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NASA AREAL Testbed and UE Power Quality Testing

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A large number of electrified aircraft propulsion systems currently in development consist of high-voltage direct current (HVDC) power systems and utilization equipment (UE). There is a need for industry consensus standards and guidelines in order to support the development and verification of these rapidly maturing systems, user equipment, and associated technologies. To support the aforementioned need, the National Aeronautics and Space Administration (NASA) Revolutionary Vertical Lift Technology (RVLT) Project is performing ongoing power quality testing on HVDC power systems and associated UE. The testing described in this paper describes the UE testing completed to date in the NASA Advanced Reconfigurable Electrified Aircraft Lab (AREAL).

I. Nomenclature

A	=	amperes
AC	=	alternating current
DC	=	direct current
dV/dt	=	change in voltage divided by the change in time
Hz	=	hertz, a unit of frequency in cycles per second
HVDC	=	high voltage direct current
Id (A)	=	motor direct-axis current
Idc (A)	=	DC current
Iq (A)	=	motor quadrature-axis current
kHz	=	kilohertz
kW	=	kilowatts or 1,000 watts (W), the amount of power a load uses
ms	=	millisecond
Nm	=	newton-meters, a unit of torque; the force acting on a lever arm
NOx	=	nitric oxide (NO) and nitrogen dioxide (NO_2), air pollutants
RPM	=	revolutions per minute, a unit of speed
Vdc	=	volts direct current
Vrms	=	root mean square voltage; measure of the average voltage of the root mean of a sine wave voltage

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II. Introduction

The increasing demand for air travel [1] has motivated international government and industry to investigate alternative means for air transportation. Electrified aircraft have the potential to satiate this need and are envisioned as the future of aviation because they can potentially reduce noise, NO_x emissions, maintenance costs, and fuel consumption [2]. These aircraft have gained significant traction over the last few years and are maturing at a rate that surpasses the development of the corresponding minimum performance standards and verification methods for the vehicles and their sub-systems.

The development of industry consensus power standards is aimed at increasing the safety, robustness, and reliability of electrified aircraft HVDC power systems. Standards regarding power quality, electromagnetic compatibility, and many more will play a major role in driving equipment providers, integrators, and airframers towards robust and reliable solutions. It is imperative to provide performance limits, verification guidelines, and test guidelines to define and test the operational boundaries for propulsion system sources and loads.

To address the need for standards and best test practices, the National Aeronautics and Space Administration (NASA) Revolutionary Vertical Lift Technology Project (RVLT) developed and built the Advanced Reconfigurable Electrified Aircraft Lab (AREAL) with electrical components and configurations that resemble electrified aircraft propulsion systems [3]. This approach provides hardware data that can be used to support the development of industry consensus standards regarding power system integration and power quality.

Existing power quality standards and specifications [4][5][6] have historically defined performance at the interface between the electrical power system (EPS) and the utilization equipment (UE), where UE refers to any piece of equipment that utilizes electric energy for electronic, electromechanical, chemical, heating, lighting, or similar purposes [7]. The location of this interface for a generic system is shown in Fig. 1. The definition of performance and verification requirements at the aforementioned location for normal, abnormal, and emergency operating conditions is convenient and beneficial for several reasons. The first is that it allows for early and independent testing of the EPS and UE. Second, reliability of the integrated system is improved as component failures are inherently reduced by defining operational boundaries, stability metrics, and proper fault recovery. Lastly, a properly defined power standard and/or specification can act as a guide to lower-level standards involving components, cables, connectors, and more.

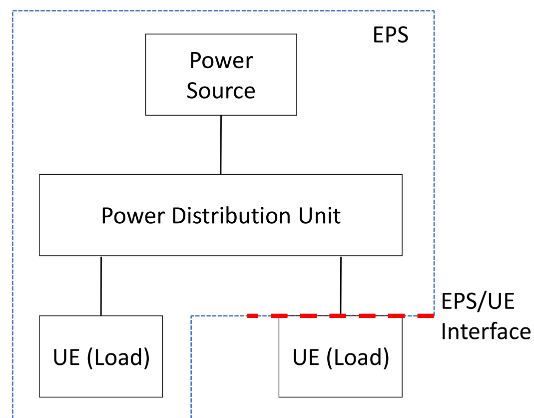

Fig. 1 Generic EPS/UE Interface Location.

The two most common types of UE on electrified aircraft HVDC power systems are inverters (feeding motors) and DC-to-DC converters. The intent of this paper is to cover several of the UE tests conducted on the AREAL testbed, with the UE under test being a 100 kW class inverter feeding an approximately 60 kW rated motor. UE testing was conducted with multiple configurations at 325 Vdc. The test results will be evaluated against draft internal UE performance limits, with additional commentary on the proposed test configurations and associated methods.

III. AREAL Testbed

A. Background

The AREAL testbed is a 200 kW electrified aircraft testbed that can operate at DC voltages from 300 Vdc to 1000 Vdc [3]. The testbed was designed to be reconfigurable, such that it can be used to conduct tests on multiple component configurations, aircraft architectures, and power levels. The diagram shown in Fig. 2 shows a hypothetical AREAL HVDC propulsion system configuration. Facility power enters the system starting with the source supplies, which are D&V Electronic's DC Emulators (DCEs), at the top of the diagram. The DCEs convert the AC facility power to a commanded voltage. Then, a main bus switching unit (MBSU) distributes that power onto two separate electrical branch circuts while also protecting those branch circuits. Power then flows to either a physical motor drive stand with permanent magnet (PM) axial flux motor and dynamometer or to a D&V Electronics Electric Motor Emulator (EME). Power is recirculatd on the AC facility bus to allow full control of the DC research bus and to eliminate the need for costly load banks.

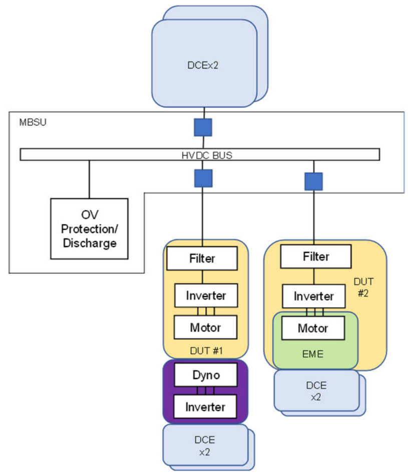

Fig. 2 Hypothetical AREAL Multi-String Configuration.

AREAL can operate in both nominal and off-nominal conditions. Steady-state and dynamic performance data can be captured within the nominal operating envelope of an electrified aircraft concept architecture. Off-nominal power system operations can also be captured by using custom-built failure inducing equipment, such as the bolted and high-impedance fault injection units. The motor emulator offers the capability of inducing failures to a motor, such as winding shorts, without damaging actual motor hardware. Off-nominal tests that involve short-circuiting the motor, for example, stress the inverter components, thus creating an environment that can be used to evaluate the inverter's ability to manage motor failures. Tests like these are also critical to determining power quality specifications.

