

Hybrid-Electric Aero-Propulsion Controls Laboratory: Overview and Capability

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A hardware-in-the-loop (HIL) laboratory is developed to investigate control technologies for electrified aircraft propulsion (EAP). The laboratory emulates a propulsion system by reproducing the mechanical shaft interface to the electrical power system in hardware. The experimental electric power system includes supercapacitor energy storage and a dynamically variable electrical load. A novel method of scaling power and inertia is provided in software to accurately reproduce the transient, off-design turbomachinery performance dynamics without including actual turbomachinery. An overview of how the HIL system can accommodate a broad range of EAP architectures, including power extraction and insertion, with capability for transient energy management is described. The real-time system operates in the 100kW power class and is instrumented to emulate turbomachinery – power system interactions. The platform is an agile, flexible laboratory for low-cost, risk-reduction development and testing of propulsion control, operability, and energy management technologies.

I. Introduction

The development of electrified aircraft propulsion (EAP) technology is a matter of great interest as a means of reducing carbon emissions for more sustainable flight [1]. The introduction of electrification to propulsion system architectures offers flexibility in the design of future air vehicles. While net-zero emissions is a long-term goal [2], only short-haul vehicles demonstrate commercial feasibility for all-electric architectures. The high energy demands of large transport vehicles preclude their all-electric viability in the near to mid-term. This is mainly because of limitations in the energy density, weight, and volume of electric energy storage devices. For these larger vehicles, hybrid-electric propulsion is being pursued, with electrical power offering flexible energy management in the mid-term and a larger portion of the thrust producing power in the far-term [3]. Energy management for EAP concepts is

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a controls challenge because of electrical energy's impact on the power balance within turbomachinery, the relative speed at which it flows, and the effect on fault propagation. However, the use of electrical energy leads to new control technologies with the potential to alter engine dynamics and improve turbomachinery performance [4].

To achieve the full benefits offered by electrification, the control of power extraction and insertion must be accounted for in the design process. Control development for propulsion systems often occurs later in the design process. Traditionally, propulsion system components are designed, tested, and integrated for steady-state performance. Afterward, a controller is designed and tuned to enable the off-design dynamic response of that system. When an engine moves off-design, there is a loss in efficiency and stall margin. The dynamic response of turbomachinery to a transient condition can be controlled by the same electric machines coupled to the shafts for power extraction. These electric machines (EM) can manipulate the turbomachinery behavior resulting in a response closer to steady state. Electrification may also eliminate the need for additional engine hardware such as bleed valves, variable stator vanes, and extra compressor stages resulting in an overall weight reduction.

Electrification results in more complicated propulsion systems and vehicle integrations, which potentially increases technology development risk. To help mitigate this risk, new approaches that involve controls technology earlier in the conceptual design phase are needed. Hardware-In-the-Loop (HIL) testing is a means to bridge the gap between model simulations and full-scale component testing [5, 6]. To support EAP technology development, HIL facilities are being developed to support electrical hardware testing, control algorithm testing, and the interfacing of propulsion systems with an electrical powertrain. Smaller scale HIL facilities allow for rapid testing of EAP concepts [7, 8, 9]; however, they typically lack energy storage elements and do not adequately address scaling to the desired system size. Other HIL facilities have focused on the larger or full-scale testing of electrical powertrains and components [10, 11]. To mature EAP technology, testing facilities need to address electrical standards [12, 13] and increased focus needs to be placed on controls development [14, 15]. The larger facilities have a lot of advantages, especially for full-scale and component testing, but these facilities are in high demand and are unnecessary for low Technology Readiness Level (TRL) concept development.

The Hybrid Propulsion Emulation Rig (HyPER) discussed in this paper is a small-scale laboratory with energy storage capabilities, a novel method of scaling power and inertia, and the flexibility to test numerous EAP control concepts. The HyPER laboratory combines real-time propulsion system modeling with electro-mechanical hardware and facilitates the testing of design concepts while largely reducing the risk and cost to do so. This laboratory was developed to evolve with the development of EAP architectures. Testing new technology on physical turbomachinery is time consuming, expensive, and potentially dangerous. HyPER presents a low-cost, low-risk alternative with rapid HIL testing that replaces physical turbomachinery with real-time simulations. This laboratory is ideal for TRL maturation of preliminary control concepts [16]. The remainder of this paper describes the HyPER design and enabled applications. Section II describes the overall laboratory design, including the electrical, mechanical, thermal, control, and data acquisition subsystems. Section III suggests potential applications of the laboratory to test proposed EAP concepts. Section IV presents some summary remarks on the laboratory and its capabilities.

II. Laboratory Overview

The HyPER laboratory is a novel, reconfigurable EAP hardware and control laboratory located at the National Aeronautics and Space Administration (NASA) Glenn Research Center at Lewis Field in Cleveland, Ohio. HyPER contains electro-mechanical and electrical power system components as well as closed-loop control and scaling that allows the system to dynamically represent electrified turbomachinery. The laboratory is built up with relatively inexpensive commercial-off-the-shelf (COTS) hardware, which reduces the risk of testing innovative propulsion system designs. Configuration changes can be made easily without disrupting the hardware setup. The novel aspects of this laboratory include the use of energy storage in the form of a supercapacitor bank and the closed loop control and scaling methodology that enables emulation of turbomachinery shaft dynamics and loads. The energy storage device allows for energy management control concepts to be implemented on hardware. The application of a closed loop control and scaling methodology allows for a full-scale propulsion system model and electric machine hardware to replace a physical propulsion system.

