



NASA Advanced Reconfigurable Electrified Aircraft Laboratory (AREAL) Utilization Equipment (UE) Power Quality Testing

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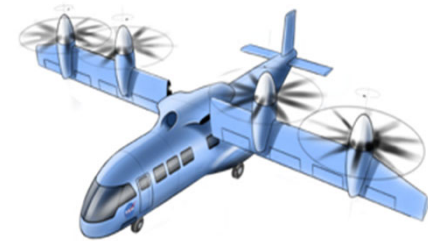
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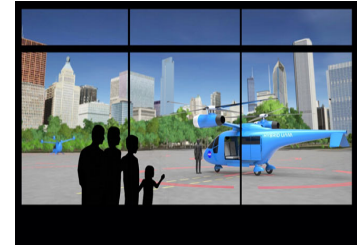
- **Background**
- **AREAL Overview**
 - UE Test Configurations
- **Test Descriptions and Results**
- **Conclusion and Future Work**



Advanced Air Mobility Background



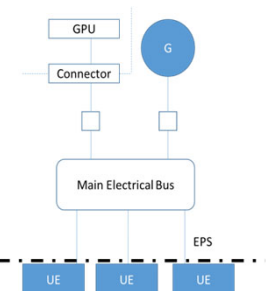
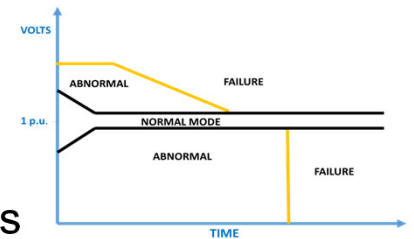
- **Many electrified aircraft are in development**
 - Vertical Takeoff and Landing
 - Small & Large Transport
- **Many of these vehicles require voltages $\gg 270$ Vdc**
 - Standards and test guideline documents are still in development
 - Lack of public test data available to community
 - Data needed to inform and validate documents and models
 - Power quality test and performance data is a prime example



DC Power Quality



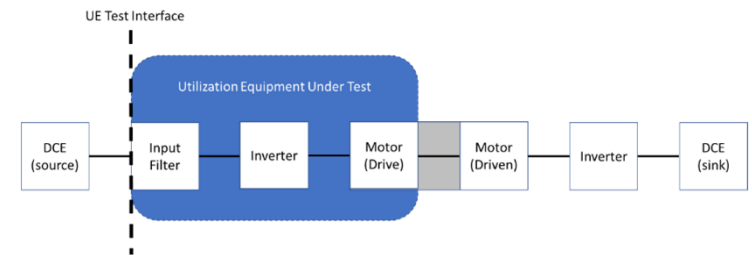
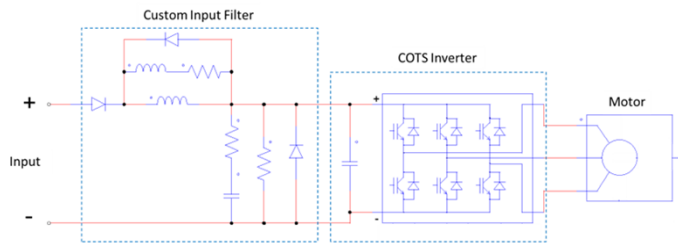
- **What is Power Quality (PQ) and why does it matter?**
 - Physical description of power, namely voltage (DC)
 - Applicable during any operational period (Normal, Abnormal, Emergency)
 - Voltage: steady-state, transient, ripple
 - Stability, fault conditions, & much more
 - Improves reliability
 - Reduces component failures by defining operational boundaries
 - Ensures stable operation
 - Defines/drives proper fault recovery
 - Move towards 'plug and play' approach to design and integration
 - Helps guide lower level standards (e.g. components, connectors, etc.)



