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Validation of the NASA Electrical Power System – Sizing and Analysis Tool (EPS-SAT)

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The electrification of aircraft propulsion systems has opened the design space for engineers by allowing for unique and highly specialized propulsion system and vehicle designs. NASA developed the Electrical Power System – Sizing and Analysis Tool (EPS-SAT) to conduct high-level trade studies and sensitivity studies on the various propulsion system designs that can be implemented in electrified aircraft. The results of these studies would be used to better direct investment dollars and determine strengths and weaknesses of propulsion system designs. In this paper, the results of the EPS-SAT tool were validated with hardware data extracted from the NASA Revolutionary Vertical Lift Technology (RVLT) Advanced Reconfigurable Electric Aircraft Lab (AREAL). Updated performance maps were added to the EPS-SAT library so that high-fidelity results could be calculated.

Nomenclature

AAM	=	Advanced Air Mobility
AFRL	=	Air Force Research Laboratory
AREAL	=	Advanced Reconfigurable Electrified Aircraft Laboratory
COTS	=	Commercial-off-the-shelf
DC	=	Direct Current
DCE	=	DC Emulator
EPS	=	Electrical Power System
EAP	=	Electrified Aircraft Propulsion
GRC	=	Glenn Research Center
HVDC	=	High Voltage Direct Current
NASA	=	National Aeronautics and Space Administration
PMAD	=	Power Management and Distribution
PQ	=	Power Quality
RVLT	=	Revolutionary Vertical Lift Technology
UE	=	Utilization Equipment

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I. Introduction

There is an international movement toward the electrification of aircraft driven by the increasing demand for air travel as well as by the desire to reduce engine noise, greenhouse gas emissions, fuel consumption, and mission operational costs [1], [2]. Electrified propulsion systems can broaden the design space of aircraft propulsion and vehicle air frame design [3]. The electrified propulsion system, however, requires careful evaluation so that the system can be as efficient and lightweight as possible and to minimize research, development, and operational costs. To help minimize the risk of increased development time and cost on sub-optimal propulsion system hardware designs (or designs susceptible to premature failure), software modeling tools are required. These tools allow engineers to conduct preliminary studies to expose strengths and weaknesses of designs, minimize the design space, and better direct investment dollars [4].

The NASA Glenn Research Center (GRC) Power Management and Distribution (PMAD) Branch is developing the Electrical Power System–Sizing and Analysis Tool (EPS-SAT) to specifically address the need for a tool to size and evaluate aircraft electric propulsion systems. This tool is being further developed and refined under the Revolutionary Vertical Lift Technology (RVLT) Project. High-level trade studies and sensitivity studies can be performed quickly in EPS-SAT to determine strengths and weaknesses of designs and better direct investments. Section II describes the EPS-SAT framework in greater detail.

This paper describes the validation of the EPS-SAT tool with hardware data acquired from the NASA RVLT Advanced Reconfigurable Electrified Aircraft Lab (AREAL). A similar modeling and validation approach as presented in [5] is followed. Characterization of the AREAL system at 718 VDC bus voltage is conducted on a single string (single-source, single-load) configuration. An initial comparison of results from the AREAL testbed and EPS-SAT output show that EPS-SAT component models require further refinement to enable motor and inverter efficiency calculations, requiring the code to be adapted to exclusively output electric engine (combined motor and inverter) efficiency and power calculations until component-specific capabilities are added to EPS-SAT.

II. EPS-SAT Framework

EPS-SAT is an object-oriented coding framework developed in the MATLAB® environment that can be used to design and evaluate electrical power systems for space, aeronautics, and microgrids. The developed framework consists of items such as run files, architectures, components, and analysis tools. The image in Figure **1** illustrates a high-level organization of the framework. For the aeronautics case, an electric propulsion system can be programmed in MATLAB® using components in EPS-SAT's object-oriented framework. All systems are first sized at the design point, such as take-off, where the highest power is required. Sometimes systems require multi-design point analysis, and this is also possible with EPS-SAT. In on-design, the software will calculate the weight of the electric propulsion system at the design point(s) defined by the user. Once the system is sized at the design point, the system can be studied in off-design, where mission profiles can be studied and energy storage can be sized. Parameter sweeps can be conducted in on-design and off-design to allow engineers to perform sensitivity studies and calculate points of diminishing return. Additionally, violations of design constraints (mass, mission range, system or component failure rate, etc.) can be evaluated, and the design space can be narrowed toward more achievable missions.

A typical EPS-SAT workflow is described in the EPS-SAT User's Guide [6]. First, a user draws the power system architecture, such as the example shown in Figure **2**. Then, they can program the power system architecture in MATLAB® using the built-in EPS-SAT component library. Once a system architecture is programmed, like the architecture shown in Figure 3, the built-in functions can be used to calculate the size and performance of the electric propulsion system.