The laboratory consists of two rooms, a control room and test cell. The laboratory floorplan is shown in Fig. 1. The test article is highlighted in yellow to distinguish it from the facility equipment. The test cell is roughly 450 square feet. It houses a table supporting the test article. The table can be moved in and out of the test cell for staging purposes or replaced with a different electro-mechanical test article while the rest of the facility equipment remains inside the test cell. This functionality facilitates rapid testing of different electrical architectures and their proposed controllers. For the purposes of this paper the facility configuration remains constant, only the test article functionality is altered to illustrate various potential propulsion architecture configurations. As shown in Fig. 1, there are three electrical cabinets affixed to the table. Cabinet A contains power components for inverters 1 and 2. Cabinet B contains power

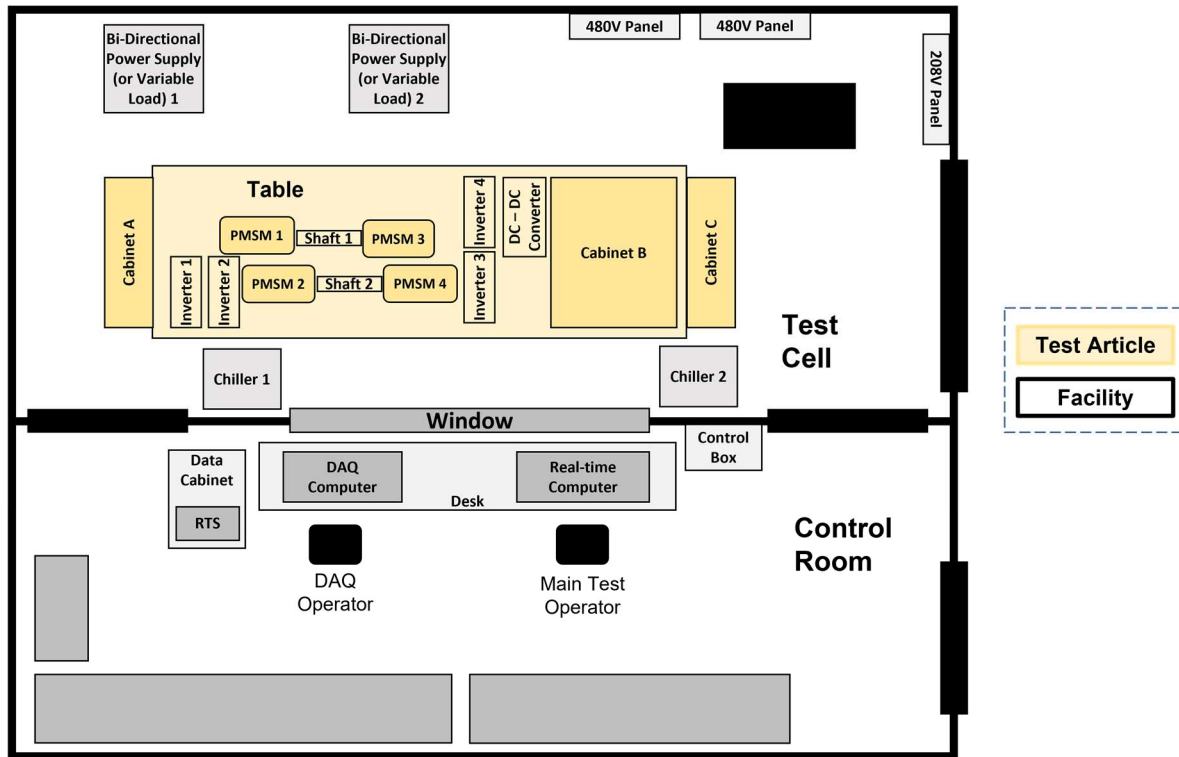


Fig. 1 HyPER laboratory floorplan.

components for inverters 3 and 4 as well as a DC-DC converter. Cabinet C contains the super capacitor bank and a brake module for the resistive load bank. Inside the control room, shown in Fig. 1, the main test operator sits behind the real-time computer equipped to command the real-time system (RTS) and monitor and record test data. An additional operator controls the data acquisition (DAQ) computer to monitor and acquire facility data.

The following laboratory overview details each subsystem, its function, and relevant components. Subsection A describes the HyPER electrical system. Subsection B covers the mechanical design and characteristics of the laboratory. Subsection C briefly presents the thermal management subsystem. Subsection D explains how HyPER uses control, scaling, and the RTS. Finally, Subsection E describes the DAQ.

A. Electrical

HyPER was designed with electrical hardware capable of dynamically transferring energy at a power level that reduces cost. Hardware components were chosen based on their relevance to the requirements associated with proposed EAP powertrain architectures. HyPER is also reconfigurable with components capable of being enabled or disabled depending on the customer's desired architecture. Fig. 2 illustrates the component layout and connections. The test table supports four 66kW, 12-pole permanent magnet synchronous machines (PMSMs). One bi-directional, 100 kW COTS inverter controls each PMSM. PMSM-inverters one and two are connected to one DC bus, while PMSM-inverters three and four are connected to a second DC bus. Both of the DC buses operate at a nominal voltage of 350 V.