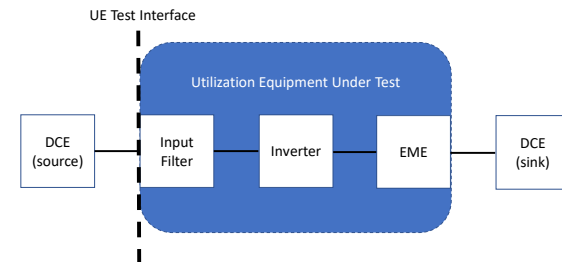
AREAL UE Configurations



- **Two primary UE configurations**
 - Physical
 - Emulated
 - 100 kW class inverter and 60 kW class motor
 - Custom input filter
- **Physical**
 - Performance and characterization testing of inverter, motor, or combination of both
- **Emulated**
 - Test inverter with an Electric Motor Emulator (EME¹) when motor not available



General Drive Stand Configuration¹



General EME¹ Configuration

1. DC Emulator (DCE) and EME are products of D&V Electronics



UE Power Quality Testing



- **Performed several PQ tests on physical and emulated UE test configurations**

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

- **Requirements were derived internally and based on inputs from ongoing standards work and inputs**
- **Nominal bus voltage 325 Vdc**

Steady-State Test Objective



- **Objective: Verify UE operates to specification at each input voltage test point, across varying speeds/torques**

Low	Nominal	High
250 Vdc	325 Vdc	370 Vdc

Speed (RPM)	Torque (Nm)
839	17
1678	112
2517	51

Steady-State Test Results (370 Vdc)



- **Results were as expected at 370 Vdc**
 - Good match between physical and emulated
 - No field-weakening present

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

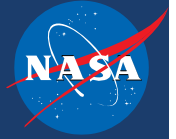
Steady-State Test Results (325 Vdc)



- **Results were as expected at 325 Vdc**
 - Good match between physical and emulated
 - No field-weakening present

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

Steady-State Test Results (250 Vdc)



- **Results were as expected at 250 Vdc**
 - Mismatch between physical and emulated during field weakening
 - Further improvement can be made to input parameters
 - Field-weakening present at 2517 RPM Test Point
 - Integrators should be aware of reduced torque capability and closely look at performance during bus transients

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

Input Impedance Test Objective

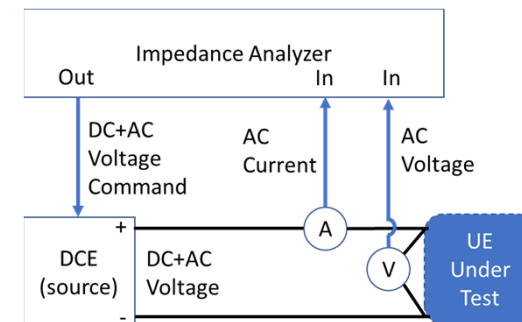


- **Objective: Measure and record input impedances from 1 Hz to 150 kHz. Test conditions are same as steady-state.**

Low	Nominal	High
250 Vdc	325 Vdc	370 Vdc

Speed (RPM)	Torque (Nm)
839	17
1678	112
2517	51

- **No internal impedance requirement was derived due to the lack of a corresponding source requirement.**
- **An input filter was included to increase damping of the corresponding UE.**



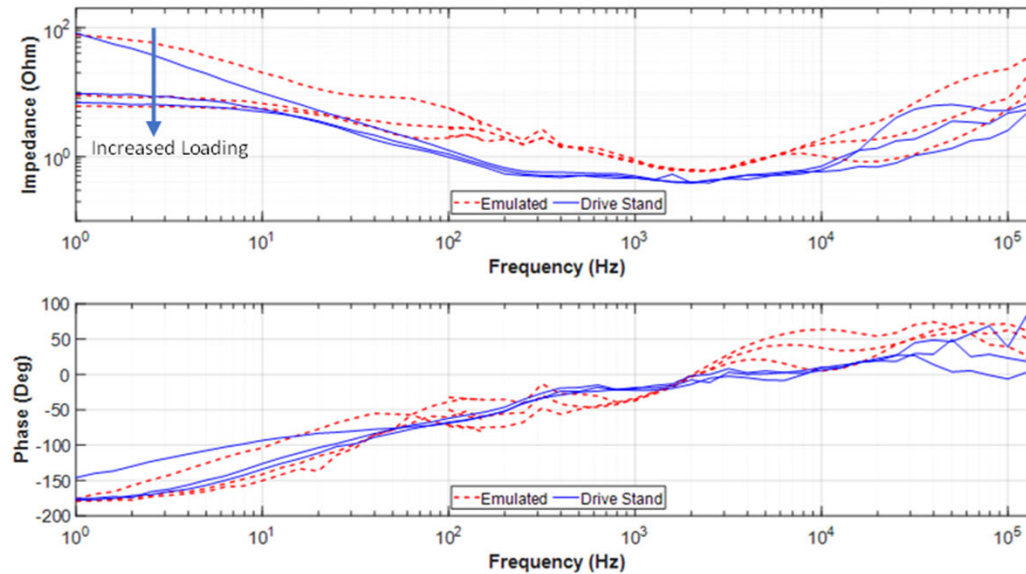
AC Injection Configuration for Physical and Emulated Input Impedance Testing.