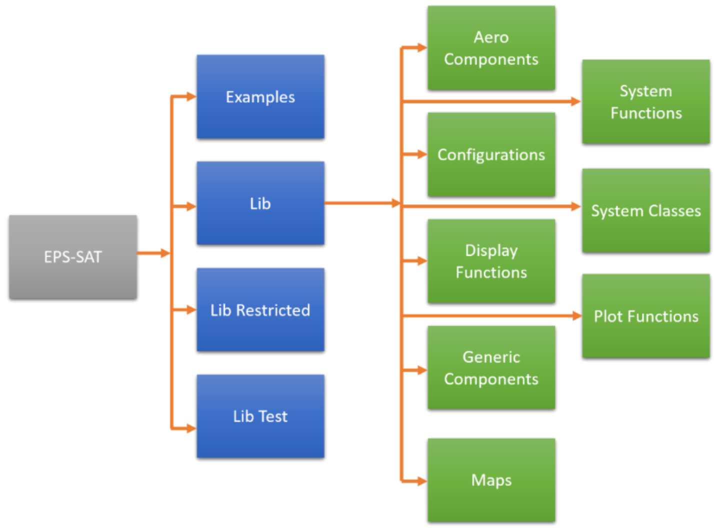


Figure 1**: EPS-SAT Library**

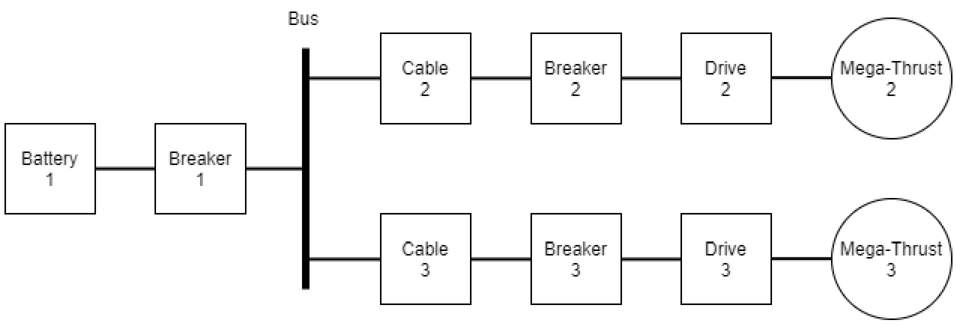


Figure 2**: Hypothetical EPS-SAT Architecture**

```
function obj = setup_architecture(obj)

% -- Initialize the branches --

    % Branch 1
    obj.components.gen1 = generator_class(400,13,0.96);
    obj.components.gen1.map = power_efficiency_map_class();
    obj.components.cp1_1   = circuit_protector_class(350,0.995);
    obj.components.wire1_1 = wire_class(29,2,5);
    obj.components.cp1_2   = circuit_protector_class(350,0.995);
    obj.components.wire1_2 = wire_class(29,2,5);
    obj.branches.branch_1 = {'gen1','cp1_1','wire1_1','cp1_2','wire1_2'};

    % Branch 2
    obj.components.wire2_1 = wire_class(29,2,5);
    obj.components.wire2_2 = wire_class(29,2,5);
    obj.components.em2     = electric_motor_class(9,0.95);
    obj.components.em2.map = power_efficiency_map_class();
    obj.branches.branch_2 = {'wire2_1','wire2_2','em2'};

% -- Initialize the busses --

    % Initialize the buses
    bus_inputs = {'branch_1'};
    bus_outputs = {'branch_2'};
    obj.busses.bus = bus_class(obj,bus_inputs,bus_outputs);
end
```

Figure 3: Example Architecture Code in EPS-SAT.

To increase its capability, EPS-SAT uses a Newton-Raphson solver, allowing a user to define independent and dependent variables and then perform analysis with system or component parameters of interest. The solver allows more complicated systems to be studied, and it allows the user to tailor their analysis to suit their needs. Typically, a user will configure the solver variables such that the source voltage is a setpoint, the required output power is a dependent, and the current is an independent variable (or a guess). The user then specifies a set of "good" initial conditions for the independent variables is required so that the solver can converge on a solution. Many times, these initial conditions can be calculated with the setpoint and dependent variables that were input into the solver. The solver will then take the independents (guesses, or initial conditions) and iterate until there is zero error in the dependent variables.

III. EPS-SAT Electric Engine Model Calculations

This section describes the electric engine modeling approach. Like other EPS-SAT models, the objective is to develop a high-level model that used lookup tables and lab data to perform calculations. In the past, EPS-SAT generalized the mechanical motor output power into a single power term. This was done for simplicity reasons. The work in this paper develops a new electric engine component that outputs speed and torque parameters, rather than only a simple output power. In the electric engine, motor output torque is scaled according to the rated DC current, and motor shaft speed is scaled according to rated DC voltage. These voltages and currents are inputs to the electric engine component, and they are iterated by the solver as inputs (or independent variables).

