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NASA Scaled Power Electrified Drivetrain

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A new transportation system is upon us, and it aims to satisfy the increasing need for air transportation. Advanced Air Mobility (AAM) has the potential to connect cities and increase air transportation capabilities and services. NASA recognizes that there is a need for standards and technology development to ensure the safety and reliability of future AAM aircraft. The NASA Revolutionary Vertical Lift Technology (RVLT) Project is using testbed data to satisfy these needs. One of these testbeds is the Scaled Power ElEctrified Drivetrain (SPEED). SPEED is a 400 VDC, 6 kW continuous, electrified aircraft propulsion system which is used to calibrate equipment, develop procedures, and perform tests at a reduced power level. This paper describes the testbed and the work it has supported at NASA.

I. Nomenclature

AAM = Advanced Air Mobility
AREAL = Advanced Reconfigurable Electrified Aircraft Laboratory
DC = Direct Current
EPS = Electrical Power System
EAP = Electrified Aircraft Propulsion
GRC = Glenn Research Center
NASA = National Aeronautics and Space Administration
RVLT = Revolutionary Vertical Lift Technology
SPEED = Scaled Power ElEctrified Drivetrain

II. Introduction

AAM has gained a high level of traction in the last few years as it can satisfy the need for increased air transportation. AAM has the potential to connect cities like they never have been before, and it can offer more direct passenger and cargo transportation. AAM encompasses a wide range of aircraft; one of the main features of these aircraft is the electric propulsion system (EPS) which can increase efficiency, decrease fuel burn and emissions, decrease emissions, and reduce noise [1]. Energy sources for these EPSs include batteries and fuel in either all-electric or hybrid-electric power trains [2]. These technologies have grown rapidly; however, this has led to gaps in safety and reliability. The NASA RVLT Project aims to increase the safety and reliability of the EPSs through the development of standards, design and validation of analysis tools, and technology development. To accomplish these tasks, RVLT has built two testbeds which are being used to provide platforms to investigate advanced technologies and generate the necessary hardware data to inform the standards and tools. The first testbed is the low-power SPEED testbed, and the second is the high-power Advanced Reconfigurable Electrified Aircraft Lab (AREAL). This paper describes the

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SPEED testbed, and it describes the various research activities it has supported, such as training engineers in an EAP ecosystem, calibrating equipment, developing procedures, and performing tests at a reduced power level.

III. Requirements

Originally, there was no distinct set of requirements for the SPEED testbed. It was developed to be a low-cost, low-power facility that NASA could use for multiple purposes, including training, component configuration, and test development. The primary design of the testbed was to be a single string of electric aircraft components at a “low” power. These components include a single source, single load powertrain topology. The RVLT project first contacted previous and current NASA Glenn projects for available equipment that could be used to outfit the SPEED testbed. There were a few components made available for the buildup of the lab, including the DC power supply, inverter, motor, and dynamometer. The availability of these components also helped mitigate supply chain delays. Ultimately, this set of components determined the requirements of the testbed. The maximum power level of the system was determined by the maximum power of the dynamometer (6 kW continuous). The maximum torque was also determined by the dynamometer (28 Nm). The maximum voltage rating of the motor (350 VDC) determined the maximum voltage of the system. The maximum speed of the system was also determined by the motor (9,338 RPM). Lastly, the maximum current was determined by the power supply (70 A). In short, the SPEED testbed is a construction of drivetrain components that are not the same power level but still operate when connected.

IV. System Overview

SPEED is a 6 kW continuous, 7 kW peak electrified aircraft propulsion (EAP) system. The operating voltage of the system is 350 VDC with torque and speed capability of 28 Nm and 9,338 RPM respectively. It is a single string of components with no branch circuits; it is a single source to single motor configuration. The buildup of the testbed began in 2019 and was completed toward the beginning of the COVID-19 pandemic. This timing allowed the testbed to be in full use during the pandemic by training engineers, developing procedures, configuring equipment, and performing tests.

Figure 1: Picture showing the SPEED testbed.

SPEED is hosted in a legacy gear noise test facility which is fully equipped with a water/glycol cooling system and sound deadening wall covering. The gear noise testbed was disassembled to make room for the new SPEED testbed. An image of SPEED is shown in Figure 1.

