This lets the EEs consume more power than the generators can provide for short periods, allowing them to respond quickly and independently to thrust commands. Independent control of the EEs enables DEP and thrust augmentation during periods of high thrust demand, such as top-of-climb or takeoff. The SBs also allow the M/Gs on the GTF shafts to be used as actuators for implementing turbine electrified energy management (TEEM), an advanced control strategy developed by NASA for improving the operability and

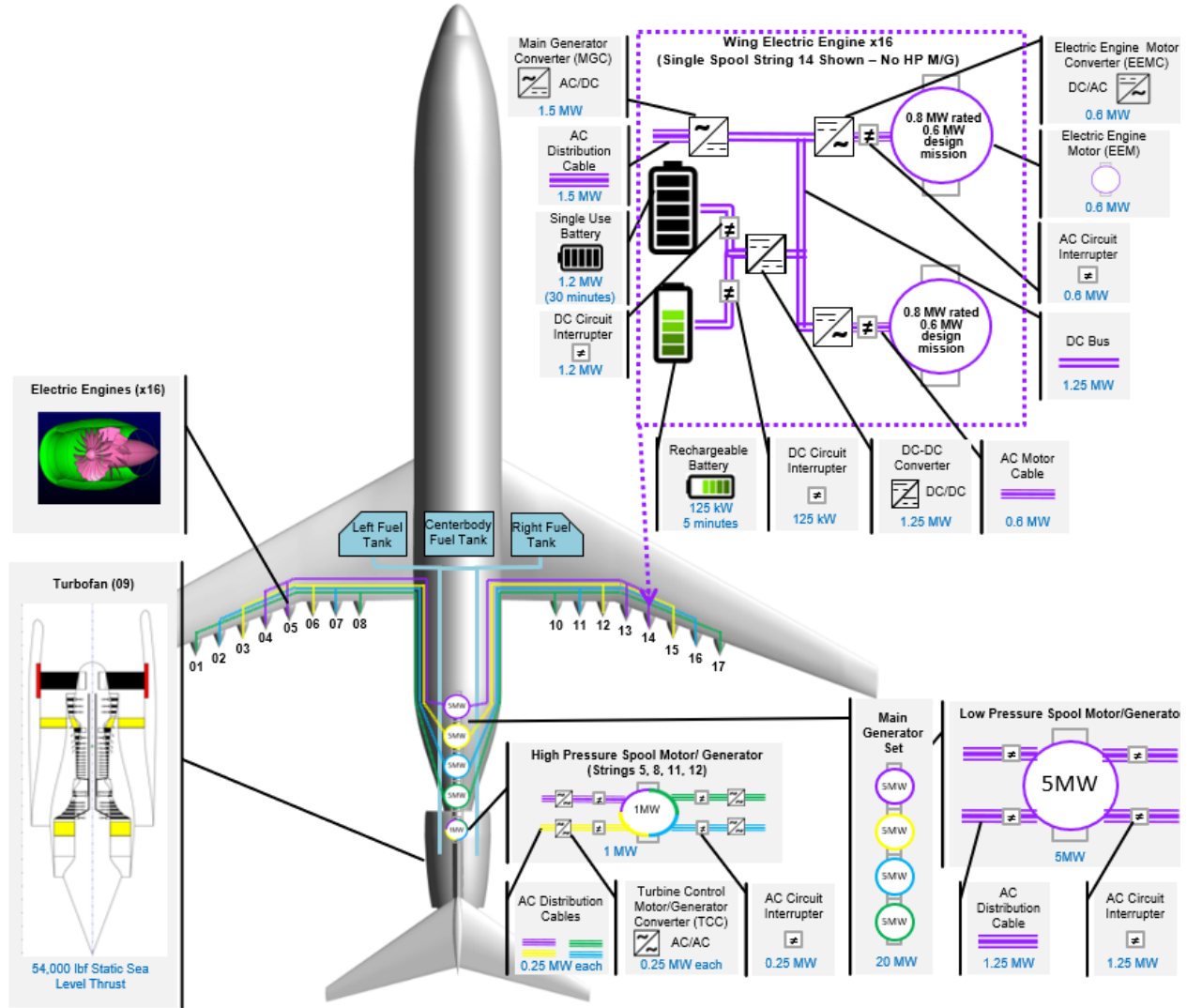


Figure 2. Subsystem diagram of the SUSAN PPS, illustrating the arrangement of 16 EE strings.