In on-design, the speed and torque are setpoint values, and they are sized at the rated operating point. To drive the voltage and current toward their respective rated speed and torque values, the electric engine component uses two conservation laws and the efficiency map as lookup tables. The first is that the calculated electric engine DC input power (from torque, speed, and efficiency map) must equal the DC input power (from solver variables). The second is that the calculated rated voltage must equal the DC input voltage to the electric engine. The illustration in Figure 4**Error! Reference source not found.** provides a visual representation of this problem-solving process.

In off-design conditions, EPS-SAT holds bus voltage constant and varies initial current. The bus voltage is set based on the calculated voltage in on-design. This is ultimately what EPS-SAT calls the rated voltage. The conservation law for voltage is no longer needed because the rated voltage is now determined. Current is then iterated until the difference between the DC input power (from solver variables) and calculated DC input power (from torque, speed, and efficiency map) are equal, as depicted in Figure 5**Error! Reference source not found.**.

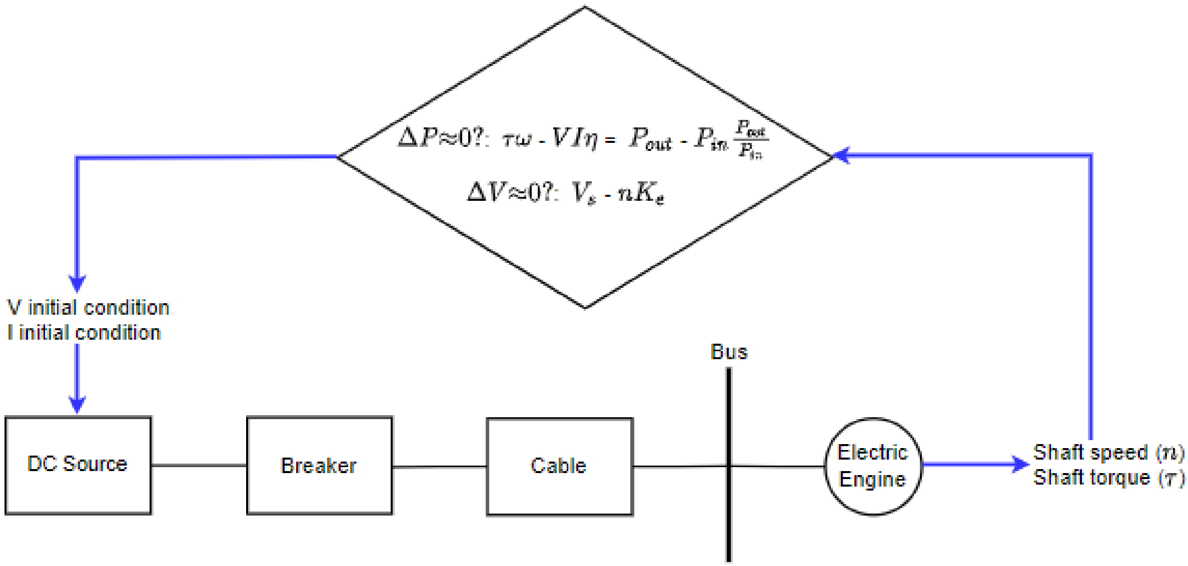


Figure 4: EPS-SAT On-Design Calculations

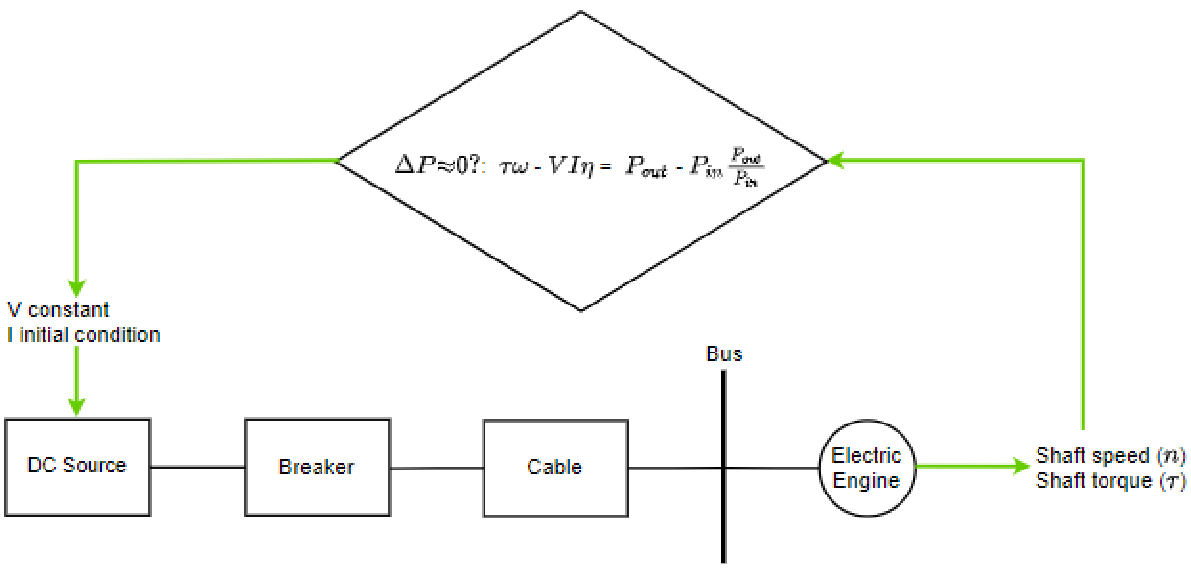


Figure 5: EPS-SAT Off-Design Calculations

IV. AREAL Testbed