Attached to each DC bus is a bi-directional power supply (BPS), capable of producing 100 kW. The BPS operates in one of four control modes: constant voltage, constant current, constant power, or constant resistance. The BPS also has three modes that manage its power flow: bi-directional, discharge, and charge. Bi-directional mode allows the device to both sink and source power during operation. Discharge mode only allows the device to sink power during operation, effectively acting as a load, while charge mode only allows the device to source power during operation. The BPSs operate in one control mode and one power flow mode. They are connected via an ethernet connection to the RTS and commanded by the operator.

The installed machine-controller firmware employs a COTS graphical user interface (GUI) that is accessible on the real-time computer. The GUIs communicate with the inverter firmware via RS-232 connection. Test operators can open the inverter GUI to customize electrically erasable programmable read-only-memory (EEPROM) parameters such as control gains, current and voltage limits, speed and torque limits, and various measurement offsets. The inverters control the torque and speed of the PMSMs based on commands delivered to the inverter from the real-time computer over a Controller Area Network (CAN) bus interface. To spin the PMSMs, torque or speed commands from the real-time computer are sent to the four inverters. The inverter operates in one of two modes. Torque mode accepts

torque setpoints from the real-time computer and controls the PMSM with unique torque control loop gains. Speed mode accepts speed setpoints from the real-time computer and controls the PMSM with unique speed control loop gains. When an inverter is disabled, there is no active control. However, the PMSM can spin freely, and the inverter will still send feedback signals via CAN.

An energy storage device (ESD) is integrated with the electrical hardware. For HyPER, the ESD consists of a bank of supercapacitors. The bank contains three supercapacitors connected in series. Individually, these capacitors have 130 F of capacitance and a maximum working voltage of 62.1 V. Together in series, this capacitor bank has 43.33 F of capacitance and a maximum working voltage of 186.3 V leading to a total energy of 750 kJ. Depending on the necessary voltage and capacitance ratings, the supercapacitor bank can be reconfigured by adding or removing capacitor units or rewiring capacitor units in parallel rather than in series. Reconnecting the three capacitors in parallel will achieve a higher capacitance of 390 F but a lower working voltage of 62.1 V compared to the series configuration.

The ESD requires an associated charging device or voltage regulator. To provide this functionality, a DC-DC converter, similar in hardware to the PMSM inverters described previously, is applied to facilitate rapid charge and discharge of the ESD in a controlled manner. The DC-DC converter operates in two modes as well. The high-side of the converter is connected to the DC bus on the right-hand side (RHS) of Fig. 2, and the low-side of the converter is connected to the ESD. High-side mode regulates the RHS DC bus to a user-defined voltage setpoint. Low-side mode regulates the supercapacitor voltage to a user-defined voltage setpoint.

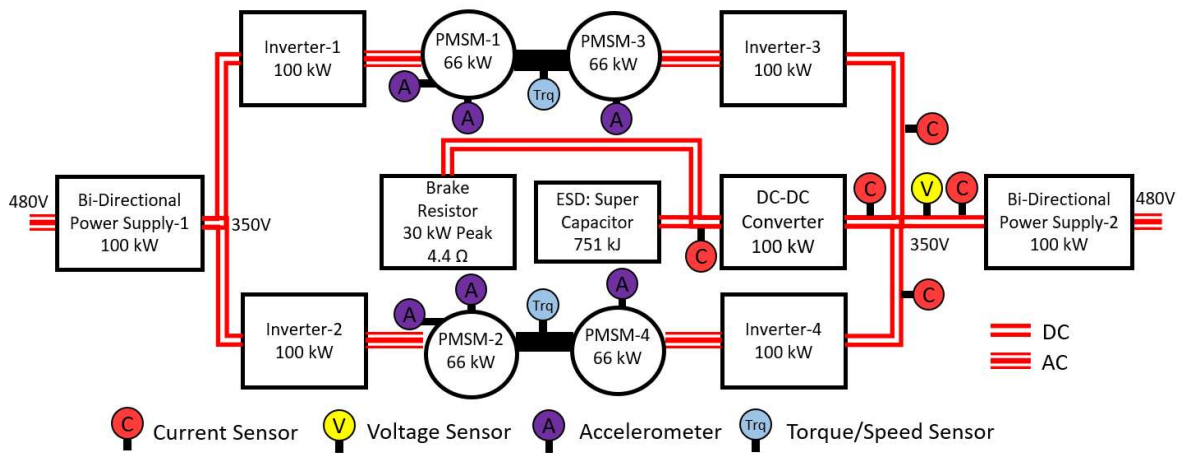


Fig. 2 HyPER laboratory hardware-in-the-loop block diagram with instrumentation.

The test article can operate with or without the DC-DC converter and energy storage device, depending on the desired configuration. When enabled, the DC-DC converter regulates power onto the RHS DC bus or into the ESD. It is used to regulate the RHS bus to a voltage setpoint using the available power stored in the ESD. The transfer of power between either side of the converter happens quickly, which is desirable for energy management in the electrified propulsion system. If no ESD is needed for a particular configuration, disabling the DC-DC converter will decouple the ESD from the RHS DC bus.

When there is power stored in the ESD it can either be consumed by PMSM 3 and PMSM 4, sent back to the grid through the BPS 2, or bled off with a brake resistor. This 4.4-ohm resistor has a peak power of 30kW. The brake resistor switch is turned off during operation. Before the test article is fully shut down, the ESD must be drained. The ESD drains in only a few minutes when the brake is on.