transient performance of hybrid-electric turbine engines [12, 13]. Because the SUSAN aircraft has one fuel-burning engine, each EPS contains a primary (single-use) battery (PB) that can provide a limited supply of backup power in the case of an engine failure, allowing the aircraft to fly for a short time only on electrical power.

Four of the EEs (05, 08, 11, and 12) have an M/G on the HP shaft as well as the LP shaft and are referred to as dual-spool strings (as opposed to single-spool). These HP M/Gs are controlled using additional turbine control converters (TCCs) and are used to maintain GTF operability by extracting power from the HP shaft at altitude, as well as for implementing TEEM control. More detail on the SUSAN PPS and control architecture can be found in [10, 14, 15, 11].

III. SUSAN Power/Propulsion System Model and Controller

The full-scale model of the SUSAN PPS is built in the MATLAB/Simulink[®] environment using the NASA developed Toolbox for the Modeling and Analysis of Thermodynamic Systems (T-MATS) [16] and the Electrical Modeling and Thermal Analysis Toolbox (EMTAT) [17]. The GTF is modeled using T-MATS as a two-spool geared turbopan engine with a variable bleed valve (VBV) and a variable area fan nozzle (VAFN). The GTF has a gain-scheduled proportional-integral (PI) fuel flow (W_f) controller to control the corrected GTF fan speed, N_{Ic} , with various limit controllers and min/max limit selection providing operability protection. The VBV and VAFN are scheduled based on altitude, Mach number (MN), and N_{Ic} . The VBV is additionally scheduled based on the level of electrical power extraction from the GTF. The EEs, which also have variable area nozzles, are also modeled using T-MATS. While the EEs in the SUSAN concept are contra-rotating electric fans driven by two EEMs, the T-MATS model

shown in Fig. 4. The HyPER lab consists of two shafts, each connecting a pair of permanent magnet synchronous machines (PMSMs) controlled by a matched inverter/motor controller. One PMSM on each shaft (normally M1 and M2 in Fig 4) is used to emulate the dynamic behavior (torque and speed response) of a sub-scale turbomachinery shaft using an Adaptive Sliding Mode Impedance Controller with Scaling (ASMICS) [19]. The other PMSMs (normally M3 and M4 in Fig. 4), along with their associated inverter controllers, are used as actuators in the EAP system. The DC-DC converter and supercapacitor provide energy storage capability, allowing the HyPER facility to be used to test a variety of EAP system architectures. The bidirectional power supplies are connected to the electrical grid and can also be used to emulate non-specific electrical loads or power sources. To enable HIL controls testing, the HyPER facility communicates with a dSPACE SCALEXIO® real-time computing system that runs a full-scale Simulink model of the propulsion system being emulated as well as the controller for that system. Communication with the inverters is handled through a Controller Area Network (CAN) connection, while the power supplies are controlled through an Ethernet connection.