The initial purpose of the SPEED testbed was to be a learning facility to familiarize engineers with EAP systems at GRC. An EAP system could be designed, built, and tested at a safer, reduced power level. Once the testbed was built, however, the pandemic arose, and focus shifted. The testbed became a calibration and integration facility for the RVLT project, and the testbed was consistently re-configured with new hardware to test various components and test configurations in preparation for higher power tests in AREAL.

The SPEED testbed is split into two rooms - a test cell, where the powertrain hardware is installed, and a control room, where the operator interface is located. The diagram in Figure 2. shows the electrical power diagram of the SPEED electrical power train.

The subsequent sections will further describe the design of the testbed. It includes more detail on the electrical and mechanical components, grounding and bonding, controls, data acquisition, cooling system, safety/interlock system, and computer model.

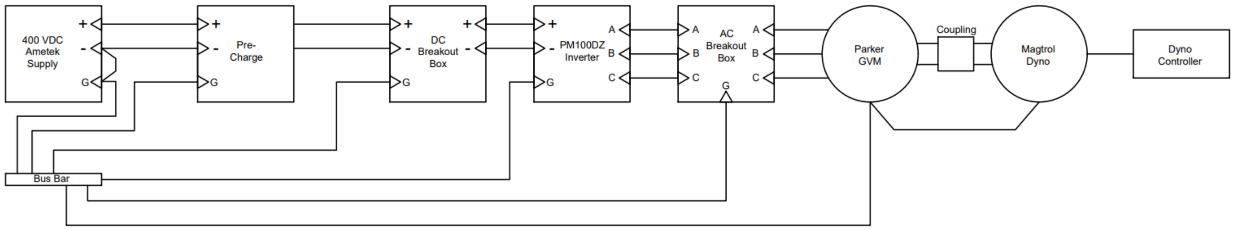


Figure 2: SPEED testbed power diagram.

A. Electrical Power, Mechanical Power, Grounding, and Bonding

The facility power at the panel is a 208 VAC system, which is then stepped up to 480 VAC with a 3-phase transformer in the basement of the test cell. The SPEED testbed requires 480 VAC to power the 400 VDC, 70 A Ametek power supply. The power supply is positioned on the floor at the rear of the testbed and is the DC source for the SPEED testbed. The power cables for the entire system are size 1/0 AWG Champlain® EXRAD cables, unshielded. The size of this cable far exceeds the power demand of the testbed, but it was selected as the transmission conductor because of its fitment with the Cascadia PM100DZ inverter.

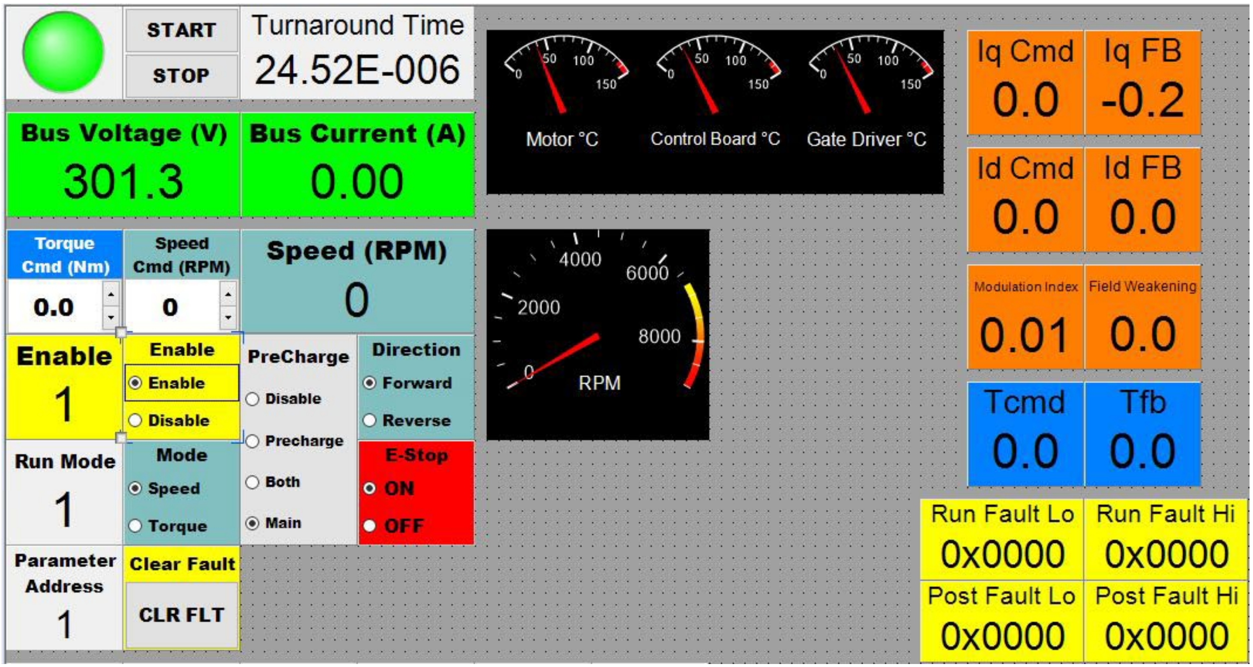
A Flexo 1.5 inch braided stainless-steel jacket is used to shield and protect the power cables on the testbed; the cable is twisted at approximately one twist per foot and inserted into the shield. The shield is bonded at both ends of the cable assembly. The shield pigtails are intended to be as short as possible to prevent interference.