This section describes the hardware in the AREAL testbed that was used for the collection of data. The AREAL testbed was built as a 200kW high-voltage direct current (HVDC) testbed with a bus voltage that could be adjusted from 300V-1kVDC [7]. AREAL was designed to be flexible enough to be used for multiple HVDC system configurations, tests, and operating scenarios (e.g., normal and faulted operation). This flexibility allowed the lab to be a multi-purpose facility and to be useful in providing performance and test data for a variety of configurations. For the work detailed in this paper, the AREAL testbed was evaluated in steady state conditions so that the results of the EPS-SAT tool could be validated.

AREAL was built to be capable of multiple configurations and to be equipped with a plug-and-play design with automotive-grade power plugs and sensor breakout boxes housing current and voltage sensors for capturing electrical telemetry. Torque and speed was measured with a Honeywell torque meter that was mounted on an Emrax 228 HV motor and Emrax 228 HV dynamometer (see Figure 6). Two D&V Electronics high-bandwidth, bi-directional DC emulators (DCEs) were used as programmable dynamic electrical sources and/or loads (see Figure 7Figure 7). By design, the AREAL testbed also used both physical motor hardware, mounted on a 60 kW drivestand with Emrax 228 HV machines, and a 275 kW D&V motor emulator, mounted in a large electrical rack. Lastly, the electric motors were controlled with Cascadia Motion Systems PM100DZ inverters. The data acquired for the work described in this paper was acquired with the physical motor hardware in AREAL.

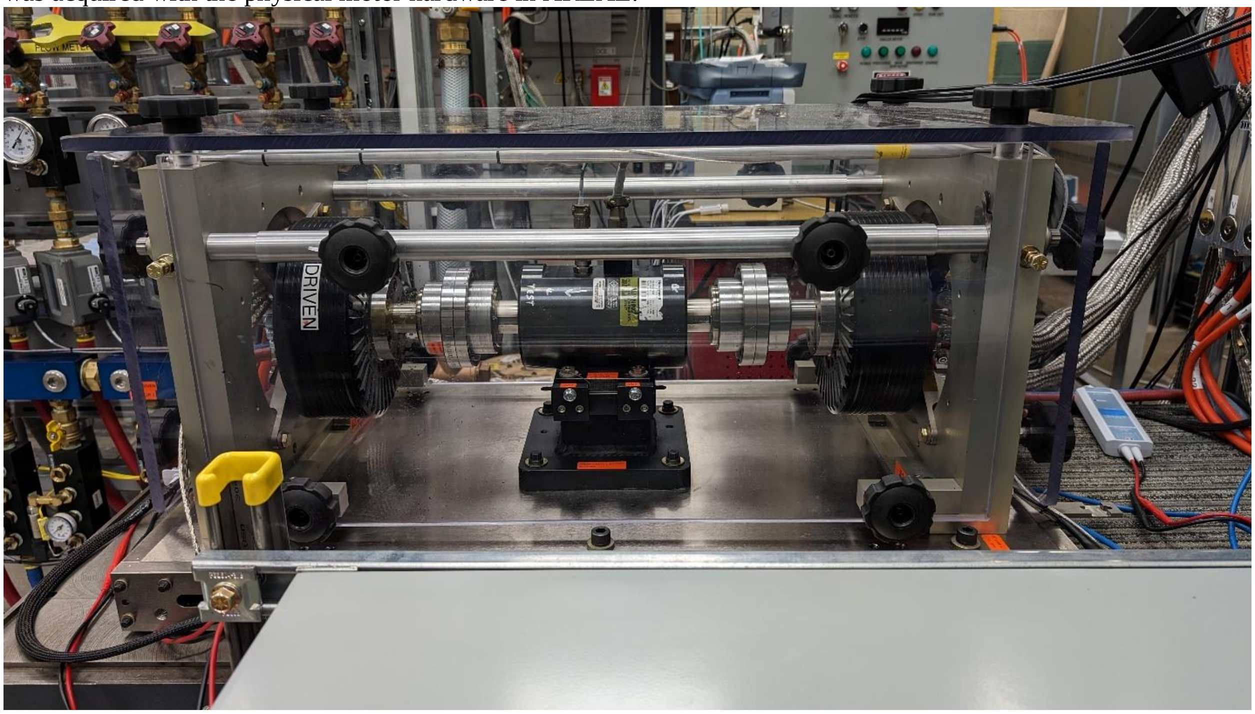


Figure 6: AREAL Motor Drivestand

Figure 7: D&V Electronics DC Emulator (Left) and Electric Motor Emulator (Right)