Figure 5 illustrates the implementation of the SUSAN PPS model into the HyPER facility. The implementation described here represents only one possible configuration for the SUSAN/HyPER integration. In this configuration, HyPER is used to replace the EPS for EE 10 in the full-scale SUSAN PPS model. EPS 10 is selected as it is the inboard-most single-spool EPS. The PMSMs M1 and M2 are used to emulate the shafts of EE 10 and the GTF LP

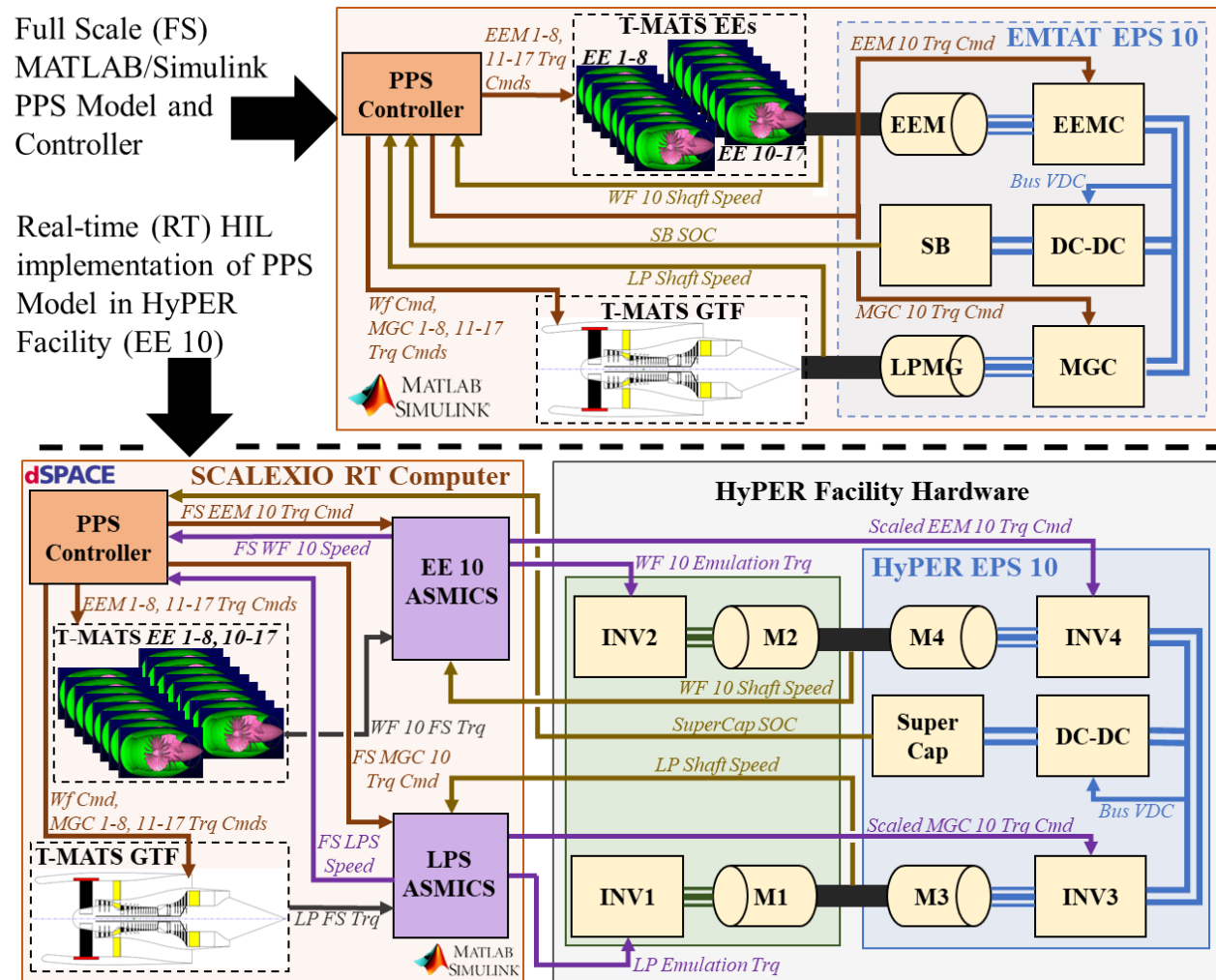


Figure 5. SUSAN PPS HyPER implementation diagram. In the base Simulink model (top), the full-scale EMTAT and T-MATS models respond to the commands of the PPS controller. In the HyPER HIL implementation (bottom), ASMICS uses the T-MATS models to drive the emulation of the WF 10 and GTF LP shafts. The SUSAN PPS uses the HyPER inverters, motors, and DC-DC converter to drive the T-MATS models through the emulated shafts and maintain the SOC of the Supercapacitor. EEs 1-8 and 11-17 still exist within the real-time model.