The ground cables for the DC power supply, sensor boxes, inverter, motor, and dyno stand are Eriflex NVent® size 1 inch braided tinned copper ground strap. All equipment is bonded to the single point ground bar at the rear of the testbed. In addition, the neutral terminal of the power supply is bonded to ground to prevent the DC bus from floating. The 1 inch braided, tinned copper ground strap was selected because it provides a low impedance path to ground. This grounding configuration created ground loops; however, the idea here is that many small ground loops are better than one big ground loop. Grounding, bonding, and shielding rules were followed per the NFPA® National Electrical Code [3] and an EATON® VFD Wiring Best Practices document [4].

A pre-charge circuit is used to charge the DC link capacitor remotely through the manual interface in the control room. The motor drive is a Cascadia Motion Systems (formerly Rinehart) PM100DZ inverter. This motor inverter is designed for integration into electric vehicles (EVs) as an EV traction inverter. It can operate up to 840 VDC and 150 Arms continuous. This inverter is the highest power component on the testbed, and it was selected and installed due to its availability and software resources. A Parker GVM-142-050K permanent magnet machine is the primary motor for the installation, and it is capable of 9,338 RPM continuous and 16.14 Nm continuous, 30.95 Nm peak. The motor is mechanically loaded down with the Magtrol HD-815-6N eddy current dynamometer. The dynamometer has a capacity of 12,000 RPM continuous and maximum of 28 Nm torque. The dynamometer can brake up to 6 kW continuous or 7 kW peak for 5 minutes.

B. Controls

The SPEED testbed is operated from a dedicated control station in the control room. The main control panel is used to enable and disable the cooling system and the DC power supply. The DC supply is activated remotely from the control panel, and the voltage and current setpoints/limits are manually selected with the dials on the power supply front panel before each test. A dSPACE unit is used to control both the pre-charge and inverter via CAN bus. All CAN connections in the testbed are converted to fiber optic to mitigate signal interference and ensure proper operation over distance in addition to applying proper bonding and shielding strategies. All inverter operations are performed via a graphical user interface shown in Figure 3.



Turnaround Time: 24.52E-006
Bus Voltage (V): 301.3
Bus Current (A): 0.00
Torque Cmd (Nm): 0.0
Speed Cmd (RPM): 0
Speed (RPM): 0
Enable: 1
Enable: ● Enable ○ Disable
PreCharge: ○ Disable ○ Precharge ○ Both ● Main
Direction: ● Forward ○ Reverse
Run Mode: 1
Mode: ● Speed ○ Torque
E-Stop: ● ON ○ OFF
Parameter Address: 1
Iq Cmd: 0.0
Iq FB: -0.2
Id Cmd: 0.0
Id FB: 0.0
Modulation Index: 0.01
Field Weakening: 0.0
Tcmd: 0.0
Tfb: 0.0
Run Fault Lo: 0x0000
Run Fault Hi: 0x0000
Post Fault Lo: 0x0000
Post Fault Hi: 0x0000

Figure 3: dSPACE control Graphical User Interface.

