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NASA AREAL Testbed High Voltage UE Power Quality Testing

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***Abstract*— This paper describes the testing related to high voltage DC power quality verification criteria for the National Aeronautics and Space Administration (NASA) Revolutionary Vertical Lift Technology (RVLT) Project. Verification of utilization equipment (UE) consisting of an input filter, inverter, and permanent magnet machine has been performed at a nominal voltage of 630Vdc using the NASA Advanced Reconfigurable Electrified Aircraft Lab (AREAL). Test results will be provided for draft verification criteria relative to both normal and abnormal inputs to the UE. Additionally, evaluation of results and commentary with respect to the test setups will be provided.**

Keywords—Power, Power Quality, High Voltage, Testing, Standards, Stability, Reliability

I. Introduction

To aid in the development of standards and best test practices for electrified aircraft, the National Aeronautics and Space Administration (NASA) Revolutionary Vertical Lift Technology Project (RVLT) repurposed an existing test cell to construct the Advanced Reconfigurable Electrified Aircraft Lab (AREAL). AREAL was developed with commercial-off-the-shelf components which could be reconfigured to investigate various electrified aircraft architectures and propulsion systems. Data obtained from associated system tests can be used to support the development of upcoming industry consensus standards, for example, the SAE AS7499 Aircraft High Voltage DC Power Quality Standard [1].

Overall development of standards for electrified aircraft drives the community towards safe, robust, and reliable solutions. With respect to high voltage power systems, standards-based requirements such as fault-detection, -response, and -recovery, system stability, and power quality play a major role in defining the robustness and reliability of the propulsion system. For these types of requirements, it is imperative to provide design guidelines and test strategies to define and test the operational boundaries for propulsion system sources and loads. The source, also known as electrical power system (EPS), and the load, also known as the utilization equipment (UE), must be evaluated for their compatibility in the electric propulsion system network.

In an effort to provide some backing data for validating standards-based requirements, operational boundaries, recommended test procedures and associated test methods, this paper discusses high voltage UE testing conducted on the AREAL testbed. UE testing was conducted and completed for normal and abnormal requirement sets with a nominal voltage consideration of 630Vdc. Evaluation of results and commentary with respect to the test setups is also provided.

II. AREAL Testbed

A. Background

The AREAL testbed is comprised of both emulated and real hardware, allowing for nominal 300 VDC to 1000 VDC and up to 200 kW operation [2]. The use of emulators allows the testbed to be reconfigurable, providing the opportunity to perform system tests on various electrified vertical take-off and landing (eVTOL) propulsion architectures at different power levels, in addition to investigation equipment performance and operation, such as motor and inverters. The AREAL can be configured to test integrated EPS performances, or stand-alone UE. The test bed utilizes high-bandwidth, bi-directional DC power supplies that can be connected in both series and parallel. The ability to series- and parallel-connect supplies enables the analysis of high-voltage direct current systems (HVDC), like those found in many electrified aircraft including eVTOL.

The diagram shown in Fig. 1 shows a generalized AREAL HVDC UE test configuration. Facility power enters the system with the source DC Emulator (DCE), which is a high-bandwidth bidirectional DC power supply. The DCEs convert the 480 VAC facility power to a commanded voltage. Power then flows to a physical motor drive stand with a motor which is coupled to a dynamometer. For general UE test configurations, AREAL can emulate normal and abnormal inputs to the UE under test at the UE test interface. Power is then recirculated from the dynamometer back through an inverter and sink DCE back onto the 480 VAC facility bus. This allows full control and isolation of the DC research bus and eliminates the need for costly load banks [2].

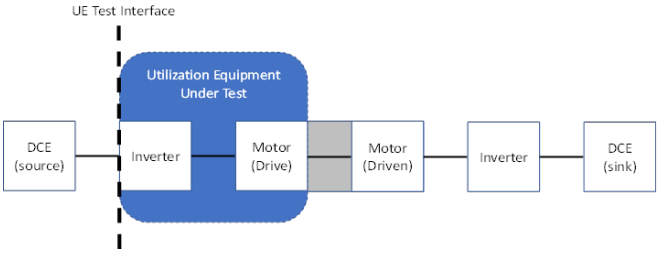


Fig. 1. Hypothetical AREAL Multi-String Configuration.

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 [3].

III. High Voltage UE Power Quality Testing

The work in this paper discusses power quality testing of an inverter fed motor as shown in Fig. 2 which also includes a custom front-end input filter as shown in Fig. 3. Testing was performed using AREAL's drive-stand configuration. The UE tests performed are listed in Table I, which includes testing under normal and abnormal (faulted) input conditions. While comprehensive testing was performed with respect to power quality at a number of test points, for the purpose of brevity a limited set of data is presented.