Safe high-power testing requires cables with sufficient voltage and current ratings. High voltage DC power delivery between the BPSs and the test table components is achieved using fully shielded battery cables. These cables are rated for 293A at 1000V. Power cable shielding is terminated to metal enclosures at both ends to protect low voltage instrumentation signals from stray electromagnetic interference (EMI). Low voltage power and instrumentation signals use 18-20AWG shielded twisted pair cables with cable shields terminated at a single point ground in the control room data cabinet. Additional actions are taken to reduce noise due to EMI. Inverter CAN and RS-232 control signals are converted and transmitted over fiber optic cables to the control room. An optical converter

box is located on the side of the test table for short electrical cable runs from the inverters before being converted. This minimizes EMI noise to the control signals and electrically isolates the test table from the RTS.

Safe high-power testing also requires a well-thought-out laboratory grounding plan. The test table is tied to the laboratory ground at a single point to prevent ground loops. All high voltage metal enclosures and mounted hardware are grounded and bonded to the test table through braided copper grounding straps and solid copper grounding bars. Ground fault circuit interrupters can automatically disconnect high-voltage power in the case of a ground fault.

B. Mechanical

As a byproduct of operating four PMSMs, substantial mechanical loads are generated in the form of vibrations and torques. To handle these loads a rigid, heavy mounting is needed. This mounting structure also supports the three large electrical cabinets, the thermal management system, and a variety of instrumentation. The table serves as the foundation for the HyPER test article. The table, and the components it supports, is located atop a structurally reinforced and damped section of the floor to provide vibration isolation and attenuation.

Fixed to the top of the table are two independent pairs of PMSMs, with the shafts of each pair connected using a high alignment coupling. These coupling devices are custom splined for compatibility with the PMSM pair. The couplings were further customized with retaining rings to constrain axial motion on the shaft to under three millimeters. This allows for the shaft itself to grow and shrink due to thermal expansion and other induced deformations all while maintaining a tolerance for misalignment. Each shaft also has a 500 Nm torque transducer installed between the coupler components. The rotating portion of the torque transducer moves with the shaft assembly while the stator portion is mounted to the table. Power and data are transferred between transducer rotor and stator hardware inductively.

The four inverters are mounted vertically on stands made from aluminum extrusion. Slots were cut into the table surface below the inverters to allow for electrical wiring to pass underneath the machine base. The machine base supports three electrical cabinets, shown in Fig. 1. Knee braces, shown in Fig. 3, made from carbon steel and machined flat on the two outward faces, support each PMSM. These knee braces provide rigidity, precise alignment, damping, and shaft stiffness. Stiffness is critical to ensure axial alignment and to prevent sag, which could negatively impact the lifespan of the couplers. Vibrational behaviors are observed in HyPER as a function of operating speed. In particular, the couplers shift axially back and forth between a gap less than two millimeters wide. This behavior happens on the order of once every couple of minutes and only occurs at speeds greater than 4000 RPM. Due to the slow speed nature of this walking, and the absence of other increased loads, this vibrational behavior is believed to be acceptable. An option to mitigate this behavior is disassembling the couplers and applying a spring force using either a rubber gasket or pad. This will provide positive force in one direction to secure the coupler against one side permanently while being flexible enough for expansion or contraction of the shaft.

C. Thermal Management System

The HyPER test article is air cooled by an air conditioning unit in the test cell, and liquid cooled by two plate-type heat exchangers, or chillers. One of the chillers is designated for cooling the four PMSMs, and the other is designated for cooling the four inverters and DC-DC converter. The collective heat load for the four PMSMs is approximately 13.5 kW and the collective heat load for the inverters and converter is about 14 kW. Each chiller is designed for 16 kW of heat removal. The chillers have an on-board six-gallon reservoir containing a 50/50 water-glycol mixture that is pumped in a closed-loop circuit at 70 psi. The resulting flow through each thermal load is approximately two to three gallons per minute. Each chiller receives an approximate eight gallons per minute open-loop supply of laboratory cooling tower water at about 20°C. This water serves as the heat sink for the thermal exchange. The thermal system also includes flow and pressure transmitters along with thermocouples to monitor these states at the thermal load inlet and exit points to ensure proper operation. It is important that proper flow be maintained to prevent damage to the PMSMs and inverters.

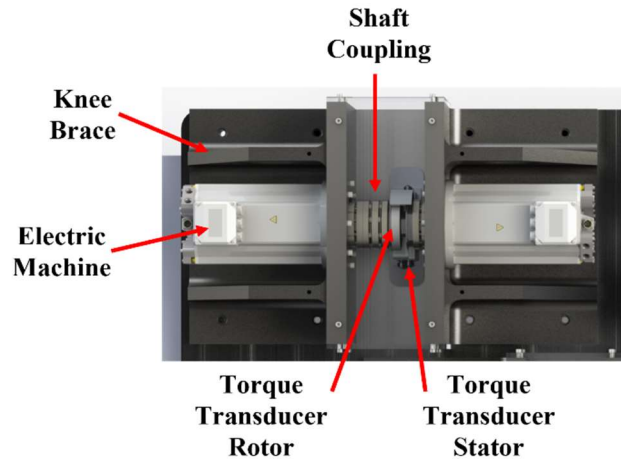


Fig. 3 PMSM Integration Assembly Top-Down View

D. Laboratory Control, Scaling, and Real-Time System

HyPER eliminates the need for including physical turbomachinery during the initial testing phase of advanced control algorithms integrated with hybrid-electric aero-propulsion systems. It achieves this by replacing the dynamic torque response of the turbomachinery with a torque producing device. The emulation approach used in HyPER replaces the physical turbomachinery with PMSMs, a novel closed-loop sliding-mode impedance controller with scaling (SMICS) [17], and a real-time propulsion system model with a controller. The approach towards emulating full-scale electrified turbomachinery in HyPER is shown graphically in Fig. 4. The top diagram represents the full-