The tests in this report validated the single string configuration, shown in Figure 8, at steady-state operating conditions. For the steady-state testing in this report, the output voltage of the DCE was fixed by the user to 718 VDC for the duration of the tests.

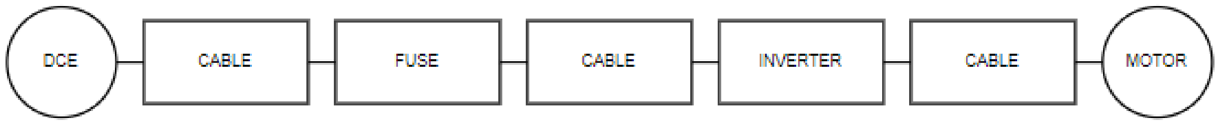


Figure 8: Single-string power diagram.

V. Test Matrix

This validation activity involved the collection of steady-state test data in the AREAL single-string configuration with one source and one load at 718 VDC bus voltage. This test voltage was selected because it was used as the max voltage setting for the power quality tests outlined in [7]. Data was collected at steady-state torques and speeds ranging from 250-5500 rpm and 20-100 Nm, respectively. The speed interval was every 250 RPM, and the torque interval was every 10 Nm. The limits for the EMRAX 228 HV machine are defined higher than what was tested, but the higher operating zones were not tested in the interest of not damaging the lab equipment.

The following parameters were recorded with the Yokogawa DL350 Oscilloscope: DC voltage, DC current, AC voltage Vab, AC voltage Vbc, AC current Ia, AC current Ib, speed, and torque. Field weakening operation was noted, and the values for Id and Iq current transmitted from the inverter readout was recorded by hand. Additionally, temperature from the internal motor thermocouple was recorded by hand. Field weakening and temperature, however, were not considered to be within the scope of this validation work. The data required post-processing, which is described further in Section VI.

The motor and inverter component mass was calculated with a key performance parameter called specific power. Specific power was calculated by extracting the mass and continuous power information from the datasheets for the motor and inverter. This was a rudimentary method for extracting and scaling the mass of the components, and it is an area for future work.

VI. MATLAB Code for Laboratory Data Processing

MATLAB® code was developed for the processing of the raw testbed telemetry data that was recorded on the AREAL testbed Yokogawa DL850 Scopecorder. The two AC line currents and two line voltages were measured such that the two-wattmeter method could be used as shown in Equations (**1**) **-** (**3**) to calculate three-phase power [8]. The two-wattmeter method minimizes the number of measurements and calculations needed for AC power calculations, an advantageous technique when sensors are costly and sensor boxes have limited available space. The AC signal complex power and power factor for each torque and speed set point were calculated with the two-wattmeter method as shown in Equations (1) **- Error! Reference source not found.**. Element-wise multiplication and summation operations were used because the measurements were converted to the frequency domain with the MATLAB® Fast Fourier Transform (FFT) operation.

$$\boldsymbol{P_{AC,1} = \Sigma(real(fft(V_{AC}).fft(I_A^*)))} \tag{1}$$

$$\boldsymbol{P_{AC,2} = \Sigma(real(fft(V_{BC}).fft(I_B^*)))} \tag{2}$$

$$\boldsymbol{P_{AC,TOT} = P_{AC,1} + P_{AC,2}} \tag{3}$$

$$Q_1 = \Sigma(abs(imag(fft(V_{AC}).fft(I_A^*))))$$

(4)

$$Q_2 = \Sigma(abs(imag(fft(V_{BC}).fft(I_B^*))))$$

(5)

$$Q_{TOT} = Q_1 + Q_2$$

(6)

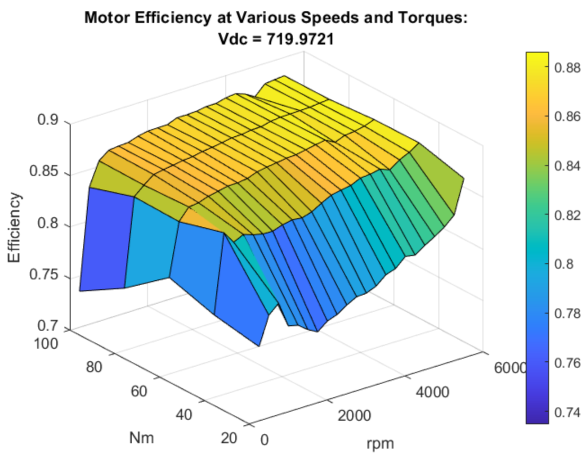
$$\theta = \tan^{-1}\left(\frac{Q_{TOT}}{P_{AC,TOT}}\right)$$