B. UE General Test Configurations

AREAL was configured to perform normal and abnormal (faulted) UE power quality testing via two separate general test configurations at a nominal 325 Vdc. The first configuration, as shown in Fig. 3, utilizes the EME to emulate an existing PM machine. As a note, the emulated motor implemented on the EME for this paper was input using the manufacturer's generic model; a more advanced model is available using flux-table inputs, however, that information was not readily available to the test team. The second configuration, as shown in Fig. 5, implements the actual PM machine on a drive stand. The physical configuration data can and is used to validate the emulated configuration for future testing. Each configuration contains a source DCE, which provides a commanded steady-state or transient voltage to the UE. The distances between the source DCE and the UE input are approximately 20 feet and 30 feet respectively for the emulated and physical configurations. The UE under test for both configurations consist of a custom input filter feeding a ~100 kW and ~700 Vdc class inverter (operating via torque-control) which then drives a ~60 kW class PM machine (operating at a commanded speed). A schematic of the UE is shown in Fig. 4. A brake module and braking resistor were present in setups in the case of an overvoltage. In the case of the emulated configuration, the EME regenerates to the facility DCE. In the case of the physical configuration, the motor under test drives an identical machine which regenerates through an inverter to the facility DCE.

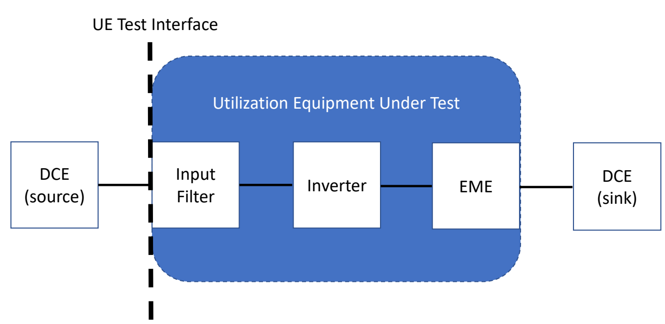

Fig. 3 Diagram for UE EME Testing.

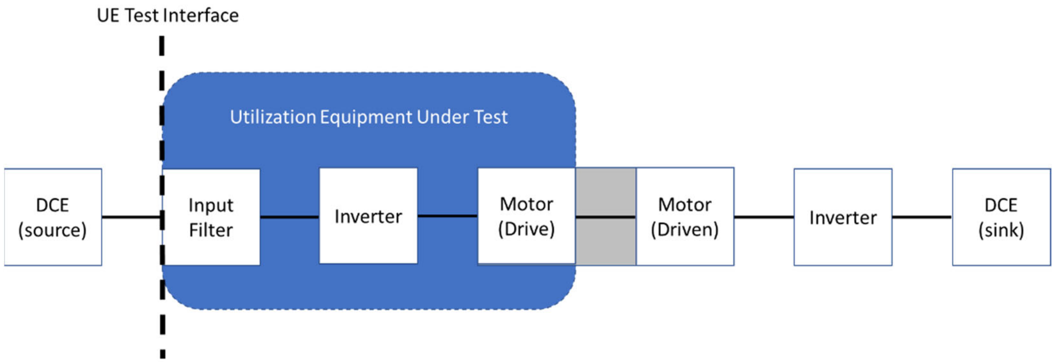

Fig. 5 Diagram for UE Drivestand Testing.

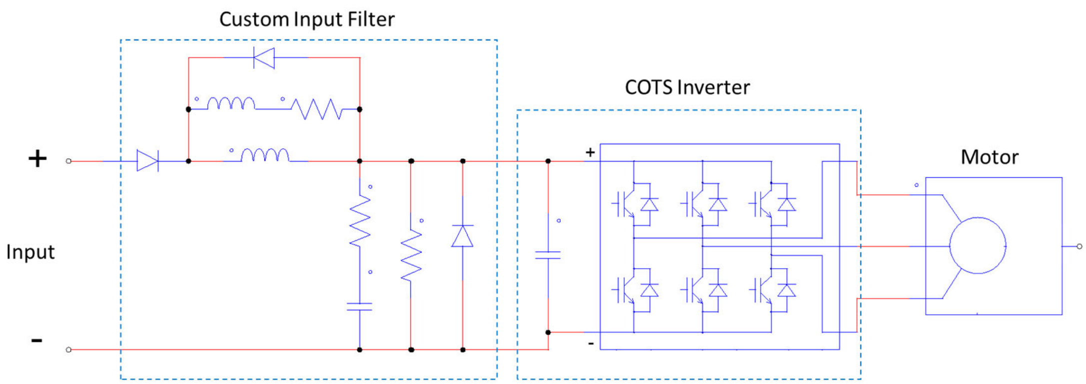

Fig. 4 UE Electrical Schematic.

IV. UE Power Quality Testing

UE power quality testing was performed on the general emulated and physical configurations shown in Fig. 2 and Fig. 3, at a nominal voltage of 325 Vdc. The types of power quality tests covered in this paper are shown in Table 1. Testing was performed using the emulated configuration first, with the physical configuration being tested at a later date. While comprehensive testing was performed with respect to power quality testing and the number of test points, for the purpose of brevity a limited set of data is presented.

Table 1 List of UE Tests.

UE Tests	Normal/Abnormal Operation
Steady State Operation	Normal
Line Step Transient Voltage	Normal
Input Impedance	Normal
Ripple Voltage Spectrum	Normal
Overvoltage Surge	Abnormal
Undervoltage Surge	Abnormal

A. Steady-State

Definition of a steady-state voltage requirement establishes an expected voltage range both for the EPS and the UE. The operating range should include expected voltage swings throughout the system, which includes varying source output and losses throughout the EPS. The range provided in Table 2 represents a hypothetical range that a battery fed EPS would provide to a general UE.

Table 2 Steady-State Voltage Limits for 325 Vdc Nominal Input Voltage.

Characteristic	Low	High
Steady-State Voltage	250	370

Performance was evaluated and documented across several loading levels, at various speeds and torques, and at the high, nominal, and low input voltages as seen in Tables 3 through 5. The UE passed if it operated as expected at the input voltage test point, and failed if it did not. The specific test configurations were of those shown in Fig. 2 and Fig. 3, where the source DCE was commanded to the high, nominal, and low voltages of the requirement.

Table 3 Steady-State Test Data for 370 Vdc Input.

UE Motor	Bus Voltage	Speed (RPM)	Torque (Nm)	Field-Weakening	Mod. Index	Id (A)	Iq (A)	Idc (A)	Pass/ Fail
Emulated	370V	839	17	No	0.32	0	22.10	4.63	Pass
Emulated	370V	1678	112	No	0.66	0	146.2	58.20	Pass
Emulated	370V	2517	51	No	0.89	0	66.60	37.96	Pass
Physical	370V	839	17	No	0.32	0	22.10	4.43	Pass
Physical	370V	1678	112	No	0.64	0	146.4	55.1	Pass
Physical	370V	2517	51	No	0.84	0	66.5	34.8	Pass

Table 4 Steady-State Test Data for 325 Vdc Input.

UE Motor	Bus Voltage	Speed (RPM)	Torque (Nm)	Field-Weakening	Mod. Index	Id (A)	Iq (A)	Idc (A)	Pass/ Fail
Emulated	325	839	17	No	0.37	0	22.10	5.16	Pass
Emulated	325	1678	112	No	0.76	0	146.0	66.62	Pass
Emulated	325	2517	51	No	1.00	0	66.70	43.75	Pass
Physical	325	839	17	No	0.36	0	22.10	4.92	Pass
Physical	325	1678	112	No	0.72	0	146.3	62.4	Pass
Physical	325	2517	51	No	0.96	0	66.5	40.2	Pass

Table 5 Steady-State Test Data for 250 Vdc Input.