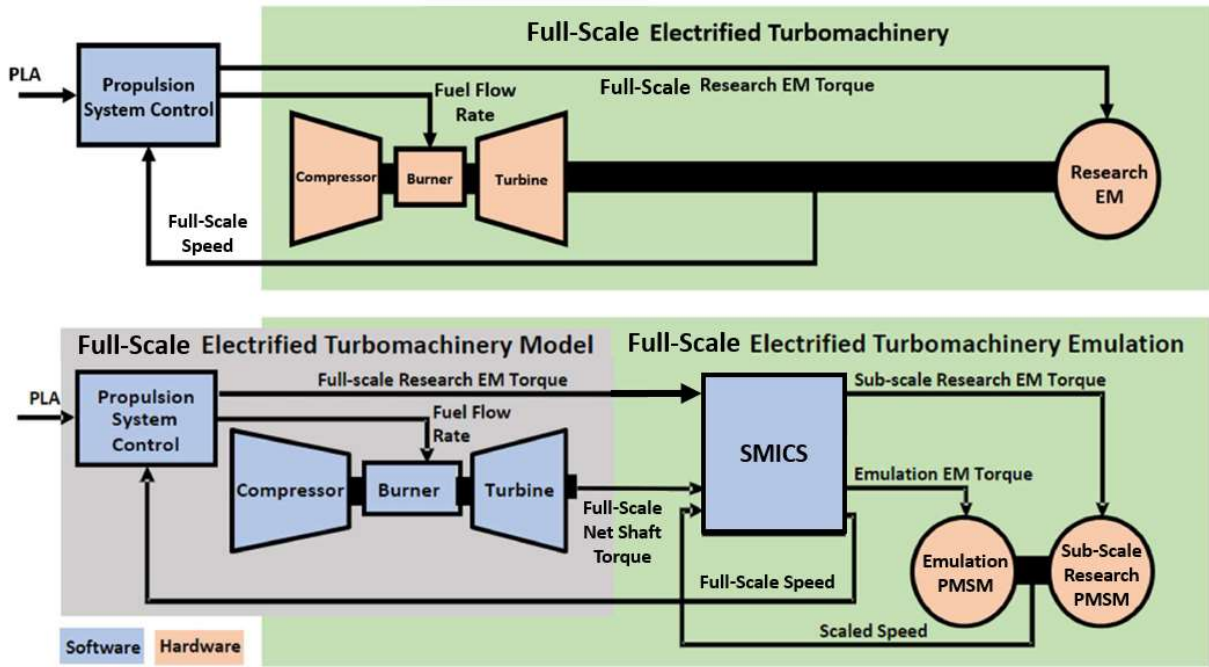


Fig. 4 Diagram representing a full-scale closed-loop electrified turbomachinery system (top) and the HyPER laboratory closed-loop control and scaling (bottom).

scale implementation of a propulsion control system on electrified turbomachinery. The bottom diagram represents the HyPER lab implementation of this same architecture. The emulation PMSM shown in the bottom half of the figure is the torque producing device that emulates a sub-scale version of the dynamics and load of the turbomachinery shaft. The closed loop control drives the emulation PMSM to produce an opposing torque to the research PMSM that is representative of the scaled inertial torque load of the turbomachinery shaft. The application of the scaled inertial reaction torque causes the coupled PMSM system behavior to represent the behavior of a sub-scale version of the physical gas turbine engine shaft.

Closed-loop control and scaling are necessary due to two fundamental differences between the mechanical shaft of the coupled PMSM system and the mechanical shaft of actual electrified turbomachinery. Firstly, the two systems likely have mechanical characteristics (i.e., rotational inertia, rotational viscous damping) that cause the shafts to respond differently to identical levels of applied torque. Secondly, the two systems have the potential to operate at drastically different power levels. In the case of HyPER, the PMSMs are not capable of producing the torques or speeds necessary to represent full-scale electrified turbomachinery. Therefore, scaled torque commands from the electrified turbomachinery model are sent to the PMSMs and scaled speed feedback from the PMSMs is sent back to the electrified turbomachinery model. The desired inertia to be achieved by the closed loop control system is also sent to the propulsion system controller. Using a low-risk, low-cost replacement for an expensive, high cost-to-operate, and high safety risk turbomachinery is desirable for low TRL testing of electrified aircraft propulsion components

and/or control schemes. The closed-loop control and scaling methodology allows realistic dynamic testing of customer power system architectures, and system level control algorithms without the use of the full-scale turbomachinery.

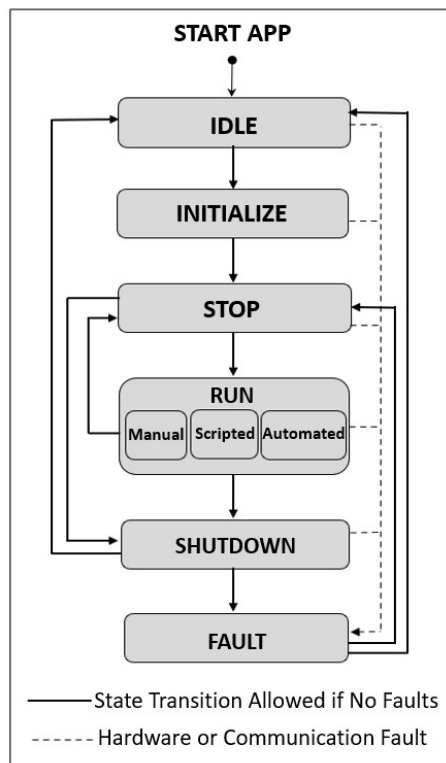


Fig. 5 Software state diagram.

inverter setpoints. In Manual mode the operator directly commands the PMSM mode (torque or speed), the torque/speed setpoint, and its state (enabled or disabled). Scripted mode allows the operator to pre-program a sequence of the same commands used in manual mode. In Automated mode, a controller utilizing an electrified turbomachinery model and SMICS computes the desired commands.