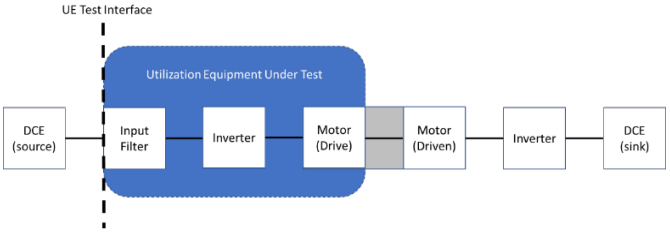


Fig. 2. Diagram for UE Drivestand Testing.

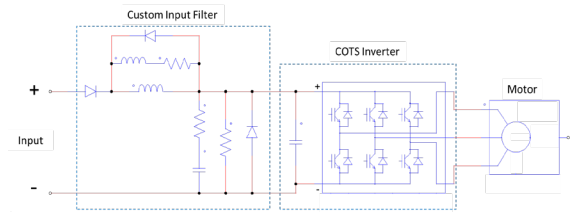


Fig. 3. UE Electrical Schematic.

TABLE I. LIST OF UE TESTS

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

A. Steady-State

The expected operating voltage range for the UE is obtained from the steady-state voltage requirement definition. Expected voltage swings during operation, including varying source output and losses in the EPS, should be used to define this expected voltage range. Table II provides the range which may be seen when the source of the EPS is a battery supplying power to a UE operating at a nominal 630 VDC.

TABLE II. STEADY-STATE VOLTAGE LIMITS FOR 630VDC NOMINAL INPUT VOLTAGE

Characteristic	*Low*	*High*
Steady-State Voltage (Vdc)	485V	718V

Tables III through V show resulting system performance when different loading levels were applied at a number of different torques and speeds, including low, nominal, and high voltages. Motor speed, inverter torque command, field-weakening status, modulation index, direct-axis current *Id*, and quadrature-axis current *Iq* were recorded. If the UE operated as expected at the stated test condition, it passed. If it did not operate as expected, it failed.

TABLE III. STEADY-STATE TEST DATA FOR 718VDC INPUT

Speed (RPM)	*Torque*	*Field-Weakening*	*Mod. Index*	*Id (A)*	*Iq (A)*	*Idc (A)*	*Pass/ Fail*
1627	17	No	0.31	0	22.1	4.3	Pass
3253	34	No	0.56	0	44.3	14.4	Pass
4880	51	No	0.82	0	66.4	30.6	Pass
5300	90	No	0.96	0	117	63.7	Pass

TABLE IV. STEADY-STATE TEST DATA FOR 630VDC INPUT

Speed (RPM)	*Torque*	*Field-Weakening*	*Mod. Index*	*Id (A)*	*Iq (A)*	*Idc (A)*	*Pass/ Fail*
1627	17	No	0.34	0	22.1	4.7	Pass
3253	34	No	0.63	0	44.3	16.1	Pass
4880	51	No	0.94	0	66.5	36.5	Pass
5300	90	No	1.08	0	117	74.1	Pass

TABLE V. STEADY-STATE TEST DATA FOR 485VDC INPUT

Speed (RPM)	*Torque*	*Field-Weakening*	*Mod. Index*	*Id (A)*	*Iq (A)*	*Idc (A)*	*Pass/ Fail*
1627	17	No	0.43	0	22.1	5.8	Pass
3253	34	No	0.82	0	44.3	21	Pass
4880	51	Yes	1.10	-36	66.5	56.6	Pass
5300	90	Yes	1.10	-104	117	118	Pass

None of the DC voltage setpoints defined in the steady-state performance matrix negatively impacted the actual versus expected inverter torque regulation of the motor output. It is noted that the maximum torque at which the inverter can regulate the motor to 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 mode. In this mode, the inverter operates in the constant power region of the motor. The applied *Iq* (proportional to torque) is effectively reduced as speed increases and an increasing fraction of the maximum motor current is required for flux-weakening of the motor.

B. Line-Step Transient

Line -step-up and –step-down transient requirement definitions establish normal operating swings in input voltage magnitude and durations at the input to the UE. The upper and lower limits should encompass transients seen at the UE interface due to voltage disturbances induced by upstream loads, busses, and/or source(s). The limits in Fig. 4 represent a hypothetical range that a battery-fed EPS would provide to a general UE on a nominal 630 Vdc bus. Requirements related to the rise- and fall- rates were not defined when the tests were conducted.