UE Motor	Bus Voltage	Speed (RPM)	Torque (Nm)	Field-Weakening	Mod. Index	Id (A)	Iq (A)	Idc (A)	Pass/ Fail
Emulated	250	839	17	No	0.45	0	22.10	6.67	Pass
Emulated	250	1678	112	No	0.98	0	146.5	88.11	Pass
Emulated	250	2517	51	Yes	1.10	-57.2	66.30	67.42	Pass
Physical	250	839	17	No	0.44	0	22.10	6.15	Pass
Physical	250	1678	112	No	0.92	0	146.4	81.0	Pass
Physical	250	2517	51	Yes	1.10	-35.0	66.5	56.7	Pass

The emulated and physical configuration performances were well matched, with the exception of the 2517 RPM and 51 Nm operating points at 250 Vdc. The discrepancy in Id is thought to be due non-linearity differences between the physical motor and the emulated model inputs. Improvements are thought to be possible if the flux-table inputs of the EME were utilized moving forward.

Inverter torque regulation was not negatively affected by any of the DC voltage setpoints required by the steady-state performance test matrix. However, the maximum torque setpoint which the inverter is able to regulate is related to the DC voltage of the inverter and speed of the motor. As the DC voltage of the inverter drops, the maximum torque the inverter can produce is reduced. This is due to an inverse relationship between motor speed and torque once the inverter enters the field-weakening region. When this occurs, the inverter transfers over from a constant-torque region to a constant-power region (of the motor). In this region, higher motor speeds result in a reduction of available torque. Also, once the inverter enters the field-weakening portion of the algorithm, there is a limited amount of flux weakening (implemented by an Id command in the field-oriented control algorithm) that can be applied before torque regulation is not able to be maintained.

B. Line-Step Transient

Definition of a line-step transient requirement establishes normal operating magnitude and durations at the input to the UE. The upper and lower limits contained within this requirement should envelop transients seen at the UE interface due to upstream switching in loads, busses, and/or source(s). The limits in Fig. 6 represents a hypothetical range that a battery fed EPS would provide to a general UE on a nominal 325 Vdc bus. Rise and fall rate requirements were not defined when the tests were conducted.

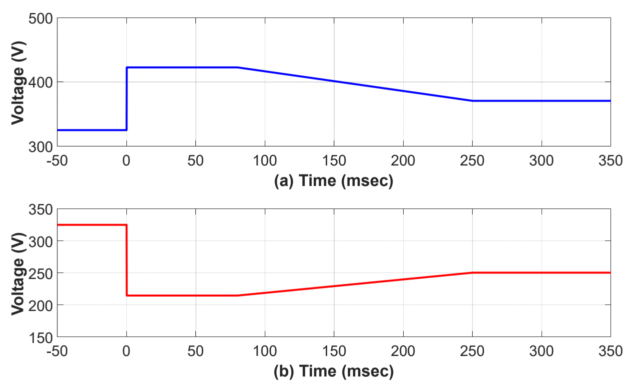

Fig. 6 Line-Step Transient (a) Upper and (b) Low Verification Limits.

Performance was evaluated and documented across several loading levels, at various speeds and torques, as shown in Table 6. The UE passed if it maintained stable operation and recovered to the expected performance after the transient, and failed if either of those conditions were not met. Success criteria will vary by UE and application, so it is recommended that UE controlling documents designate what successful performance entails. The specific test configurations were of those shown in Fig. 2 and Fig. 3.

Table 6 Line-Step Transient Test Data

UE Motor	Line-Step Test	Speed (RPM)	Torque (Nm)	Pass/Fail
Emulated	Up	839	17	Pass
Emulated	Up	1678	112	Pass
Emulated	Up	2517	51	Pass
Physical	Up	839	17	Pass
Physical	Up	1678	112	Pass
Physical	Up	2517	51	Pass
Emulated	Down	839	17	Pass
Emulated	Down	1678	112	Pass
Emulated	Down	2517	51	Pass
Physical	Down	839	17	Pass
Physical	Down	1678	112	Pass
Physical	Down	2517	51	Pass

The line-step up and line-step down input data is provided for both the emulated and physical configurations in Fig. 7 through Fig. 10 respectively. The post-transient inverter torque regulation was not negatively affected by any of the line-step transient voltage injection profiles, as observed by the operators. The input data demonstrates a stable ride through (from the viewpoint of an EPS) at the input of the UE, which resulted in a pass for all verification tests.

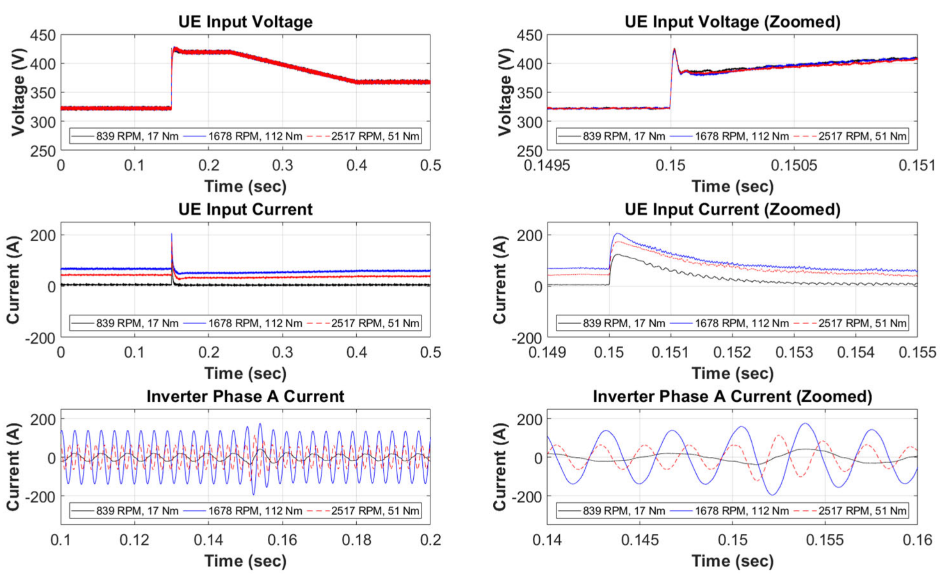

Fig. 7 Line-Step Up Transient Data for Emulated Configuration.

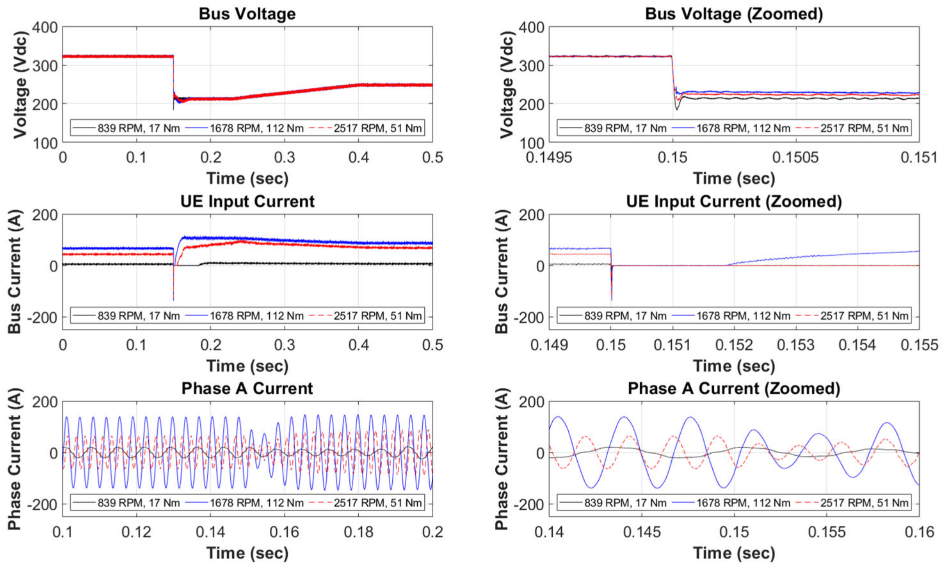

Fig. 8 Line-Step Down Transient Data for Emulated Configuration.