spool respectively. M3 and INV3 are used as the LP M/G and the MGC for EPS 10, and M4 and INV4 are used as the EEM and EEMC. The HyPER DC-DC Converter directly matches the SUSAN one, and the HyPER Supercapacitor is used to represent the SUSAN SB as a generic energy storage device (ESD). While the discharge characteristics of a battery and a supercapacitor are different, the use of the nondimensional SOC as a feedback parameter representing the total energy stored allows the supercapacitor to stand in for the SB as a generic energy storage device. The SUSAN PPS controller sends torque commands to INV3 and INV4, which control M3 and M4. The ASMICS uses M1 and M2 to determine the inertial response of the turbomachinery shafts (GTF LP shaft and WF 10 shaft), and the measured shaft speeds are fed back to the SUSAN PPS. The Supercapacitor SOC is also measured and fed back to the PPS controller. In this test configuration, the bidirectional power supply supporting the DC bus connected to INV3 and INV4 is disconnected, and the DC-DC converter is used to support the bus voltage (as shown in the bus voltage control loop in Fig. 3).

Dynamic and static scaling of the torques and speeds is handled by the ASMICS, reducing the speed, torque, and power commands to the actuators and keeping the system operating within the limits of the HyPER hardware. While the HyPER hardware and sensors do not represent flight-like components, they still allow the SUSAN PPS model and controller to be validated on a kW-scale using real electric machines, motor controllers, sensors, and energy storage devices. Table 1 compares relevant values between the full-scale PPS model and sub-scale components. This implementation of the SUSAN model also represents the first time a series/parallel partial hybrid EAP architecture has been tested in the HyPER facility and illustrates the flexibility of HyPER for representing diverse EAP systems. Similar work, where the HyPER facility has been used to represent other EAP architectures, is presented in [20].

Table 1. Full-scale vs. sub-scale EPS 10 system parameters

EPS Parameter	Full-Scale Value	Sub-Scale Value
Max LP Shaft Speed	5504 RPM	3300 RPM
Max EE 10 EM Shaft Speed	3300 RPM	3300 RPM
MG 10 Peak Torque	1604 lbf*ft	168.6 lbf*ft
EEM 10 Peak Torque	2463 lbf*ft	168.6 lbf*ft
ESD Useful Energy Capacity	60 MJ	751 kJ
DC Bus Voltage	2000 V	350 V

V. Test Data and Performance Analysis

This section presents data from the HIL tests. The behavior of the model with the EE 10 EPS replaced by the sub-scale HyPER hardware (the bottom diagram in Fig. 5) is compared to the full-scale Simulink model, referred to here as the Software-in-the-loop (SIL) implementation (the top diagram in Fig. 5). There are two test cases discussed in this section. The first test is the “Boost” case, which represents the propulsion system using the SBs to augment the thrust of the EEs at a “top-of-climb” flight condition. The second test is a transient throttle profile, which demonstrates the ability of the system to rapidly respond to changes in commanded thrust while overall maintaining the SOC of the SBs. For each test case, the GTF and EE inlet conditions (altitude and MN) are simulated in the model and the thrust commands are sent to the propulsion system in the form of a Power Lever Angle (PLA) for each EE and the GTF. Each PLA command corresponds to a corrected shaft speed setpoint, N_c (the GTF uses the corrected fan speed, N_{1c}). For this test each PLA command is sent separately to demonstrate specific system behaviors. In the full-scale SUSAN concept, the PLA commands come from the pilot or flight control system as seen in the control architecture diagram in Fig. 3. The throttle commands for each test are shown in Fig. 6.