The graphical interface (GUI) displays speed, torque, DC voltage, and bus currents with other motor drive data from the inverter. In addition, the GUI is used to issue speed or torque commands for each of the test scenarios. The dynamometer can be controlled in one of two ways depending on the test conditions. The first is by directly interfacing with the front panel of the rack-mounted controller. The second is with the Magtrol software by connecting a PC to the rack-mounted controller. The hardware and operation of the testbed will be described further in the conference paper.

C. Sensors and DAQ

All testbed data is collected using sensors measuring voltage and current (both AC and DC) and is shown in Figure 4. Voltage measurements, both AC and DC are acquired via a fluxgate transducer capable of up to 1000V_{RMS} nominal and a primary-to-secondary conversion ratio of 150V:1V. In addition, AC and DC current measurements are taken with a Hall effect sensor scaled with a 20Ω burden resistor capable of measuring up to 200A. The Hall effect sensors have a 1000A:1A primary-to-secondary conversion ratio, resulting in a 50-times conversion factor of the voltage measured across the burden resistor:

$$\frac{200A_{PRIM}}{1000} = 0.2A_{SEC} * 20\Omega = 4V_{MAX}$$

$$\frac{200A}{4V} = \frac{50A}{1V} * V_{MEAS}$$

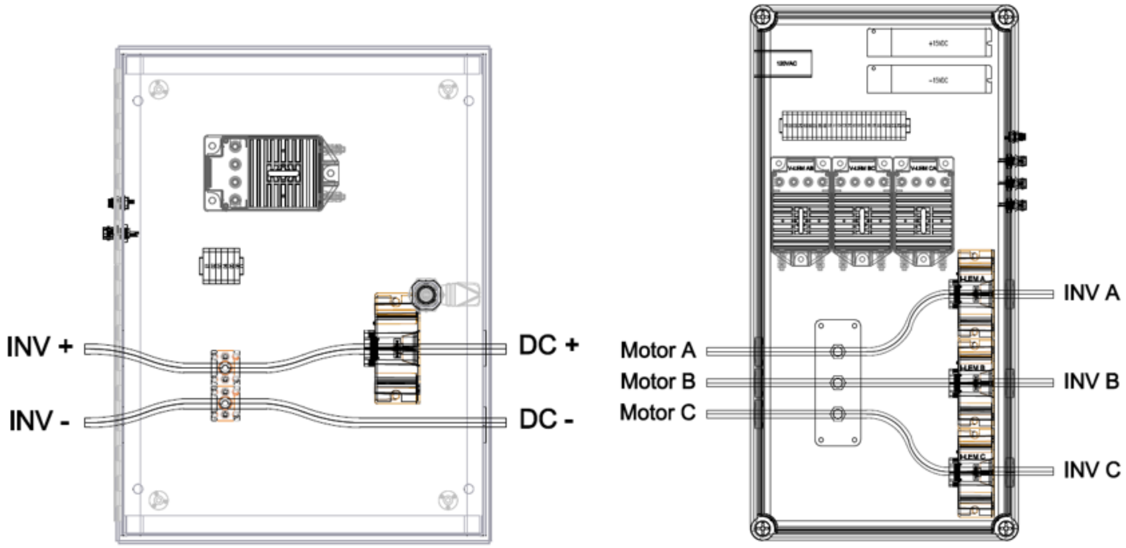


Figure 4: DC (left) and AC (right) sensor boxes.

Measurements acquired via the sensor boxes adjacent to the testbed are sent via BNC cable to a control room, where the voltage and current scaling factors are adjusted on a Yokogawa DL850 Scopecorder oscilloscope for live observation and troubleshooting. Testing personnel also have the option to capture dynamic and higher-frequency measurements on a DEWESoft® DEWE-43A data acquisition system.

D. Cooling System

The cooling system in the SPEED testbed uses multiple cooling loops to maintain temperature. The first cooling loop is the building cooling loop which is a water/glycol blend that transfers testbed heat to the outdoor heat exchangers. The second cooling loop is the local cooling loop which is a 50/50 water/glycol mix. This coolant flows through the system to cool the motor and inverter. The coolant is filtered to prevent damage to the equipment. In addition, flow monitors ensure operation of the cooling system – this is mentioned in the interlock section below.