E. Data Acquisition

One main goal of this laboratory is to collect useful data for verification and validation of EAP control concepts. Data acquisition is therefore crucial to the maturation of these technologies. Data are acquired by both the RTS and the data acquisition system (DAQ). The DAQ includes a chassis capable of supporting up to 9 I/O modules. Table 1 lists the capabilities and number of modules currently used. The DAQ collects experimental data and displays a custom GUI for monitoring laboratory signals. Cooling fluid flow rate, pressure, and temperature data are taken from various distributed cooling flow stations. In addition, vibrational measurements from accelerometers mounted to each of the four PMSMs are recorded. The DAQ GUI also displays experimentation signals such as voltages, currents, shaft speeds, and torques. This GUI serves as an interface for recording data and visualizing live measurements but does not send control signals to the test article.

The RTS also collects data from the test article through CAN bus and can support analog or digital I/O modules. The RTS communicates with the DAQ via ethernet connection so that signals collected by the DAQ can be used in the RTS for control. Control data, such as torque and speed commands, and feedback data as well as fault triggers are collected over CAN by the RTS. Along with data collected from the test article, propulsion control and turbomachinery simulation parameters are acquired by the RTS when running in Automated mode.

A real-time application, directing the operation of the PMSMs, is employed to meet the strict time constraints required by the hardware-in-the-loop simulation. This application is built using dSPACE® ConfigurationDesk®, which compiles the MATLAB and Simulink code related to the propulsion system model, controller, and the DAQ. The hardware of the RTS hosting the real-time application consists of a dSPACE® SCALEXIO®, which provides various digital and analog input/output (I/O) for data capture and interfaces for implementing communication methods, and a SCALEXIO® Processing Unit for delivering supplemental computation power. A graphical user interface, developed using dSPACE® ControlDesk®, allows the operator to send commands to the application, edit test-specific settings, check the status of faults and alarms, capture telemetry from the test article, and capture data from Simulink models processed in real-time.

The high-level state machine diagram in Fig. 5, illustrating the behavior of test operations, is implemented using Simulink® Stateflow®. State transitions occur based on conditions from user inputs and/or data captured. The IDLE state is the initial state of the system where the communication with the equipment is established before a user can initiate a transition to the INITIALIZE state. The INITIALIZE and SHUTDOWN states implement automated processes that respectively charge/discharge the supercapacitor and each electrical bus. Any entry into the STOP or FAULT states will trigger the inverters to be disabled, thus halting any test in progress while stopping the rotation of the machines. Before exiting the FAULT state, the user must acknowledge and clear any fault. The RUN state implements one of three modes (Manual, Scripted, Automated) that are responsible for determining the

Table 1. DAQ I/O Capability

Count	I/O	Type	Data
1	32 Channel	Digital	Fault Detection
2	32 Channel	Analog	Voltage and Current
1	32 Channel	Thermocouple	Temperature
2	8 Channel	Analog	High Bandwidth Voltage and Current

III. Potential Applications

The reconfigurable nature of the test article gives future users the ability to model and test a variety of architectures including the six EAP architectures shown in Fig. 6. These EAP architectures appear in many propulsion and aircraft concepts developed both by NASA and industry [18]. Electrification brings flexibility to the design space for EAP concept vehicles with the introduction of new propulsion sources, energy storage devices, and other power system components. Electrification enables advanced control concepts such as Turbine Electrified Energy Management (TEEM) [19], which uses EMs to transfer power between the engine shafts during accelerations and decelerations, resulting in improved engine operability and potential weight reduction [4]. The capabilities and reconfigurability of HyPER enable the maturation of these new concepts.

The subsections below provide a description of the six EAP architectures shown in Fig. 6 along with a discussion of their mapping to a specific configuration of HyPER. Subsection A describes the parallel hybrid architecture. Subsection B briefly describes the series hybrid architecture. Subsection C lays out one possible configuration to test the series/parallel partial hybrid architecture. Subsection D explains the implementation of a fully or partially turboelectric architecture. Finally, subsection E proposes a testing configuration for an all-electric architecture.