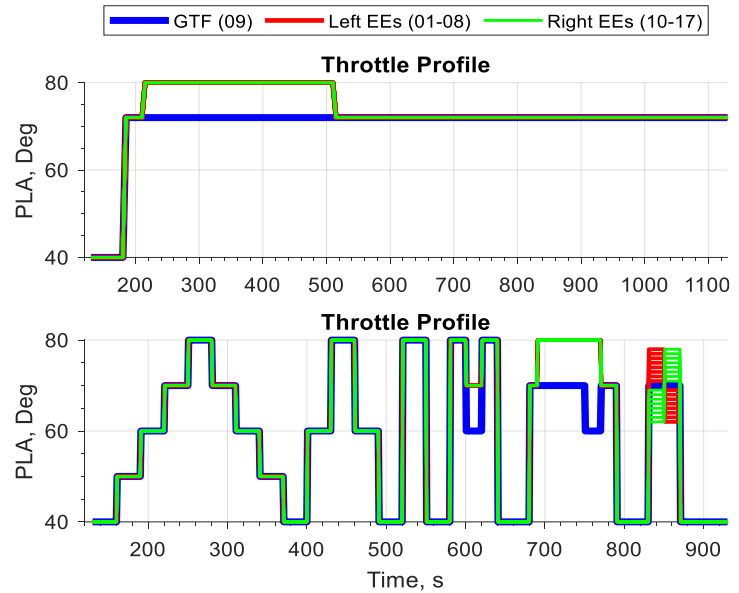


Figure 6. Test throttle profiles for the Boost (top) and Transient (bottom) cases, shown as a power lever angle (PLA) command sent to each engine (EEs and GTF).

The Boost test case demonstrates thrust augmentation for a simulated climb, which is done by bringing the system to climb power (72 degrees PLA) and virtual inlet conditions matching 30,000 ft, 0.6 MN. The EEs are commanded to full power (80 degrees PLA) and the climb is simulated by linearly increasing the altitude and MN until the SUSAN cruise condition is reached (37,000 ft, 0.785 MN). The EEs are then throttled back to match the engine power setting and the SBs are allowed to recharge. Results from the Boost test are shown in Fig.7, comparing the behavior of the full-scale SIL model with the real-time HIL implementation. The shaft speeds align very closely indicating both models respond similarly to the same throttle inputs. The behavior of the HyPER DC bus and ESD generally match the SIL model, although the SOC recovers more quickly in the HIL implementation. The bus voltage is held very close to the setpoint under the changing loads, and the ESD drains during the boost and then recharges as the SOC control loop extracts additional power from the LP shaft. Compressor stall margins (SMs) are shown for the low- and high-pressure compressors (LPC and HPC) in the GTF to show how the performance of the GTF matches in both implementations. There are inconsistencies between the HIL and SIL results such as the variation in LP shaft speed at low power, the faster recharging of the ESD, and the LP M/G torque profile. These discrepancies are due to challenges