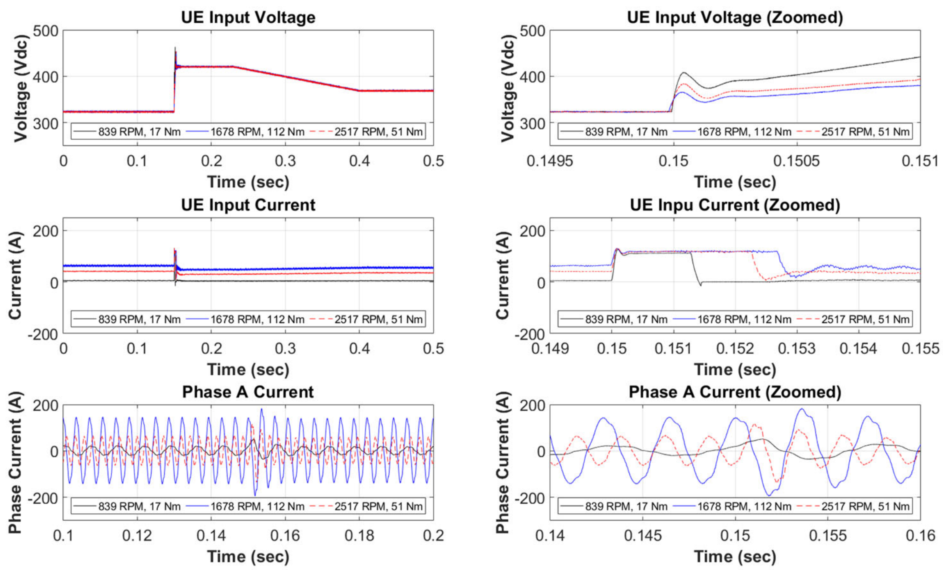

Fig. 9 Line-Step Up Transient Data for Drivestand.

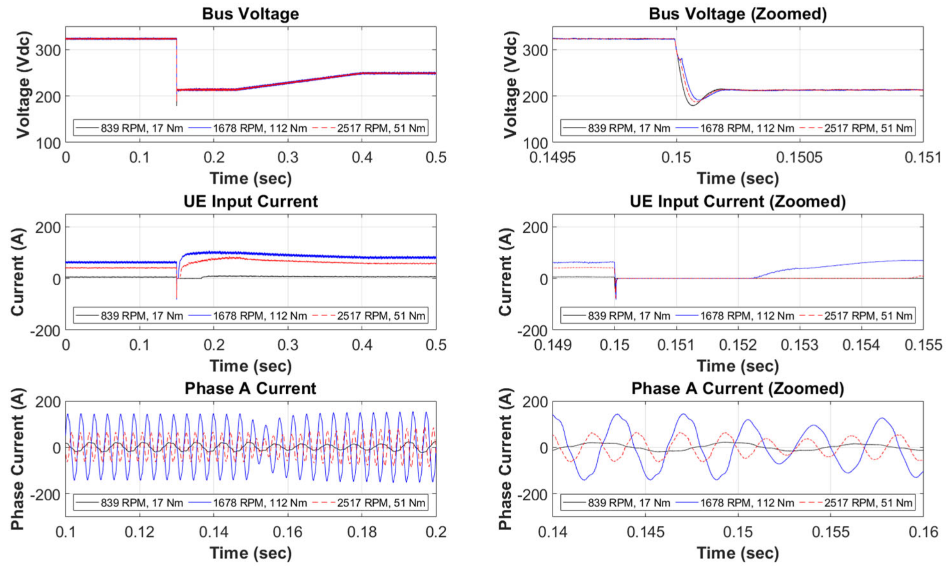

Fig. 10 Line-Step Down Transient Data for Drivestand.

With respect to the line-step down transients, it is noted the maximum torque setpoint which the inverter is able to regulate is related to the DC voltage magnitude of the inverter and speed of the motor. As the DC voltage of the inverter drops, the maximum torque the inverter can produce is temporarily reduced. This is due to an inverse relationship between motor speed and torque once the inverter enters the field-weakening region. When this occurs, the inverter transfers over from a constant-torque region to a constant-power region (of the motor). In this region, higher motor speeds result in a reduction of available torque. Also, once the inverter enters the field-weakening portion of the algorithm, there is a limited amount of flux-weakening (implemented by an Id command in the field-oriented control algorithm) that can be applied before torque regulation is not able to be maintained. Based on these dynamic effects, it is recommended that designers and integrators pay special attention to operational limits when designing/sizing inverters motors and de-rate per the application, especially if operational performance constraints are not entirely known.

C. Input Impedance

Definition of an input impedance requirement is one possible way of providing a metric to evaluate stability for an integrated system. This requirement should be developed in concert with a source requirement for the EPS. While no input impedance limit was formulated for the UE under test in the case of this paper, the custom input filter integrated with the commercial-off-the-shelf inverter was designed to minimize any oscillatory behavior with a number of generic EPSs.

While no requirement was derived for the UE under test, the UE impedances were characterized from 1 Hz to 150 kHz using modified setups to those shown in Fig. 3 and Fig. 4. These setups integrate an impedance analyzer to perturb the output voltage of the DCE across the frequency range of interest, which is generically shown in Fig. 11. The input voltage and input current to the UE is then fed back to the impedance analyzer, which then calculates the impedance of the UE on a per frequency basis.

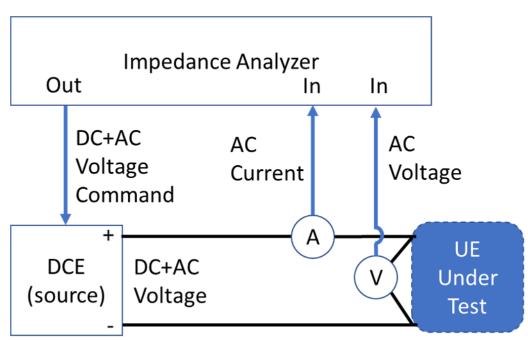

Fig. 11 AC Injection Configuration for Physical and Emulated Input Impedance Testing.

The input impedance *Z* of the UE measured a nominal voltage of 325 Vdc, along with the high and low voltages listed in Table 2. The corresponding torque-speed operating points for those voltages are identical to the test points listed in Tables 3 through 5 for line-step transient testing. Results are shown in Fig. 12 through Fig. 14 below. For all test cases, it was observed that as loading was increased, the magnitude curves trended downward at low frequency for each suite of curves. Analytically this is justified through Ohm's Law, such that the $Z = V/I$, and as I increases (at low frequency approaching DC), Z decreases proportionally. The phase trends to -180 degrees at lower frequencies due to the constant power load effect. At mid-band frequencies of 100 Hz to 1000 Hz, it was noted that for a fixed torque and voltage, the magnitude curves decrease and phase curves increase with increases in motor speed. On the other hand, as speed and voltage were held constant with varying torque, no appreciable trend was observed. This may be due to the fact that the inverter was operating in torque-mode, and additional studies are required on impedance trends when the inverter is operating in speed mode moving forward. The results differ slightly but remain consistent at each operating voltage. The results of the input impedance sweeps remained similar at frequencies over 500 Hz regardless of the applied speed and torque load. The impedance reaches a minimum at 500-600 mΩ around 2-3 kHz due to the damping effect of the input filter. Above ~2-3 kHz, the input inductor of the filter dominates the response. Degraded performance of the inductor is seen at higher load due to non-linear effects, although a respectable impedance of great than 10 Ω is seen at 100 kHz worst-case. This should aide in prevention of source-load stability issues for systems with regulated sources. Comparing the emulated configuration impedances to the physical configuration impedances, magnitudes were in good agreement. Slight differences can somewhat be explained via input filter component variations, with the emulated configuration having slightly better damping. Phase plots were in excellent agreement. No appreciable differences were identified with variations across input voltages, emulated or physical configurations.