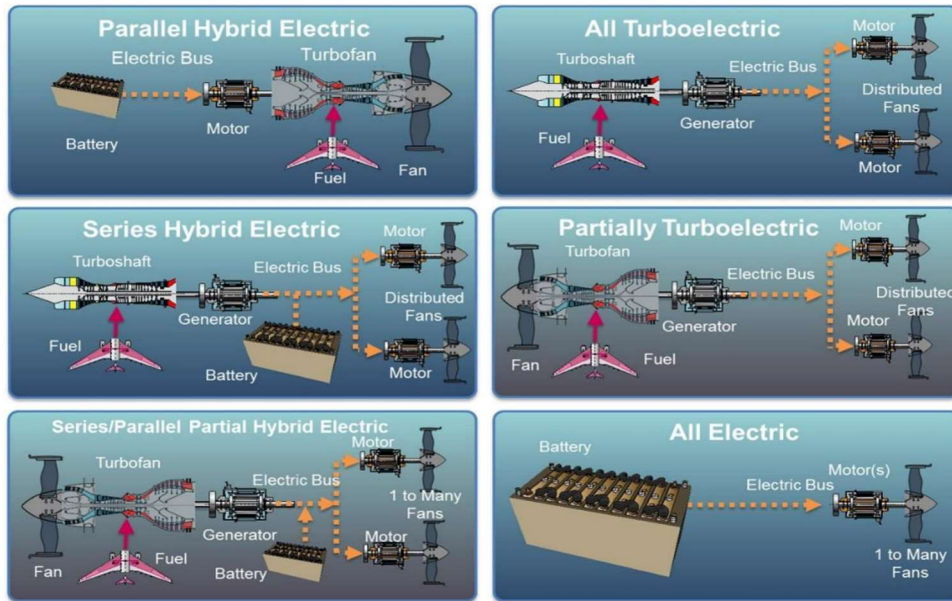


Fig. 6 Six primary electrified aircraft propulsion architectures [18].

A. Parallel Hybrid

The first implemented configuration of HyPER tested the parallel hybrid propulsion system architecture shown in Fig. 6. Parallel hybrid architectures consist of thrust producing fuel burning engines (FBE) and energy storage devices that interact with EMs mechanically coupled to the engine shafts. The ESDs either provide power when the EMs are inserting shaft power or sink power when the EMs are extracting shaft power [18]. This configuration uses the advanced geared turboprop 30,000 pound thrust class engine (AGTF30) with TEEM [19] in simulation. The AGTF30 is a dual spool turboprop engine and is electrified with two EMs, one on the high-pressure spool (HPS) and one on the low-pressure spool (LPS).

This architecture was implemented in HyPER with the configuration shown in Fig. 7. PMSMs 1 and 2, which emulate turbomachinery shaft loads, were powered by BPS 1, and controlled by inverters 1 and 2. Torque outputs from the model of the AGTF30 were scaled and sent to the inverters. Shaft 1 emulates the LPS, and shaft 2 emulates the HPS. The RHS PMSMs, 3 and 4, represent the LPS EM and HPS EM, respectively. PMSMs 3 and 4 source and sink power with the ESD, since this architecture demonstrates both power extraction and insertion.

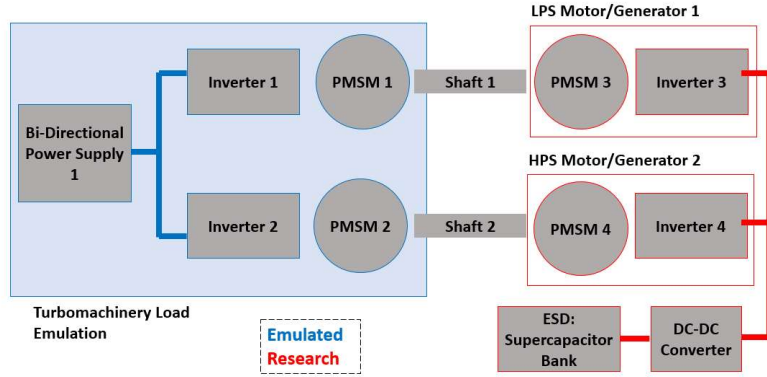


Fig. 7 Parallel Hybrid – AGTF30 with TEEM

The additional storage of energy with a supercapacitor enables rapid transfer of power for advanced controls testing.

B. Series Hybrid

Contrary to the parallel hybrid architecture, the series hybrid propulsion system, shown in Fig. 6, has a FBE that does not produce thrust, but rather provides mechanical shaft power to an attached EM. This power is converted to electricity and used to either charge an ESD or power a downstream electric engine [18]. The term ‘electric engine’ is used here to describe an EM mechanically coupled to a fan or propulsor installed on the aircraft.

Converting the test article to represent a different propulsion system architecture is straightforward. To transition to the series hybrid from the parallel hybrid, shown in Fig. 7, BPS 2 is enabled resulting in a configuration shown by Fig. 8. Since all thrust production happens downstream, the DC bus connected to BPS 2 must incorporate emulation of a thrust producing electric engine. The BPSs can emulate electric engines when put in variable load, or discharge, mode. With the electric engine(s) modeled in simulation, the dynamic current demand can be sent to the BPS for load emulation. In this configuration, PMSM 3 and 4 only extract power from the shafts.

C. Series/Parallel Partial Hybrid

The series/parallel partial hybrid propulsion architecture consists of a thrust producing FBE, thrust producing electric engines, and energy storage devices that interact with EMs on the FBE shafts and the electric engines. An example of this architecture is the Subsonic Single Aft Engine (SUSAN) electro fan concept aircraft [20]. SUSAN has one turbofan engine in the tail, 16 electric propulsors on the wings, four EMs on the LPS, and one EM on the HPS. Due to the EMs on each shaft, SUSAN can apply TEEM control. There exists a unique relationship between ESD, shaft EMs, and electric engines in a series/parallel partial hybrid configuration. The shaft EMs can extract power from the FBE to charge the ESD or to power the electric engines. The EMs can also inject power from the ESD on the shafts.