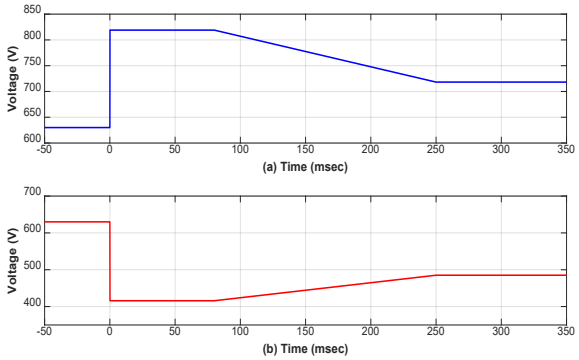


Fig. 4. Line-Step Transient (a) Upper and (b) Lower Verification Limits.

Performance was analyzed and recorded across several loading levels, at various speeds and torques documented in Tables III through V for both line-step up and line-step down transients. Success criteria will vary by UE and application, so it is recommended that UE controlling documents and/or original equipment manufacturer (OEM) designate what successful performance entails. For the purposes of this paper, success was defined as the UE inverter maintaining control of the UE motor, without noticeable impact by the test engineer. As seen in Table VI, the UE passed across all documented test conditions as it maintained stable operation and recovered to the expected performance after the transient. Figures 5 and 6 show the applied line-step- up and -down transient voltage waveforms and resultant input DC and output AC currents for each test. The UE rode through the applied transients with little noticeable impact to the UE operation itself. A disturbance was seen at the initiation of the transient for both tests, but this transient only impacted a few AC cycles at the output of the inverter. No appreciable impact was seen for the torque regulation of the motor for either test.

TABLE VI. LINE-STEP TRANSIENT TEST DATA

Line-Step Test	*Speed (RPM)*	*Torque (Nm)*	*Pass/Fail*
Up	1627	17	Pass
Up	3253	34	Pass
Up	4880	51	Pass
Up	5300	90	Pass
Down	1627	17	Pass
Down	3253	34	Pass
Down	4880	51	Pass
Down	5300	90	Pass

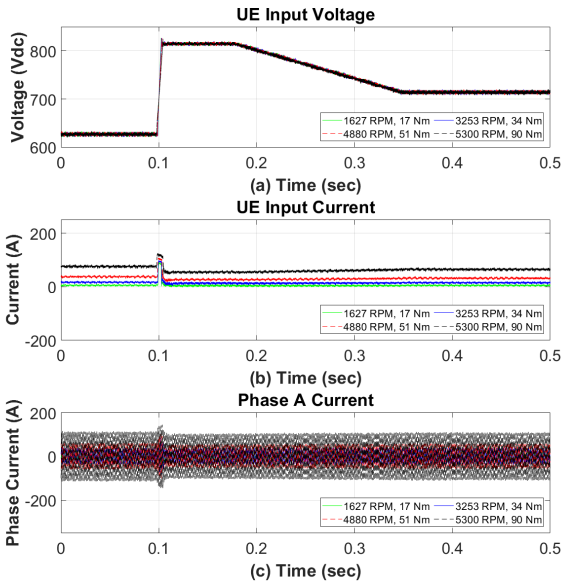


Fig. 5. Line-Step Up Transient.

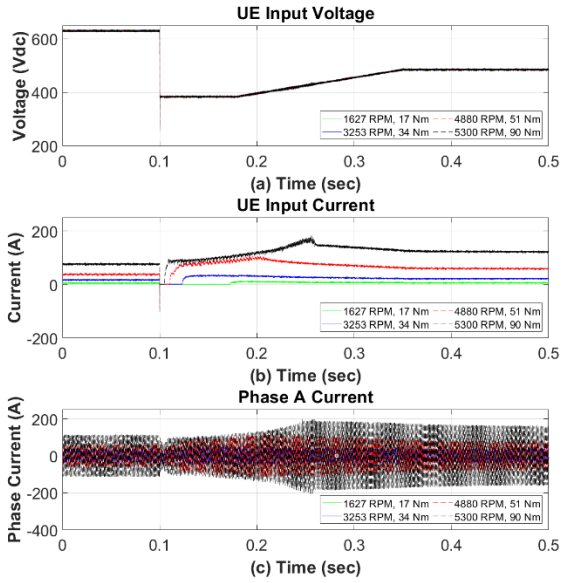


Fig. 6. Line-Step Down Transient.