Input Impedance Test Results (370 Vdc)



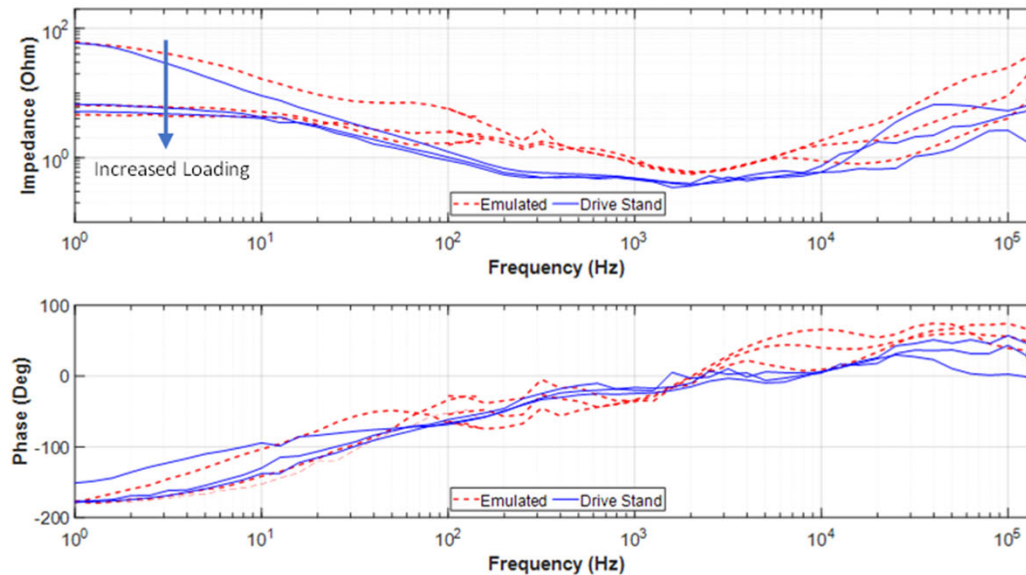
- Physical and Emulated Results Similar
- Constant power trend below ~30 Hz



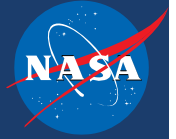
Input Impedance Test Results (325 Vdc)