(7)

$$pf = \cos(\theta)$$

Separate motor and inverter component efficiencies were calculated, and electric engine efficiencies were calculated by multiplying those two efficiencies together. These calculations enabled motor, inverter, and electric engine efficiency maps to be created, which in turn enabled EPS-SAT electric engine efficiency and power calculations to be validated. Additionally, the electric engine efficiencies were calculated using an alternative method, by dividing the DC input power by the mechanical output power. The electric engine efficiencies that were calculated by multiplying individual motor and inverter efficiencies matched electric engine efficiencies that were calculated with DC and mechanical powers, providing a road map to modeling engine efficiencies in EPS-SAT. Examples of three-dimensional motor and inverter efficiency plots are shown in Figure 9**, and an engine efficiency plot is shown in Figure** 10

Figure **10**.



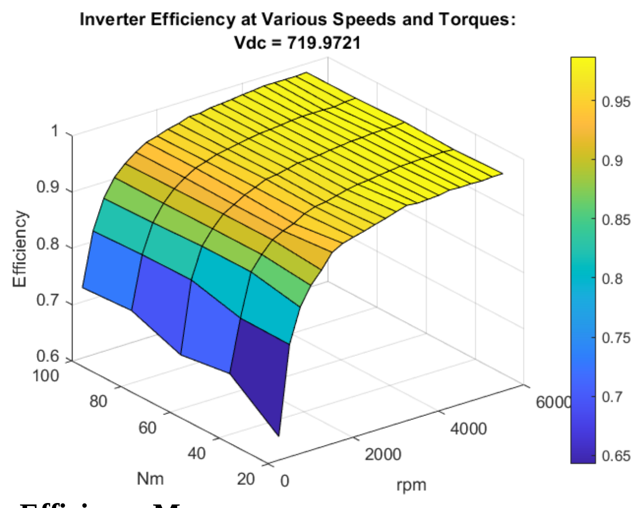


Figure 9: Motor and Inverter Efficiency Maps

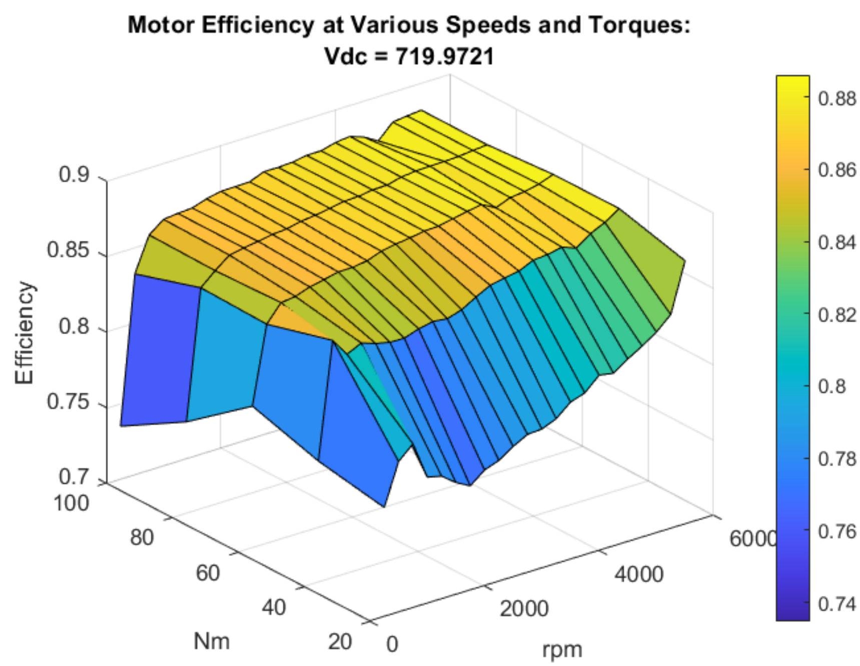


Figure 10**: Electric Engine Efficiency Maps**

VII. EPS-SAT and AREAL Validation

A visual inspection of overlaid voltage, current, torque, and speed data plots for steady-state test points provided a subjective assessment of an acceptable match between model and real-world data. Appropriate non-quantitative matches between AREAL and model power and electric engine efficiency data for given torque-speed setpoints indicated that the EPS-SAT tools predicted real-world values with reasonable accuracy.

110 unique data points were taken in the AREAL testbed for validation of EPS-SAT at the steady state points given in Table 1. Figure 11 shows that speeds and torques calculated in EPS-SAT in on-design and measured in AREAL were nearly identical. Likewise, Figure 12 shows a close match between lab and EPS-SAT voltages and currents, with a voltage drop between the voltage source and the bus. The same match between laboratory and EPS-SAT was achieved with electric engine efficiencies (Figure 13).