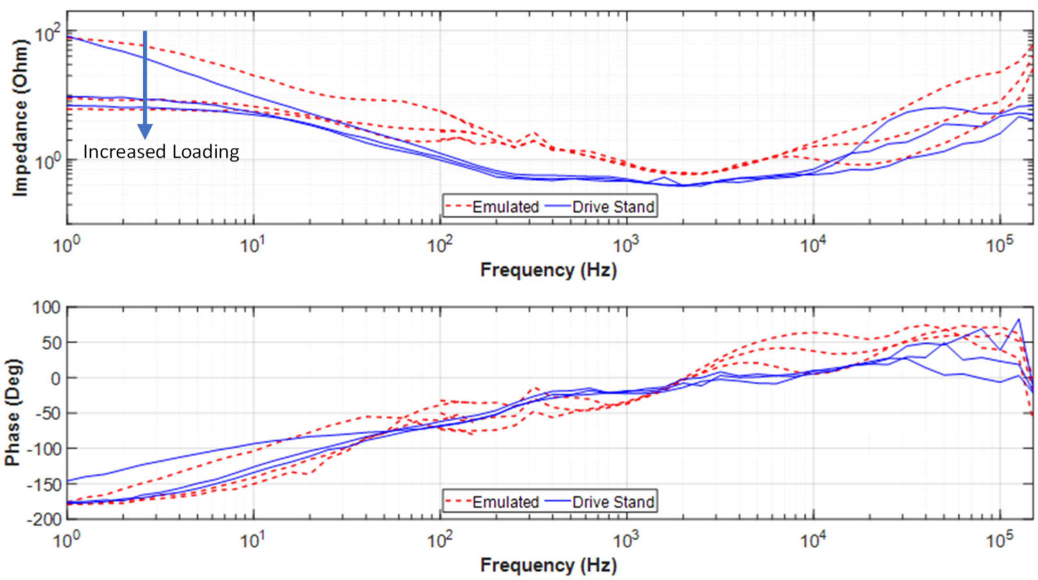

Fig. 12 370 V Input Impedance Results. Magnitude (Top) and Phase (Bottom).

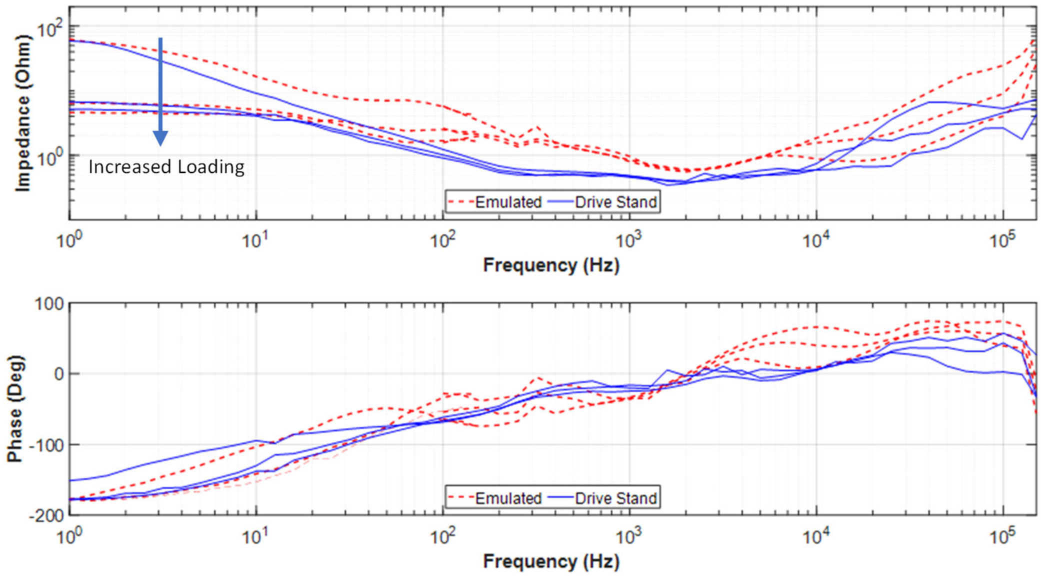

Fig. 13 325 V Input Impedance Results. Magnitude (Top) and Phase (Bottom).

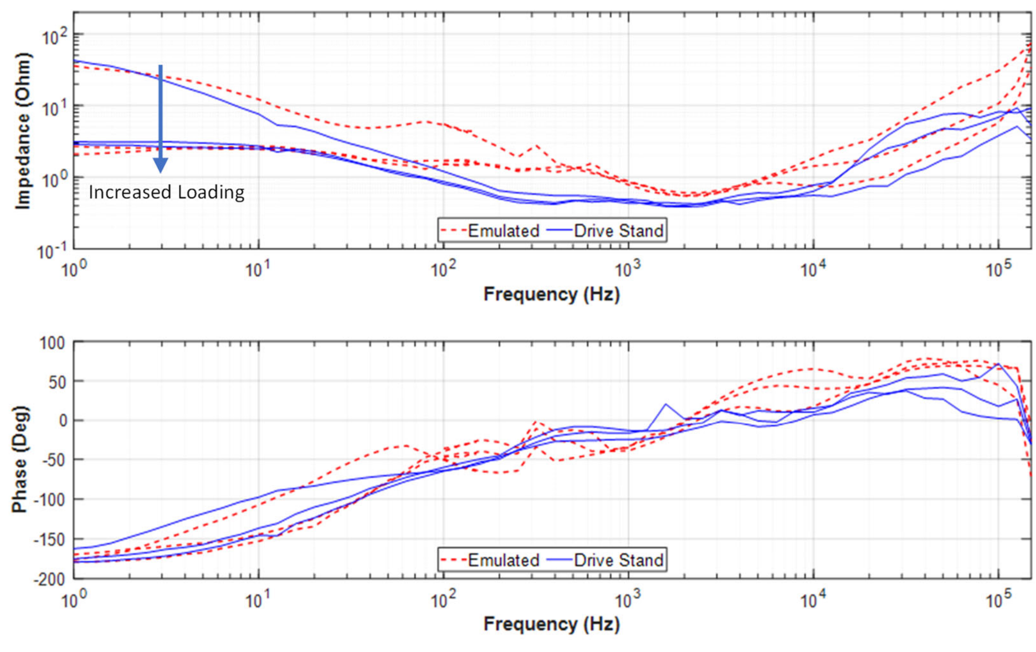

Fig. 14 250 V Input Impedance Results. Magnitude (Top) and Phase (Bottom).