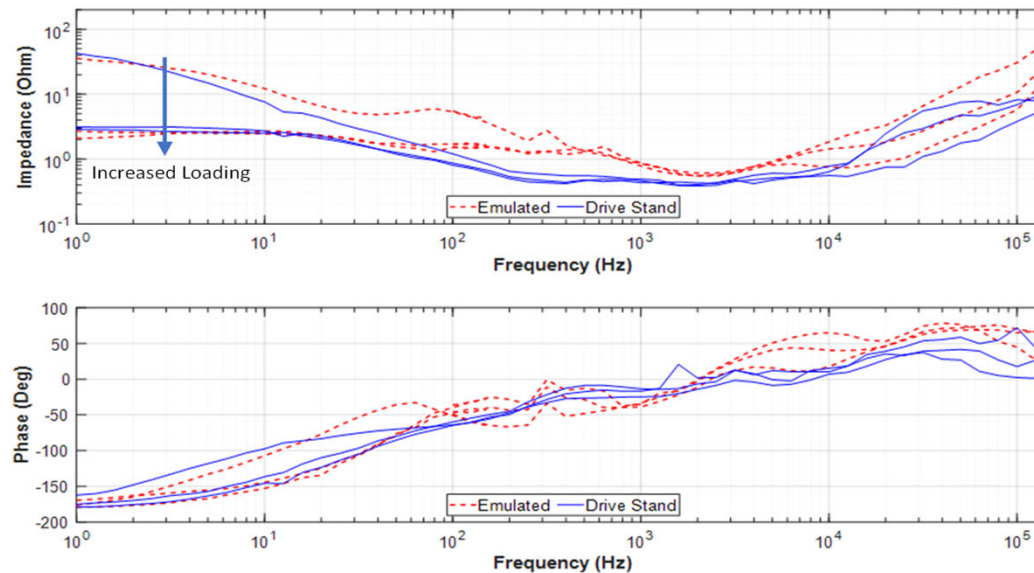
- Physical and Emulated Results Similar
- Constant power trend below ~30 Hz



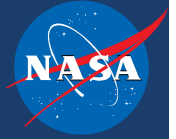
Input Impedance Test Results (250 Vdc)



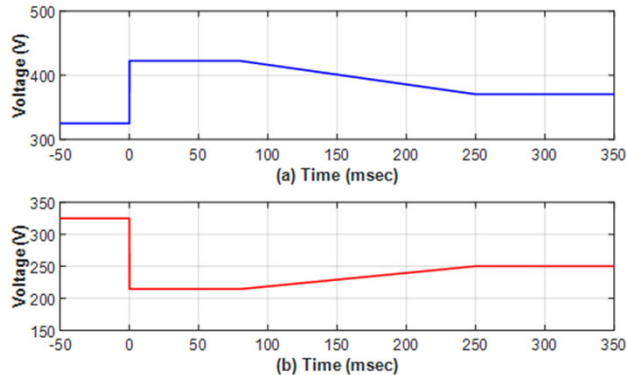
- Physical and Emulated Results Similar
- Constant power trend below ~30 Hz



Line-Step Transient Test Objective



- **Objective: Verify UE maintains stable operation and recovers to the expected performance level after the applied transients.**



Speed (RPM)	Torque (Nm)
839	17
1678	112
2517	51

Line-Step Transient Test Results Summary



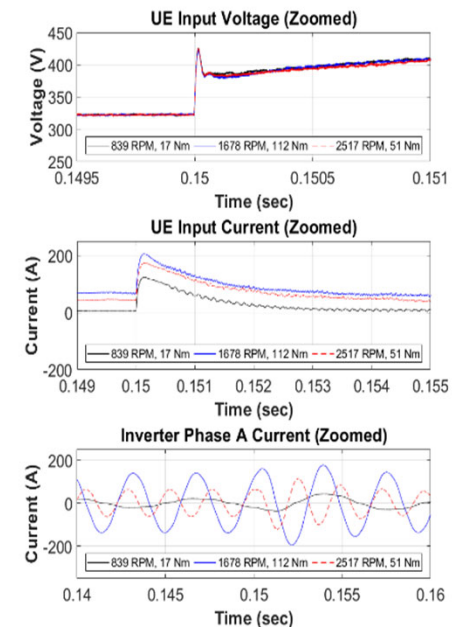
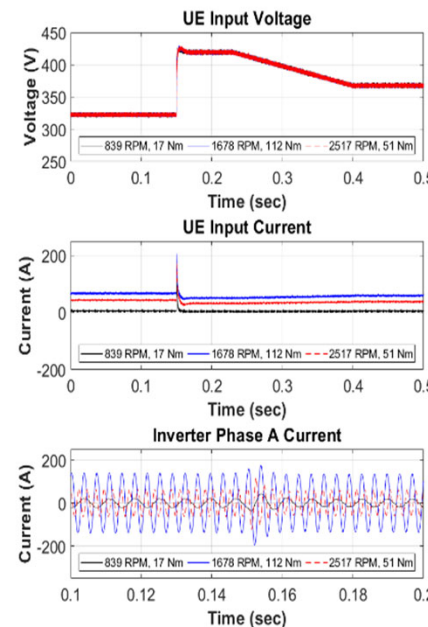
- Overall, physical and emulated UE remained stable and recovered to expected performance after the line-step- up and – down transients were applied