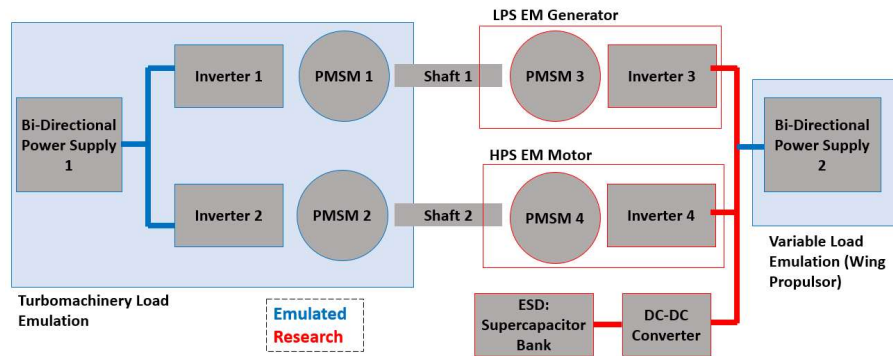


Fig. 8 Series/Parallel Partial Hybrid – SUSAN

The powertrain on the series/parallel partial hybrid is quite complex and verifying this system design through HIL testing will reduce uncertainty about how the power system and propulsion architecture interact. The HyPER laboratory configuration for a series/parallel partial hybrid propulsion system has similarities with that of a series hybrid. PMSMs 1 and 2 are powered by BPS 1 and emulate the turbomachinery dynamics for both the LPS and HPS on shafts 1 and 2, respectively. PMSMs 3 and 4 operate as either motors or generators depending on the need for

power extraction or insertion. The ESD provides a reservoir to store power extracted from the shaft or to deliver power for insertion to the shaft. The DC-DC converter regulates the power transfer between ESD and RHS DC bus. BPS 2 emulates the down-stream electric engines in variable load mode. The HyPER laboratory layout for a series/parallel partial hybrid propulsion system is shown in Fig. 8. Similarities in hardware setup between series and series/parallel partial hybrid systems demonstrates the laboratory flexibility. The differences in emulating a thrust producing FBE and a turboshaft are all captured in simulation. To convert a PMSM from motor to generator requires only a change in torque command supplied to the inverter.

D. Partial/Fully Turboelectric

Non-hybrid-electric systems can also be modeled in HyPER. Turboelectric architectures replicate the previously mentioned hybrids but without the use of energy storage devices. A fully turboelectric propulsion system architecture consists of a generator attached to the shaft of a FBE that doesn't produce thrust, and electric engines. Here, vehicle thrust is produced by the electric engines, which consume extracted power from the FBE. In this configuration, power extraction is the key to thrust production. A partial turboelectric propulsion system architecture also consists of an FBE, and attached generator, and thrust producing electric engines. However, unlike in fully turboelectric configurations, the FBE in partial turboelectric configurations serves the dual-purpose of supplying offtake power and producing thrust directly.

Configuring the HyPER laboratory for full and partial turboelectric systems is the same. As previously stated, the differences in emulating different FBEs are captured in the real-time model. Because the DC-DC converter and ESD are removed from the RHS bus, and because the laboratory is symmetrical and bi-directional, it makes no difference whether PMSMs 1 and 2 or PMSMs 3 and 4 emulate the turbomachinery. Either way, outputs of the simulated turbomachinery are scaled and sent to the emulation PMSMs.

E. All-Electric

An all-electric propulsion system architecture, in essence, consists of an energy storage device and an electric engine. The ESD provides power to the electric engine, which produces thrust. No FBE emulation is needed for this configuration. Instead, the propulsor dynamics are emulated with either a BPS in variable load mode or using a combination of PMSMs. The supercapacitor is charged before testing, much like an on-board battery. Power stored in the supercapacitor is transferred to the PMSMs through the DC-DC converter. The all-electric HyPER configuration is shown in Fig. 9.

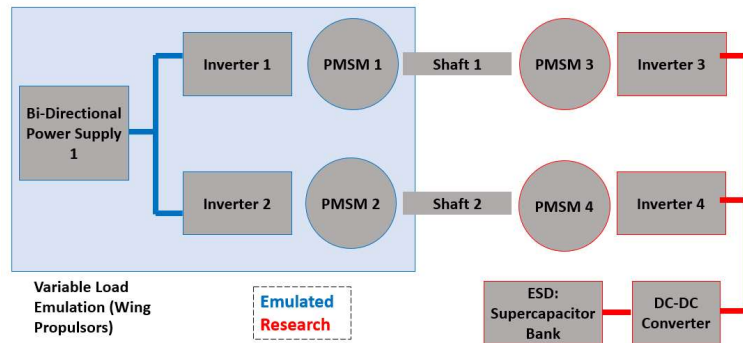


Fig. 9 All-Electric

IV. Summary

A hardware-in-the-loop (HIL) laboratory was developed to investigate control technologies for electrified aircraft propulsion (EAP). The Hybrid Propulsion Emulation Rig (HyPER) laboratory is a sub-scale representation of an electrified powertrain that enables initial testing of advanced control technologies for various hybrid-EAP systems at a low cost and risk to mature the Technology Readiness Level (TRL). A novel method of scaling power and inertia is applied that accurately reproduces the transient, off-design turbomachinery performance dynamics with electric machines in the lab and without using any physical turbomachinery. HyPER can be rapidly reconfigured to model a variety of EAP architectures. A parallel hybrid was discussed that was implemented in HyPER and additional implementations are discussed for future EAP controls HIL testing and TRL maturation.

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