Historical input impedance tests requirements such as [6], have required measurements be conducted from 30 Hz to 100 kHz. The lower frequency range is typically established due to test limitations of injection transformers used in an alternative test [8][9]. Due to constant power effects (which can be destabilizing to a power system) being observed down to 1 Hz, and many electromagnetic compatibility measurements being started at 150 kHz, it is recommended that future tests expand the input impedance measurement range from 1 Hz to 150 kHz. To minimize cost impacts for test facilities that do not currently have high power- and/or high- bandwidth amplifiers, one possible test alternative can utilize a mix of a DC power supply and a standard transformer injection type method. The DC power supply can be perturbed from frequencies from 1 Hz up to 30 Hz, and the instrument transformer can be used to perturb the load at the higher frequencies. This alternative setup and test strategy can be visualized in Fig. 15 and Fig. 16 respectively.

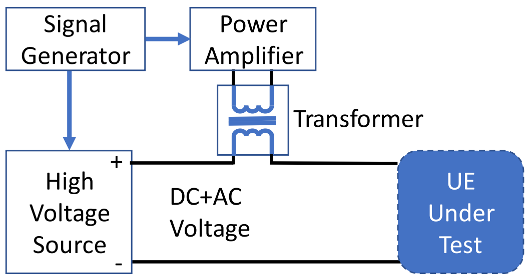

Fig. 15 Alternate Test Strategy to Inject AC Ripple (Impedance Analyzer and corresponding measurements not shown).

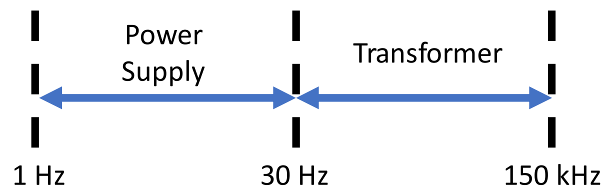

Fig. 16 Test Range of Power Supply or Power Amplifier versus Injection Transformer.

D. Ripple Voltage Spectrum

Definition of a ripple-voltage spectrum requirement should establish a worst-case spectrum susceptibility requirement; this requirement should provide a worst-case envelope of the upstream ripple contributions of source(s) and parallel loads that a UE would be susceptible to. The spectrum in Fig. 17 represents a hypothetical range that a battery fed EPS would provide to a general UE based on a nominal 325 Vdc input, along with the test points which were able to be conducted in AREAL. These test points are also defined in Table 7. While it is recommended, based on the results of the input impedance tests that the ripple voltage spectrum definition be lowered down to 1 Hz, the analysis and conclusions for that recommendation were not available at the time the spectrum identified for testing was defined.

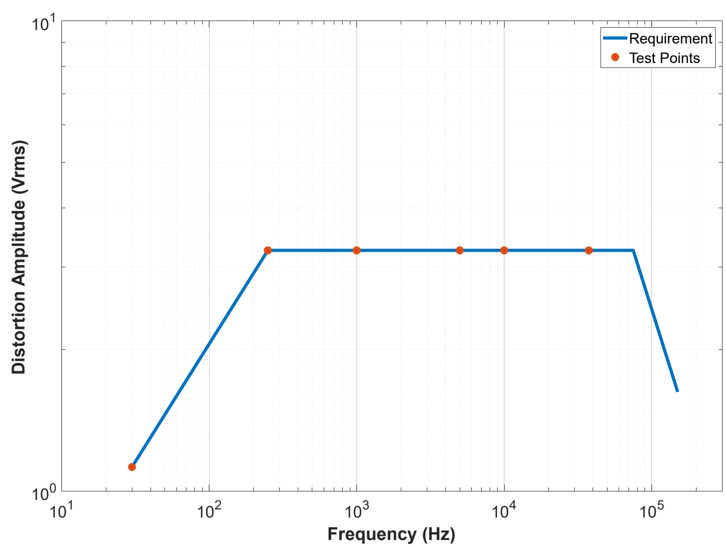

Fig. 17 Ripple Voltage Spectrum Requirement for 325 Vdc Bus.

Table 7 Ripple Test Points for Emulated and Physical Configurations.

Frequency (Hz)	Distortion Amplitude (Vrms)
30	1.13
250	3.25
1000	3.25
5000	3.25
10000	3.25
37500	3.25

Performance was arbitrarily evaluated and documented at loading levels of approximately 15% and 85% of rated power at 325 Vdc. These operating points are shown in Table 8. The UE passed if it maintained stable operation when subjected to the defined input ripple and failed if that condition not met. Success criteria will vary by UE and application, so it is recommended that UE controlling documents designate what successful performance entails. The specific test configurations were the same as those shown in Fig. 2 and Fig. 3, with the exception that the DCE was commanded to provide the required AC ripple superimposed on top of its DC output. Frequencies above 37.5 kHz were not feasible with the existing test setups due to hardware limitations.

Table 8 Motor Operating Points.

Speed (RPM)	Torque (Nm)
831	51
2517	95

The test results for the emulated and physical configurations are shown in Table 9. The UE in both test configurations operated without degraded performance, regardless of the injected input AC voltages. Effects relative to overheating of the input filter components were not observed, although future work can evaluate the effects of ripple relative to overall reliability ratings.

Table 9 Ripple Spectrum Test Results at 325 Vdc.

UE Motor	Speed (RPM)	Torque (Nm)	Frequency	Injection (Vrms)	Pass/Fail
Emulated	839	51	30 Hz	1.13	Pass
Emulated	2517	95	30 Hz	1.13	Pass
Emulated	839	51	250 Hz	3.25	Pass
Emulated	2517	95	250 Hz	3.25	Pass
Emulated	839	51	1 kHz	3.25	Pass
Emulated	2517	95	1 kHz	3.25	Pass
Emulated	839	51	5 kHz	3.25	Pass
Emulated	2517	95	5 kHz	3.25	Pass
Emulated	839	51	10 kHz	3.25	Pass
Emulated	2517	95	10 kHz	3.25	Pass
Emulated	839	51	37.5 kHz	3.25	Pass
Emulated	2517	95	37.5 kHz	3.25	Pass
Physical	839	51	30 Hz	1.13	Pass
Physical	2517	95	30 Hz	1.13	Pass

Physical	839	51	250 Hz	3.25	Pass
Physical	2517	95	250 Hz	3.25	Pass
Physical	839	51	1 kHz	3.25	Pass
Physical	2517	95	1 kHz	3.25	Pass
Physical	839	51	5 kHz	3.25	Pass
Physical	2517	95	5 kHz	3.25	Pass
Physical	839	51	10 kHz	3.25	Pass
Physical	2517	95	10 kHz	3.25	Pass
Physical	839	51	37.5 kHz	3.25	Pass
Physical	2517	95	37.5 kHz	3.25	Pass

Due to the limitations in the abilities of the test setups to test the entire range of the susceptibility limits, future work is planned to improve these setups. The alternative test setups described for input impedance measurements, as seen in Fig. 15 and Fig. 16, can be used to inject high quality AC ripple across the entire frequency range of interest. The recommended future test range and ripple spectrum definition is 1 Hz to 150 kHz.

E. Overvoltage/Undervoltage Surge

Definition of an overvoltage/undervoltage requirement establishes a worst-case envelope of input voltage that a UE may experience in the event of an upstream failure, fault, or malfunction within the EPS. The limits in Fig. 18 represent worst-case overvoltages and undervoltages a UE may see on a hypothetical 325 Vdc battery-fed EPS. Rise and fall rate requirements were not defined when the tests were conducted.