Bus Voltage (VDC)	Motor Shaft Speed (RPM)	Motor Torque (Nm)
718	250:250:5500	20:20:100

Table 1: AREAL Steady-State Test Points

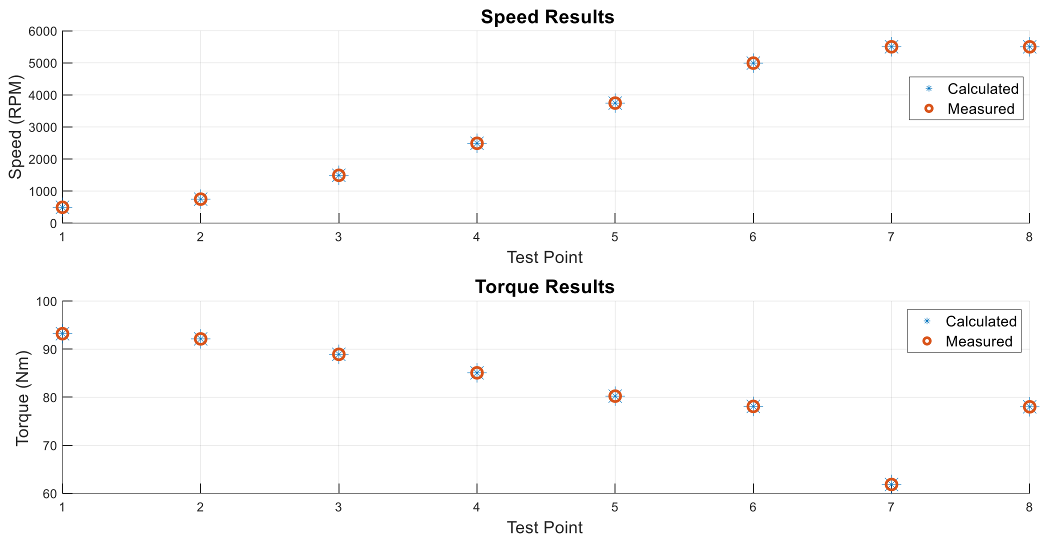


Figure 11: Speed and Torque Comparison Between EPS-SAT and AREAL

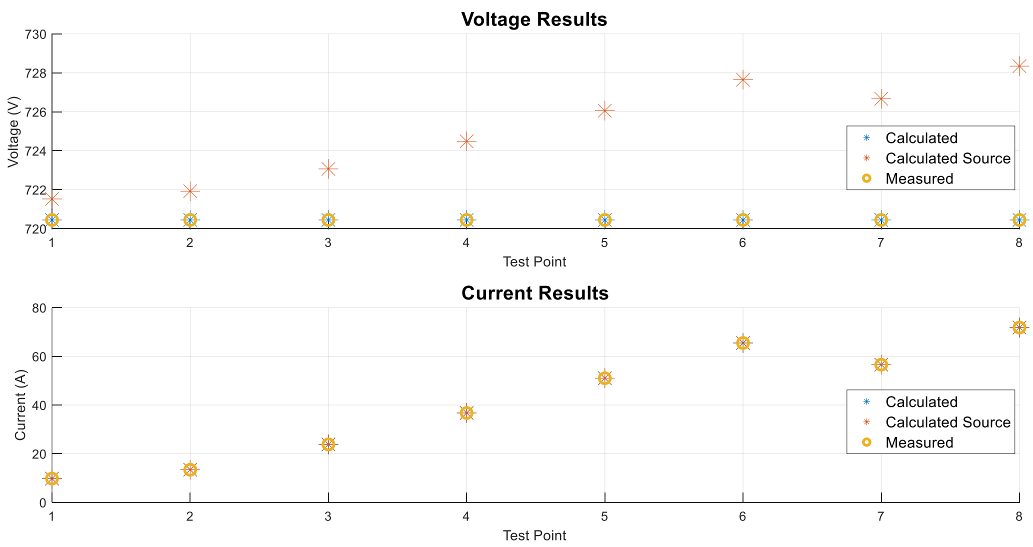


Figure 12: Voltage and Current Comparison Between EPS-SAT and AREAL

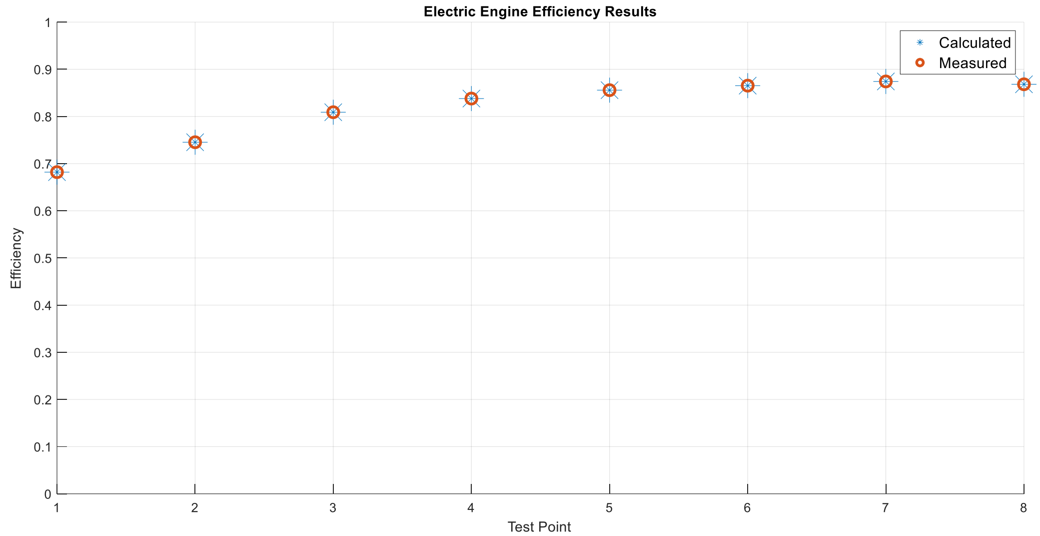


Figure 13: Electric Engine Efficiency Comparison Between EPS-SAT and AREAL

VIII. Future Work

Future work items include the following: (1) adding the capability to model inverter and motor AC powers and motor and inverter efficiencies in EPS-SAT and (2) comparing realistic flight profile data measured in AREAL to flight profile data modeled in EPS-SAT. Noise present in the power system was incorporated into real power calculations as set forth in VI, but no such capability to inject noise into EPS-SAT models yet exists. Frequency domain analysis of AC signals also showed that the noise present in the system was not a function of a fundamental frequency, meaning that this noise needed to be included in laboratory post-processing power calculations. A torque transducer also introduced torque measurements which lagged DC power measurements when a flight profile was tested in AREAL. This lag would have created mechanical efficiencies greater than one throughout the profile. This problem could likely be solved by installing a faster torque transducer. In addition to the measurement problem introduced by the torque transducer, unforeseen delays caused by equipment failures and lab build-up logistics prevented the flight profile from being run in AREAL in time for publication.

IX. Conclusion