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

Line-Step Up Transient Test Results (Example)



- Emulated shown, physical showed close matching
- Inverter rides through disturbance
- Input surge current observed
 - DC and AC
 - No impact on overall performance

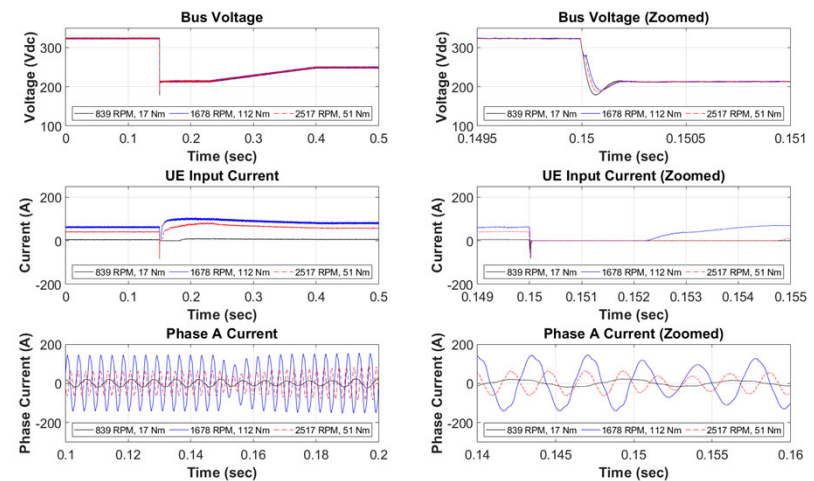


Line-Step Up Transient Data for Emulated Configuration.

Line-Step Down Transient Test Results (Example)



- Drive stand shown, emulated showed close matching
- Inverter rides through disturbance
- Field-weakening can occur transiently
- Input surge current observed
 - DC and AC
 - No impact on overall performance
 - Blocking diode prevents reverse current



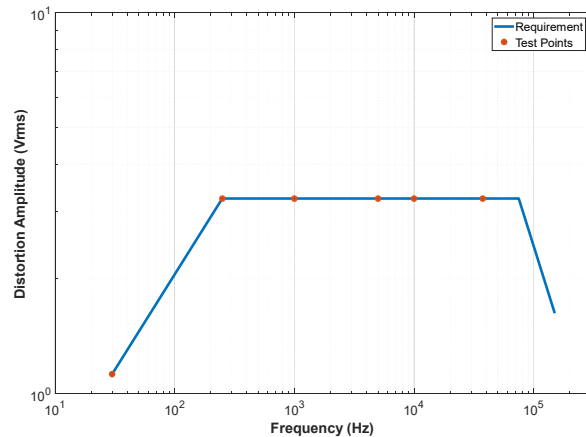
Line-Step Down Transient Data for Physical Configuration.



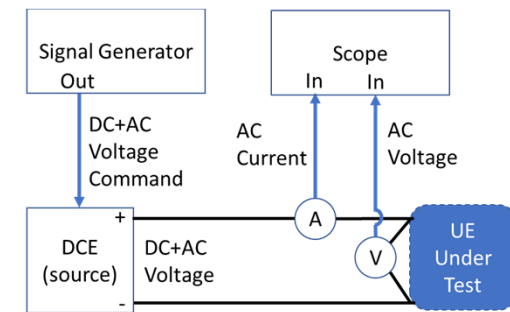


Ripple Voltage Spectrum Test Objective

- **Objective: Verify UE maintains stable operation when subjected to the define input voltage ripple susceptibility limits**