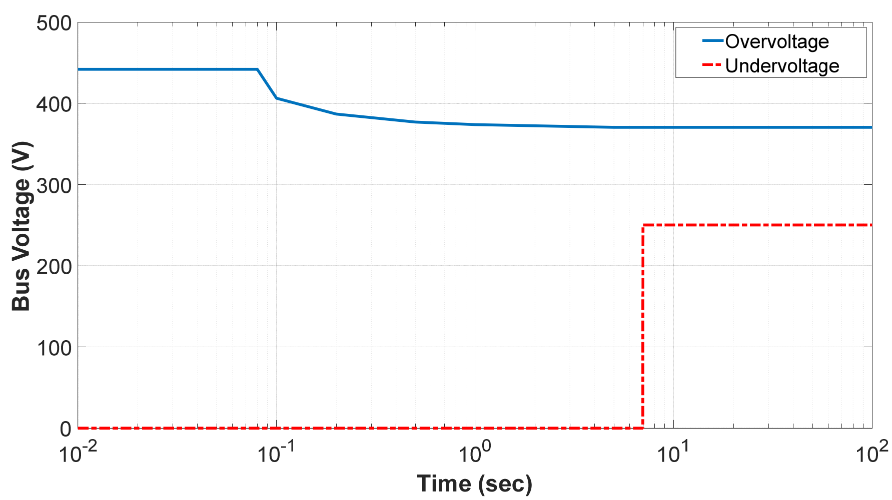

Fig. 18 Overvoltage/Undervoltage Surge Requirement for 325 Vdc Bus.

Performance was evaluated and documented across several loading levels, at various speeds and torques, as shown in

Table 10. The UE passed if it was not damaged and was able to maintain operation or restart operation after the transient. The UE failed if either of those conditions were not met. Success criteria will vary by UE and application, so it is recommended that UE controlling documents designate what successful performance entails. The specific test configurations were of those shown in Fig. 2 and Fig. 3. It is noted that the inverter undervoltage lockout setting was set to 50 V.

Table 10 Overvoltage/Undervoltage Test Points Success Evaluation.

UE Motor	Surge Test	Speed (RPM)	Torque (Nm)	Pass/Fail
Emulated	Overvoltage	839	17	Pass
Emulated	Overvoltage	1678	112	Pass
Emulated	Overvoltage	2517	51	Pass
Physical	Overvoltage	839	17	Pass
Physical	Overvoltage	1678	112	Pass
Physical	Overvoltage	2517	51	Pass
Emulated	Undervoltage	839	17	Pass
Emulated	Undervoltage	1678	112	Pass
Emulated	Undervoltage	2517	51	Pass
Physical	Undervoltage	839	17	Pass
Physical	Undervoltage	1678	112	Pass
Physical	Undervoltage	2517	51	Pass

The overvoltage test results are shown in Fig. 19 and Fig. 20 for the emulated and physical test configurations respectively. While there was slight variation in the short-term transients (<3 ms), overall performance matched well between emulated and physical configurations. In both test configurations and across all tests, the respective UE rode-through the overvoltage event without tripping. Operation was well maintained during and after the overvoltage event. No damage or issues with the UE post testing was observed, so the tests were considered a success.

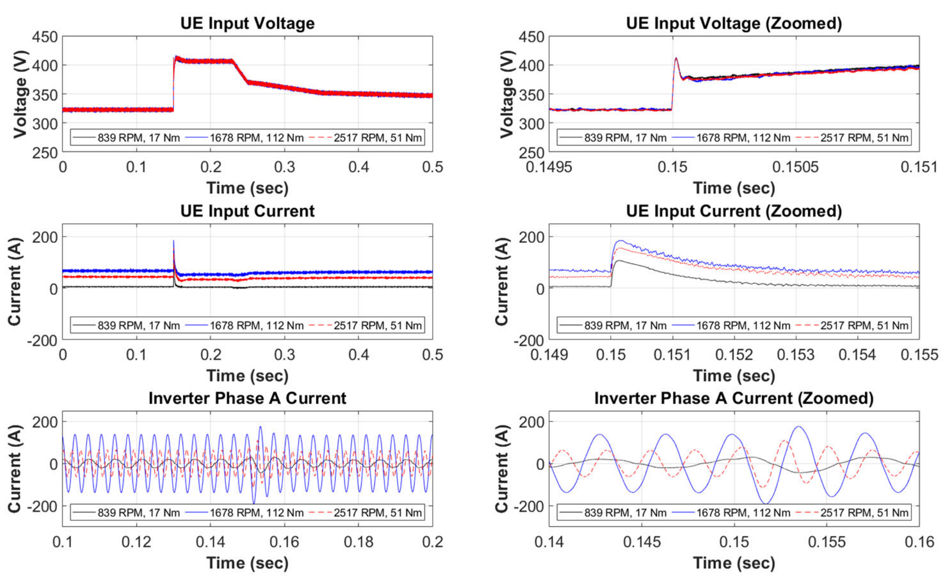

Fig. 19 Overvoltage Transient Data for Emulated Configuration.

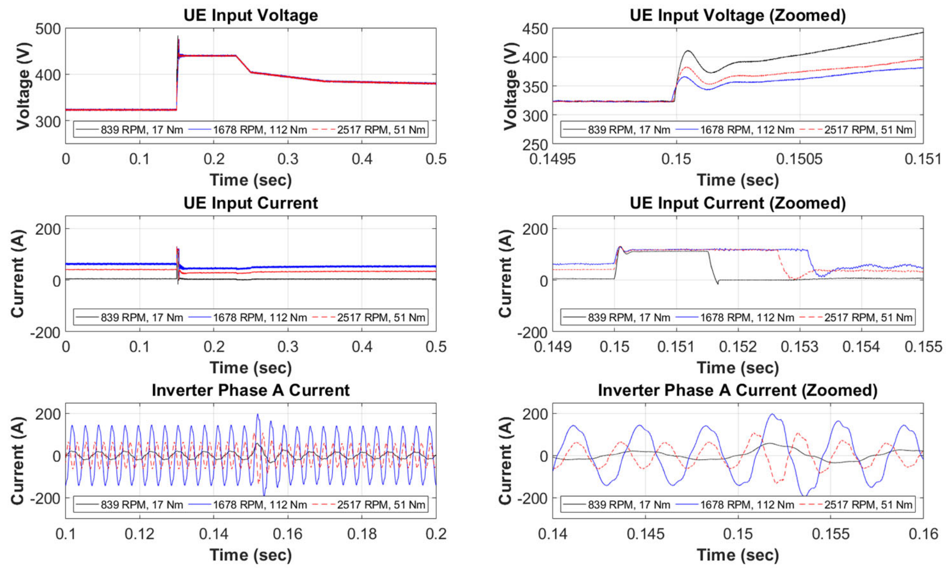

Fig. 21 Overvoltage Transient Data for Drivestand Configuration.

The undervoltage test results are shown in Fig. 21 and Fig. 22 for the emulated and physical test configurations respectively. While there was slight variation in the transient performance, the overall matching was good. In both test configurations and across all tests, once the UE input voltage dropped below 50 V, the inverter dropped out. Test means were not available to quantify the exact timing of the dropout relative to the event. It is noted that the UE was able to be restarted and regain functionality and control for both respective configurations and across all respective operating points after the undervoltage event. No damage or issues with the UE post testing was observed, so the tests were considered a success.