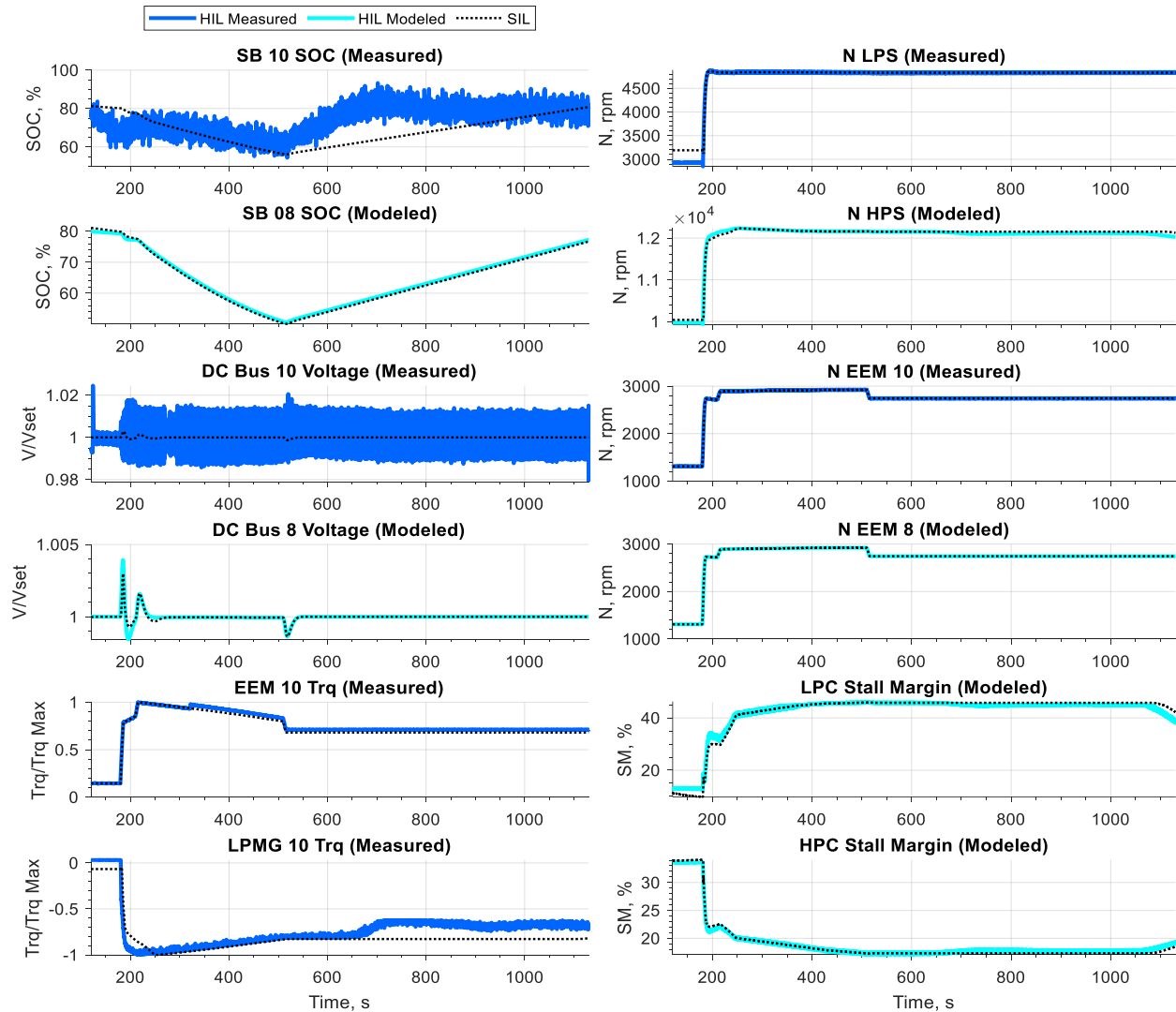


Figure 7. Comparison between HIL and SIL implementations of the SUSAN PPS model for the Boost test case, where the EEs augment the total thrust at top-of-climb (from 30,000 ft, MN 0.6 to 37,000 ft, MN 0.785).

Dark blue indicates the results are directly measured from the HyPER hardware (LP and EEM 10 shaft emulation, EPS 10 DC bus voltage, SB 10 SOC) while cyan indicates the result is from the real-time model (HP and EEM 08 shaft speeds, EPS 08 parameters, SMs). Results are compared to the SIL implementation (black). Bus voltage and actuator torques are shown non-dimensionally to allow direct comparison between the sub-scale and full-scale systems.

encountered while implementing the model in HIL and scaling it to match the HyPER hardware and are discussed at the end of this section.