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



AC Injection Configuration for Ripple Testing

- **Testing was performed at approximately 15% and 85% loading**
- **System testing limited to 37.5 kHz**

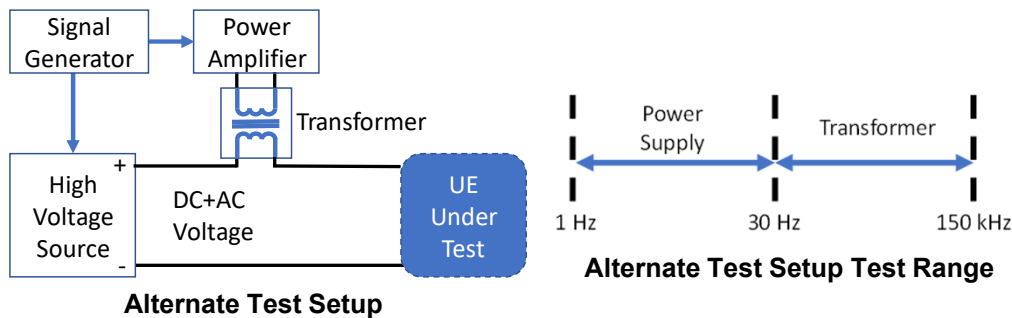
Speed (RPM)	Torque (Nm)
831	51
2517	95



Ripple Voltage Spectrum Test Results and Recommendations



- **Emulated and Physical UE maintained stable operation when subjected to the defined spectrum**
- **Input filter provided sufficient damping to mitigate current ripple**
- **Alternative test setup needed moving forward to test entire spectrum**

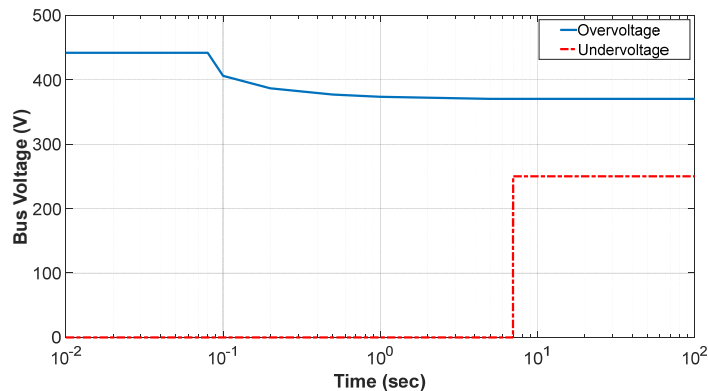


UE Motor	Speed (RPM)	Torque (Nm)	Frequency	Injection (Vrms)	Pass/Fail
Emulated	839	51	30 Hz	1.13	Pass
Emulated	2517	95	30 Hz	1.13	Pass
Emulated	839	51	250 Hz	3.25	Pass
Emulated	2517	95	250 Hz	3.25	Pass
Emulated	839	51	1 kHz	3.25	Pass
Emulated	2517	95	1 kHz	3.25	Pass
Emulated	839	51	5 kHz	3.25	Pass
Emulated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

Overvoltage/Undervoltage Surge Test Objective



- **Objective: Verify UE is not damaged and is able to maintain or restart operation after the subjected transients**