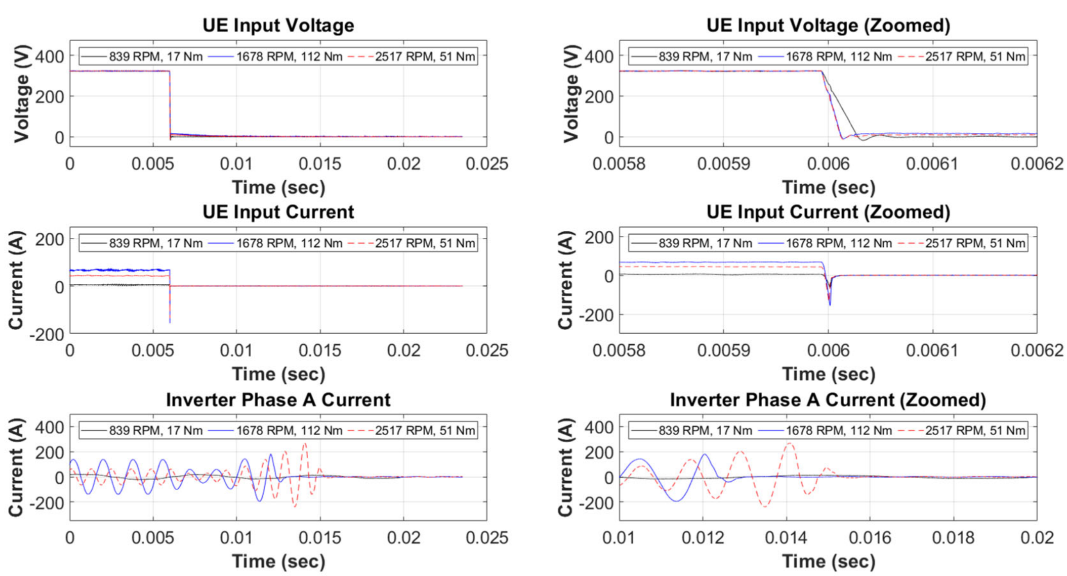

Fig. 20 Undervoltage Transient Data for Emulated Configuration.

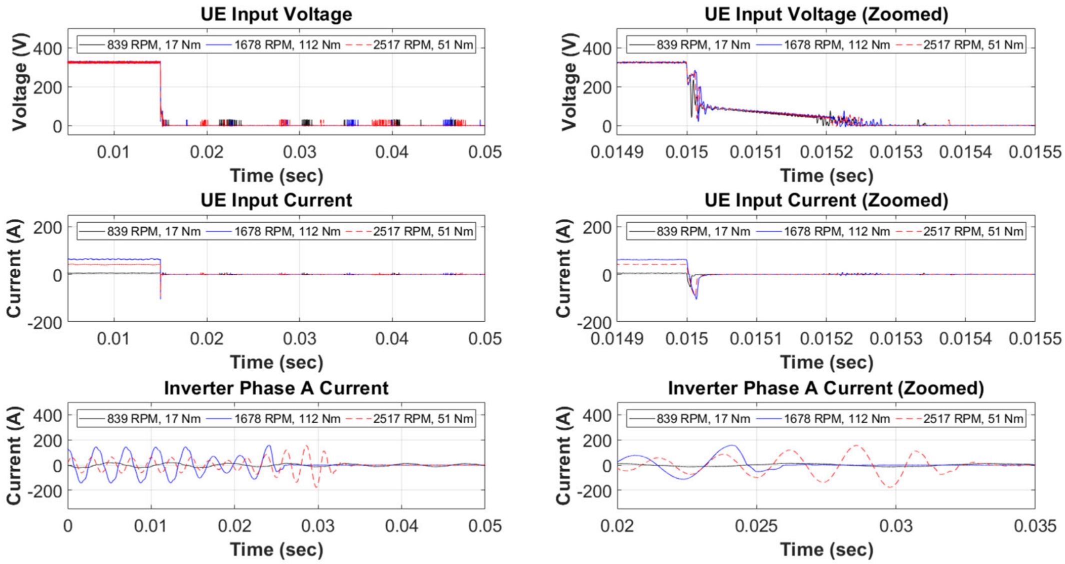

Fig. 22 Undervoltage Transient Data for Drivestand Configuration.

One alternative test setup for test facilities that lack high voltage, high bandwidth power supplies is shown in Fig. 22. In this test configuration, the high voltage source is providing power at the UE under test, with switch *S1* closed and switch *S2* open. *S1* is then opened while *S2* closes into a controlled impedance (or short) which meets the required dV/dt requirements of the test. A general rule of thumb is to synchronize the opening and closing of *S1* and *S2* within 10µs of one another. Timing requirements will need to be analyzed along with freewheeling diode and transient voltage suppression needs and performances however.

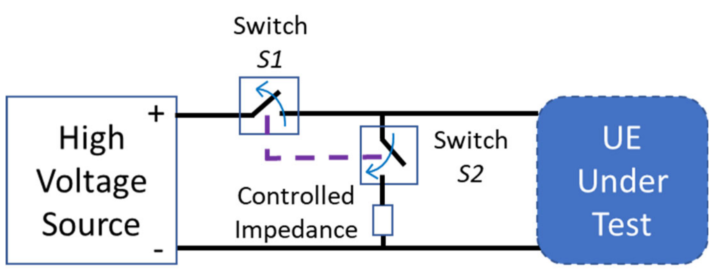

Fig. 23 Alternative Test Setup for Undervoltage Surge Testing. Freewheeling diodes and transient voltage suppression means not shown.

V. Conclusion

The development of standards and best test practices will be a crucial component in guaranteeing safe and reliable electrified aircraft. The NASA AREAL was configured to conduct UE testing for a variety of standard power quality tests, with the goal to inform future standards and test related documents. Results were provided for both emulated and physical UE, with additional commentary regarding specifics to analysis and testing. Future work will be performed to expand test results to requirements related to inrush/surge, large-signal stability, EPS testing, and integrated system testing. Transient voltage test rates will also be investigated for transient tests.

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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] David J. Sadey, Linda Taylor, Patrick Hanlon, Keith Hunker, Casey Theman, Xavier Collazo-Fernandez, Nuha S. Nawash, Trey Rupp, Brian Malone, Henry Fain, Greg Kimnach, Paul Nowak, Mark Valco, Timothy Dever and Alan Revilock. "NASA Advanced Reconfigurable Electrified Aircraft Laboratory (AREAL)," AIAA 2023-3991. AIAA AVIATION 2023 Forum. June 2023.

[4] Department of Defense Interface Standard MIL-STD-704, Aircraft Electric Power Characteristics, Revision F (DOD, 12 March 2004).

[5] Department of Defense Performance Specification MIL-PRF-GCS600A(ARMY), Characteristics of 600 Volt DC Electrical Systems for Military Ground Vehicles, Baseline (DOD, 28 July 2010)

[6] SAE International Standard, "Space Power Standard," SAE Standard AS5698A, Rev. Sept. 2018.

[7] National Fire and Protection Agency Code NFPA 70, 2023 National Electric Code, (12 August 2022).

[8] Gray, M. (2019, December 10). Measuring the input and output impedance of power supplies (Part 1). *Venable Instruments*. Retrieved June 6, 2024, from https://www.venableinstruments.com/blog/measuring-input-and-output-impedance

[9] Gray, M. (2020, March 17). Measuring the input and output impedance of power supplies (Part 3). *Venable Instruments*. Retrieved June 6, 2024, from https://www.venableinstruments.com/blog/measuring-input-and-output-impedance-part3