E. Safety and Interlocks

The safety and interlock system for the SPEED testbed is designed to prevent damage to operators, technicians, and equipment. The interlock system will de-energize or prevent energizing of the DC bus through the on-board interlock system in the Ametek DC power supply. The interlock system monitors coolant flow, dSPACE emergency shutdown control bit, E-STOPs, and the DC supply set/reset button. E-stops are found in three areas: one physical button mounted on the testbed in the test cell, one physical button mounted on the control panel in the control room, and one final digital E-STOP button in the dSPACE control interface.

In the event of an emergency shutdown, the DC power will be cut off, and the system will spin down to zero speed or be rapidly decelerated with the dynamometer brake (if the brake is activated). If the system is spinning, the inverter will drain the DC link capacitor of all voltage, due to active switching components. If the system is not spinning, the user would need to perform the discharge task manually by activating the switching function on the inverter to rapidly discharge the bus. The bus will discharge more slowly over time if not actively discharged through a bleed resistor inside of the inverter.

F. Computer Model

To support the research conducted in the SPEED testbed, a PSIM® model of the testbed was developed. The simulation proved itself useful in determining the nominal and off-nominal operation of the testbed as well as evaluating resonant points that carry the potential to cause damage. The PSIM® model was designed to accurately resemble the physical hardware in the lab, including the voltage source, DC cable system, inverter, AC cable system, and the electric motor.

In the PSIM® model, the Ametek DC power supply was a simple DC voltage source. The Champlain Exrad cable system resistance and inductance were measured with a Wayne Kerr Model PMA3260A LCR meter, and the measurements from the device were entered into the cable model. The Cascadia PM100DZ inverter were modeled with an electrolytic capacitor for the DC link and a 3-phase, full bridge, IGBT power stage. The DC link capacitance of 280 µF was entered into the model from the datasheet. The Parker GVM-142-050-K electric motor model was taken directly from the PSIM® library, and the respective datasheet parameters are entered into the electric motor model.

The control system in the model used vector control with space vector pulse width modulation (SVPWM) to control the electric motor signal. This type of control is common in high performance traction drives because of its responsiveness and ability to use the full DC bus voltage more effectively.

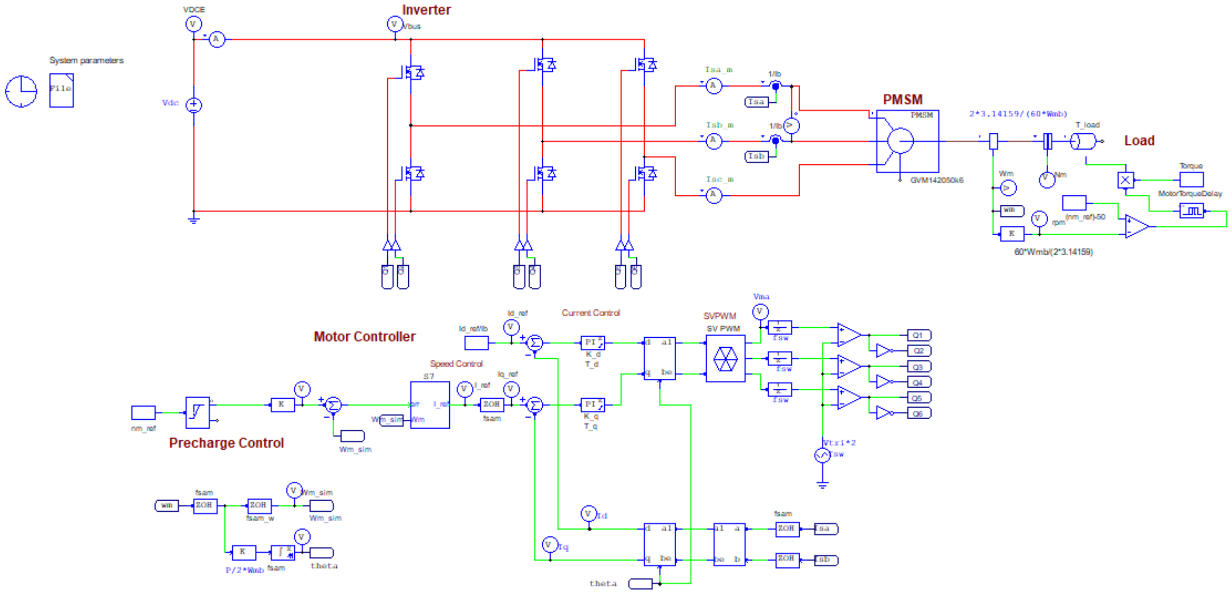


Figure 5: PSIM computer model of the SPEED testbed hardware.