C. *Input Impedance*

Definition of an input impedance requirement is critical for evaluating stability of an integrated system. This requirement definition should be performed in concert with the source requirement for the EPS. Due to the lack of a corresponding source impedance for this paper, no input impedance limit was derived for the UE under test. The custom input filter integrated with the commercial-off-the-shelf inverter in Fig. 3, however, was designed to provide adequate damping and minimize any unwanted oscillatory behavior with a number of generic EPSs.

The complex input impedance Z of the UE measured a nominal voltage of 630 Vdc, along with the low and high voltages listed in Table II. The corresponding torque-speed operating points for these voltages are identical to the test points listed in Tables III through V for steady-state voltage testing. Results are shown in Fig. 7 below. For all test cases, it was observed for frequencies less than 100 Hz that as loading was increased, the magnitude curves trended downward. Analytically this is confirmed by fixing the voltage term in Ohm's Law, such that with $Z = V/I$, as I increases (at frequencies trending towards DC), Z decreases proportionally. The phase trends to -180 degrees at lower frequencies due to the constant power load effect [3]. No variations of note were observed for the curves in the frequency range of 100Hz to 1,000 Hz. The impedance reaches a minimum at 500-600 mΩ around 1 to 3 kHz due to the damping effect of the input filter. Above approximately 3 kHz, the input inductor of the filter dominates the characteristics of the response. Higher loading degrades performance of the inductor due to non-linear effects, although a moderate impedance of 1 to 5Ω is seen at 150 kHz worst-case. Increasing the value in the future should aide in prevention of source-load stability issues for systems with regulated sources.

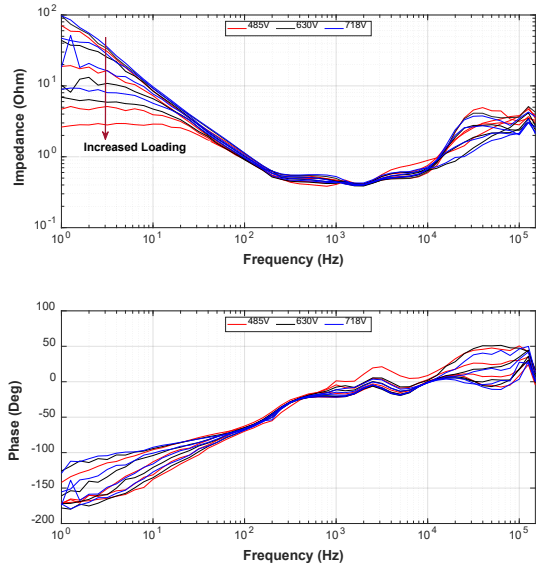


Fig. 7. Input Impedance Results. Magnitude (Top) and Phase (Buttom)

D. *Overvoltage/Undervoltage Surge*

Overvoltage and undervoltage requirements establish a worst-case envelope of input voltages that a UE may be subjected to due to various potential upstream faults, failures, or malfunctions within the EPS. The limits in Fig. 8 represent potential worst-case voltages a UE may see on a hypothetical 630 Vdc battery-fed EPS during abnormal conditions. Requirements related to the rise- and fall- rates were not defined when the tests were conducted.

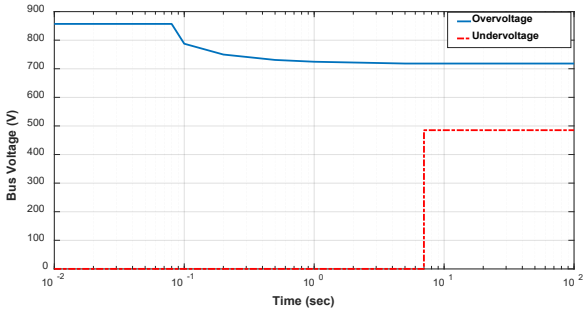


Fig. 8. Overvoltage/Undervoltage Surge Requirements for 630Vdc Bus.

Performance was evaluated and documented across several loading levels, at various speeds and torques, as shown in Table VII. The test was considered successful if the UE was not damaged due to the applied transients and was able to restart or maintain continued operation after the conclusion of the transient. The UE failed if either of those criteria were not met.