Results from the transient throttle profile are shown in Fig. 8. The transient profile is run at the SUSAN design cruise condition (37,000 ft, 0.785 MN) and includes both small and large throttle movements as well as nominal boost and DEP throttle movements to demonstrate the full capability of the SUSAN PPS. The large throttle movements are also an opportunity to demonstrate the system's use of TEEM control. The data shows the same agreement between the HIL and SIL implementations as the previous test. The shaft speeds illustrate a nearly identical thrust response, while the bus voltage and SOC controllers are able to maintain the energy level of the ESD and the DC voltage levels respectively. As in the Boost case, there are slight differences in the GTF operation and variations in the SOC of the real and modeled ESDs due to the same implementation challenges.

The discrepancies between the SIL and HIL results are due to the methods used for modeling and emulating the turbomachinery components, the significant difference in power levels between the real and modeled components, and unmodeled physical effects that appear in the HIL tests. The differences in scale between the multi-megawatt SUSAN design and the kilowatt-scale HyPER hardware are illustrated in Table 1. The scaling is driven by the size of the HyPER supercapacitor, as it is proportionally smaller than the SUSAN SB relative to the EEMs and LPMGs. This meant that the HyPER electric machines had to be scaled well below their nominal operating power ranges, reducing

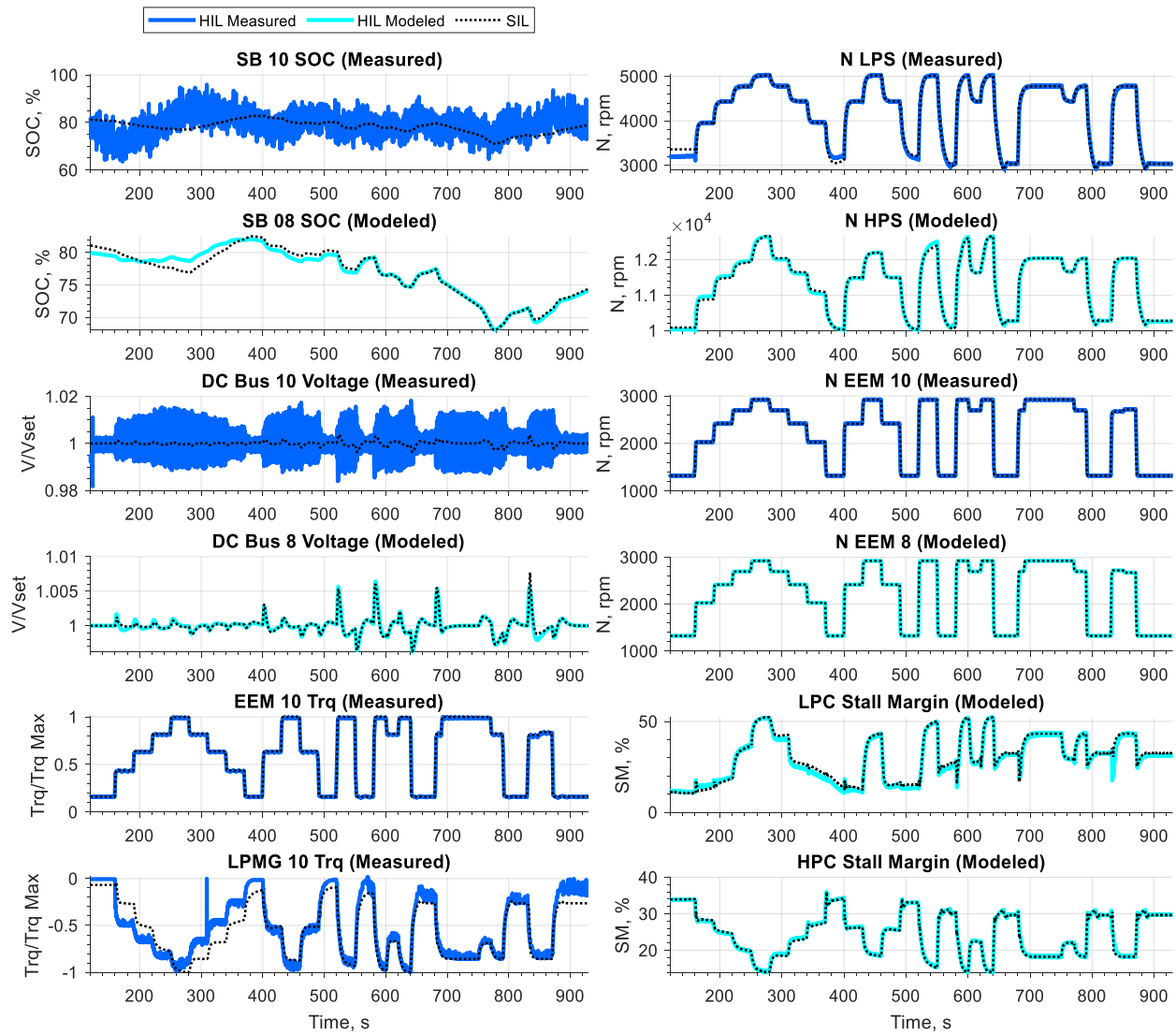


Figure 8. Comparison between HIL and SIL implementations of the SUSAN PPS model for the transient throttle profile test case, run at cruise conditions (37,000 ft, 0.785 MN). The LP M/G torque in the bottom left combines power extraction feedforward, TEEM, and SOC control torque commands, as shown in Fig. 3.

the precision with which they could be commanded by the SUSAN PPS controllers and the ASMICS emulation controller. Additionally, the voltage measurements from the HyPER supercapacitor and DC bus are significantly noisier than the measurements simulated in the model controllers. Another cause of the disagreements is unmodeled effects, which lead to slight differences in the initial conditions and performance of each component. Effects such as non-linear shaft