Results of steady state testing for the single string AREAL testbed configuration at 718 VDC have been used to validate the results of the EPS-SAT software. The AREAL hardware configuration was modeled in EPS-SAT, and the test results were compared to the software output, showing almost no difference between electric engine efficiencies, speeds, torques, DC voltages, and DC currents. This validation of the EPS-SAT software shows it to be a useful tool for high-level, rapid design and evaluation of electrified aircraft propulsion systems. .

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References

[1] "Future of Aviation," [Online]. Available: https://www.icao.int/Meetings/FutureOfAviation/Pages/default.aspx.

[2] *Hathaway, M.D., Del Rosario, R., and Madavan, N.K., "NASA Fixed Wing Project Propulsion Research and Technology Development Activities to Reduce Thrust Specific Energy Consumption," NASA TM 2013-216548, July 2013*..

[3] V. Sheehan, "Vertical Flight Society Electric VTOL Aircraft Directory Reaches 500 Concepts," 9 August 2021. [Online]. Available: https://vtol.org/news/vfs-electric-vtol-aircraft-directory-reaches-500-concepts. [Accessed 2 December 2023].

[4] S. Suryanarayanan, S. Puradbhat, V. Bhavaraju, P. Balasubramanian, A. Kapoor and L. C. Zhang, "The Microgrid Controller: An Empowering Technology at the Grid Edge: Realizing Benefits From Microgrids Via Sequential De-Risking of Controller Technology," *IEEE Power and Energy Magazine,* vol. 22, no. 2, pp. 78-89, 2024.

[5] B. P. Malone and G. L. Thomas, "Numerical Propulsion System Simulation (NPSS) Electrical Modeling Validation," Vertical Flight Society (VFS), Hampton, 2023.

[6] G. L. Thomas and P. A. Hanlon, "EPS-SAT User's Guide," [Online]. Available: https://software.nasa.gov/software/LEW-20017-1.

[7] P. A. Hanlon, D. J. Sadey, L. M. Taylor, B. P. Malone, K. R. Hunker, X. Collazo-Fernandez, C. J. Theman and P. Nowak, "NASA AREAL Testbed EPS and UE Power Quality Testing," in *AIAA Aviation*, Las Vegas, 2024.

[8] A. K. Rajput, "Simulation based measurement of three phase active, reactive and apparent power by Two Wattmeter Method with Labview," *Indian Journal of Engineering,* vol. 3, no. 7, pp. 49-51, 2013.