V. Accomplishments

The following sections will describe the activities and accomplishments that have been completed in the SPEED testbed. The testbed has been used to train engineers and introduce them to motor testbed design and integration, configure multiple motors and drives, and establish a testing technique for evaluating electrical input impedance of motor and drive loads.

G. Training

One of the primary objectives of the SPEED testbed was to be a training experience for young engineers and engineers who may not have had experience building an electric motor testbed. The facility accomplished that objective in numerous ways. Areas of experience gained include integration with existing lab infrastructure, sizing of power system components and cables, grounding and bonding, communication, control, and data acquisition.

Another area in which the testbed has been a valuable training tool is in educating test engineers on the minimum and maximum operating points of the electro-mechanical equipment; the test operators needed to develop a special awareness that is unique to motor testbeds. For example, there are software provisions in place that prevent the system from overheating; however, the power mismatches of the components present some limits that are not readily programmed in the control algorithm. This primarily includes navigating around the maximum torque, speed, and power limits of the dynamometer when operating the system. With the DC supply set to 350 VDC, the electric motor can permanently damage the dynamometer if the power level is not monitored. The maximum continuous speed, torque, and power of the dynamometer are 12,000 RPM, 28 Nm, and 6 kW respectively. The operator is required to maintain awareness and keep at or below these limits. Simple electrical and mechanical power equations are the only items needed to keep track of these power limits.

H. Multiple Motor and Inverter Configuration

The first configuration of the SPEED testbed included the integration of the Cascadia Motion Systems PM100DZ inverter and the Parker GVM-142-050-K. These original components were installed to be a learning opportunity for the RVLT electric propulsion (EP) team. Once this first system was fully operational, the EP team integrated a fiber optic communication bus for communication between the inverter and the dSPACE system in the control room.

At this point, the COVID-19 pandemic was in full swing. Project milestones shifted due to supply chain issues and limited on-site work rules. SPEED became a configuration and calibration facility for equipment to be transferred to the high-power AREAL testbed. This way, supply chain delays were compensated for by having motor and drive equipment ready for service in the AREAL testbed.

A SEVCON Gen4 inverter and a Parker GVM-142-050-K electric motor were then installed. The SEVCON inverter required a new Parker motor with different rotor position sensor be installed - a sin/cos resolver. The integration of this motor produced a new challenge - the communication protocol was different than the previous Cascadia motor. Once the CANopen communication protocol was configured, the system performed as expected, and the testbed was again re-configured to operate with a third motor. The third motor was the EMRAX 228 motor, specifically chosen to be installed into the AREAL testbed because of its prevalence in industry. This motor was not connected to the Magtrol dynamometer because of the large number of mechanical modifications required to mount the motor. Instead, a temporary stand with containment shield was mounted to the SPEED drivestand, and the EP team configured the EMRAX motor to spin with no load.

I. Electrical Input Impedance Measurement

Not only has SPEED been of benefit for training personnel and determining how to successfully integrate motors and inverters to be used in AREAL, but the testbed was used to develop important procedures for impedance measurements in a first-of-its-kind, publicly available test campaign. These tests and associated results are detailed in a corresponding paper, “Impedance Measurements of Motor Drive and Supply in SPEED Testbed” [5] and will not be repeated here.

In summary, the SPEED testbed proved itself to be a valuable asset in configuring and calibrating numerous motors and drives for the AREAL testbed. The RVLT EP team was able to acquire all the necessary software tools and knowledge required to bring the motor systems online, which was especially important when operating the AREAL testbed.

VI. Future Work

Future work in the SPEED testbed may include integration of high-frequency SiC and GaN inverters for motor drives. NASA is interested in this research because it can reduce the size of filter components, thus minimizing the size and weight while increasing efficiency of the RVLT class of vehicles. In addition, SPEED may be modified to research the AC electric propulsion system. At this time, proposals are being made to obtain the necessary hardware for these modifications.

VII. Conclusion

The SPEED testbed has proven itself invaluable to NASA because it has allowed the RVLT EP team to make strides when parts shortages and uncertainties were present. The system was constructed and immediately put to use in calibrating and integrating equipment and performing tests. Lessons learned and best practices were translated directly into the operations of the high-power AREAL testbed.

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