damping, differences in efficiency between real and modeled components, and electrical transients not modeled by the EMTAT toolbox all lead to variations in system performance observed as discrepancies between the model and the hardware. For example, in the SUSAN PPS the MGC is located far from the DC-DC Converter in the aft-mounted engine and the EEMC is located next to the converter in the wing. This extra cabling represents an additional source of loss that is not accounted for in HyPER, where all of the components are in close proximity. While these real-world effects lead to differences in behavior between the SIL and HIL implementations, the SUSAN PPS controller still functions as designed in both environments.

VI. Conclusions

Electrified Aircraft Propulsion (EAP) systems are a promising approach toward reducing carbon emissions from the commercial aviation sector. However, these systems present novel challenges when it comes to control design due to their complexity and the tight coupling between their subsystems. Hardware-in-the-loop (HIL) testing is important for enabling the rapid development of EAP control algorithms in low-risk environments. This paper presents the results of a HIL test of the power/propulsion system (PPS) control architecture for the SUBsonic Single Aft eNginE (SUSAN) Electrofan concept aircraft. Test data shows good agreement between the behavior of the SUSAN PPS model in pure simulation and in the HIL implementation. The results also illustrate how the SUSAN PPS control architecture is able to simultaneously balance the energy levels between the electrical and turbomachinery systems, control the SB SOC, and deliver the required thrust response from the complex tightly coupled system while running real-time with physical components. Future work could include demonstration of additional configurations of the SUSAN PPS in the HIL environment, as well as improving the realism of the test environment by increasing the power level, adding additional electromechanical components, or running the controller on flight-like hardware. The test also illustrates the capabilities of NASA Glenn Research Center's Hybrid Propulsion Emulation Rig (HyPER) by demonstrating its ability to represent complex EAP architectures for the purpose of control design and verification.

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