Speed (RPM)	Torque (Nm)
839	17
1678	112
2517	51

Overvoltage/Undervoltage Surge Test Result Summary



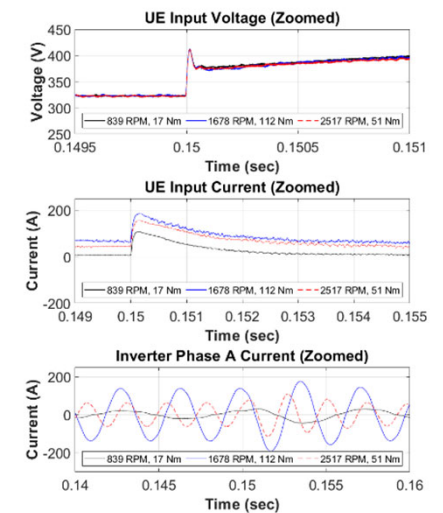
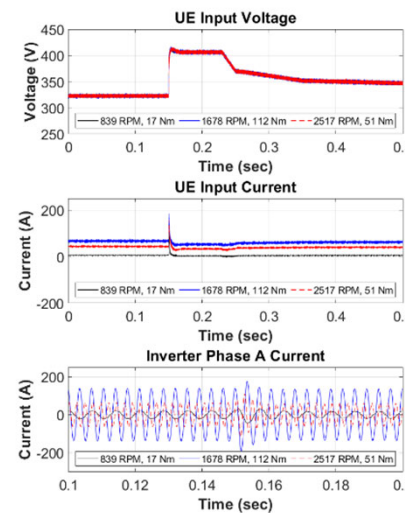
- **Emulated and physical performance was similar**
- **No damage was observed during any test**

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

Overvoltage Test Details



- UE from both configurations rode through the overvoltage transient
- Surge observed in DC input and AC output currents
- No impact on output torque regulation post transient observed by operators



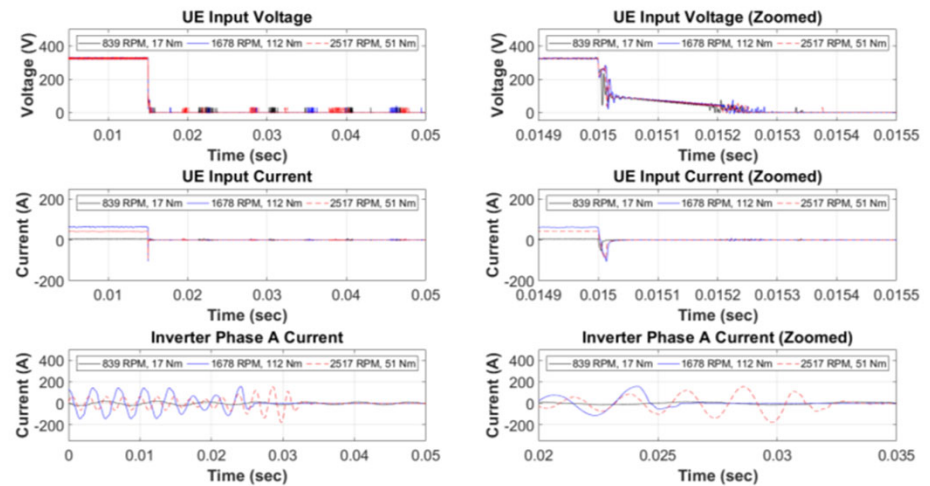
Overvoltage Transient Data for Emulated Configuration.



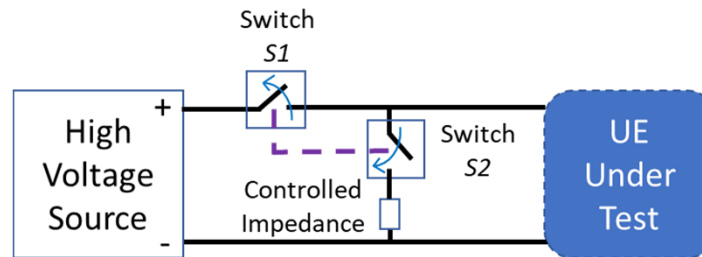
Undervoltage Test Details



- UE from both configurations tripped at 50Vdc, and were able to be restarted after the bus voltage recovered at the end of the transient
- Blocking diode prevented reverse current
 - Reverse recovery current negligible
- Alternative test configuration can be implemented:



Undervoltage Transient Data for Drive Stand Configuration.



Conclusion and Future Work



- **Performed power quality testing on physical and emulated UE**
 - Normal and abnormal tests
 - Custom Input Filter + Inverter + Motor
- **Documented results**
 - To be fed for standards requirement development
- **Identified alternative test setups**
 - Either improve test quality or if different equipment is available
- **Future Work**
 - Expand testing to 630 Vdc
 - Include inrush/surge and isolation testing
 - Expand ripple test capability to 150 kHz

Acknowledgments



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Questions





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