TABLE VII. OVERVOLTAGE/UNDERVOLTAGE TEST POINT SUCCESS EVALUATION

Surge Test	*Speed (RPM)*	*Torque (Nm)*	*Pass/Fail*
Overvoltage	1627	17	Pass
Overvoltage	3253	34	Pass
Overvoltage	4880	51	Pass
Overvoltage	5300	90	Pass
Undervoltage	1627	17	Pass
Undervoltage	3253	34	Pass
Undervoltage	4880	51	Pass
Undervoltage	5300	90	Pass

The overvoltage and undervoltage test results are shown in Figures 9 and 10, respectively. The UE tripped due to internal overvoltage and undervoltage protection limits for each of the four test points during each respective power quality test. For the undervoltage tests, no reverse current was generated due to the presence of the input blocking diode seen in Fig. 3. The UE was able to be restarted upon restoration of the input voltage for all tests, and no subsequent damage or issues to and with the UE were identified at the conclusion of each test. The UE was therefore considered compatible with the applied waveforms and the tests successful.

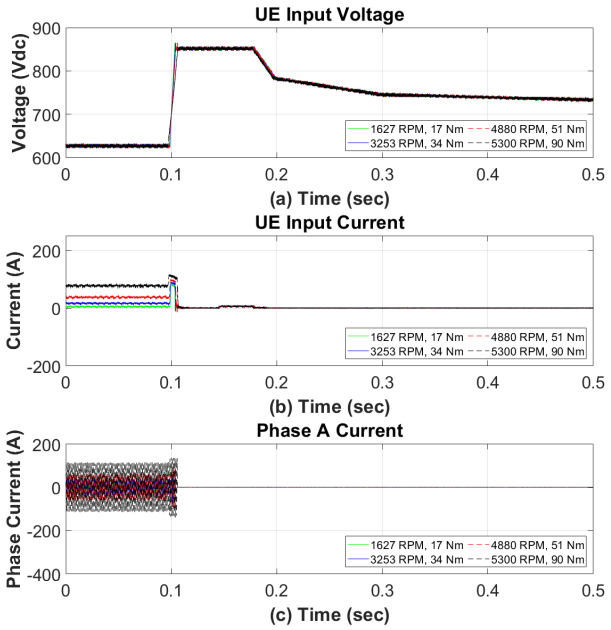


Fig. 9. Overvoltage Test Results (a) Applied waveform, (b) UE DC input current, (c) Inverter AC output current

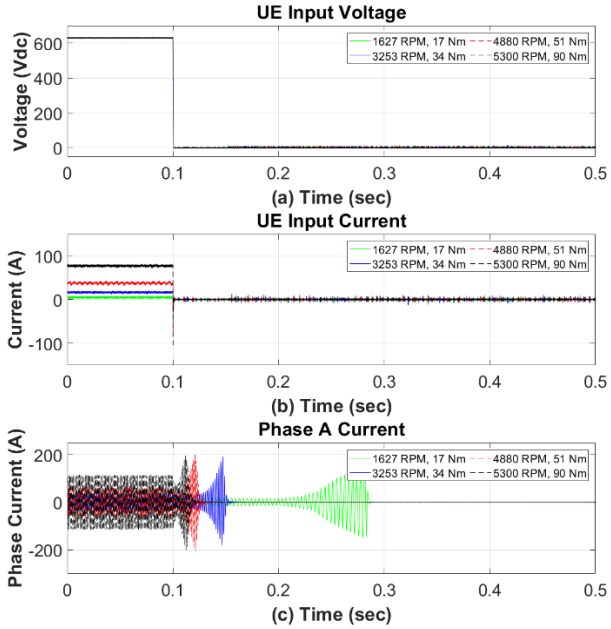


Fig. 10. Undervoltage Test Results (a) Applied waveform, (b) UE DC input current, (c) Inverter AC output current

IV. Conclusion

In order to ensure safe and reliable electrified propulsion for vertical takeoff and landing aircraft, the development of standards and best test practices will be crucial. To continue addressing this need, the NASA AREAL testbed was configured to conduct high voltage UE testing for a number of standard power quality tests. Data from these tests will be used to inform these future standards and related test documents. This paper provided results of the high voltage UE testing, along with additional insights on the specifics of the analysis and testing performed. Future work will expand test results to requirements related to ripple, inrush/surge, large-signal stability, EPS testing, and integrated system testing.

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References

[1] “Aircraft High Voltage DC Power Quality Standard,” sae.org. https://www.sae.org/standards/content/as7499/ (accessed Mar. 27, 2025).

[2] 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.

[3] David J. Sadey, Xavier Collazo-Fernandez, Patrick Hanlon, Keith Hunker, Casey Theman, Linda Taylor, Paul Nowak and Brian Malone. "NASA AREAL Testbed and UE Power Quality Testing," AIAA 2024-3705. AIAA AVIATION FORUM AND ASCEND 2024 . July 2024.