Power Quality Analysis for a High Voltage Power System for Urban Air Mobility Application

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Maturation of electric power technologies has opened the door for deployment of new types of aircraft within urban air mobility (UAM) markets. These new types of aircraft use non-conventional designs, which do not fall within existing regulatory requirements; this is especially true for the design and verification of the high voltage primary power systems which are being proposed for many of these aircraft. The purpose of this paper is to investigate and inform integration requirements, mainly related to power quality, based on a point design of a NASA Lift-plus-Cruise Vehicle Electrical Power System (EPS) and Utilization Equipment (UE). The results will be used to inform normal and abnormal operating performance of the EPS and UE for future standards in regards to Power Quality.

I. Nomenclature

DC	=	Direct Current
EPS	=	Electrical Power System
EAP	=	Electrified Aircraft Propulsion
HVDC	=	High Voltage Direct Current
NASA	=	National Aeronautics and Space Administration
PQ	=	Power Quality
RVLT	=	Revolutionary Vertical Lift Technology
UAM	=	Urban Air Mobility
UE	=	Utilization Equipment

II. Introduction

The maturation of electric power systems and components, especially in regards to enhanced power and/or energy densities and efficiencies, have opened the door for development and deployment of new types of aircraft for Urban Air Mobility (UAM) markets. These aircraft may use non-traditional designs and implementations for thermal, mechanical, electrical, and propulsion systems that do not fall within current regulatory requirements and standards. As such, there has been a large push within the community to develop standards that can be used for purposes of design, verification, and testing of new types of systems and components. This is especially true for the primary power systems within these vehicles.

The primary power systems for many of the proposed UAM vehicles are unique in the fact that their intended use is for propulsion power. Load requirements are in the hundreds of kilowatts to megawatt range, requiring bus voltages of 300V to 1kV, and possibly higher to obtain reasonable system mass and efficiency. In addition to unique voltage requirements, the available power source capacity to load consumption ratio approaches one; this requires designers to pay close attention (for design and test) to stability margins to ensure stable and safe operation of the power system over the flight profile. These unique power system performance requirements, among others for normal and abnormal conditions for power systems, have typically been defined in Power Quality Standards for aerospace vehicles. Historical Aerospace Power Quality Standards, however, were not written to address normal and abnormal power

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system operating requirements for the Electric Power System (EPS) and corresponding Utilization Equipment (UE) for high voltage and high power primary propulsion applications. New Power Quality Standards, such as SAE AS7499 High Voltage DC Power Quality for Aircraft[1], are being written to provide performance and verification requirements to fill these gaps. These standards are typically developed across industry based on a mix of historical experience, simulation and test data, and rigorous analysis.

Under the NASA Revolutionary Vertical Lift Technology (RVLT) program, a detailed power system model of the Lift-plus-Cruise vehicle was developed in coordination with PC Krause and Associates (PCKA) to investigate aspects of the power quality and power system integration. Detailed design models of the EPS and UE were utilized to measure the power quality performance of the system. The system and loads were continuously tweaked to meet minimum performance requirements for steady-state voltage, load-step transient response, stability, and abnormal voltage response. Voltage ripple was not assessed. While the design process is not within the scope of this paper, the results will be presented to help provide guidance for worst-case envelope requirements defined within upcoming Power Quality Standards. This paper will provide a brief overview of Power Quality, a brief overview of the Lift-plus-Cruise EPS and UE, cover several EPS tests, and provide a conclusion and future work.

III. Power Quality

The formal definition of power quality has historically been debated within the power community, and can also vary based on whether one is referring to AC or DC power quality[2]. In this paper and in regard to DC systems only, power quality is defined as a physical description of the quality of power, namely voltage, which a user can expect to experience during any operational period. The physical description includes steady state voltage limits, transient voltage limits in normal/abnormal (faulted) conditions, ripple voltage, stability, fault conditions, and more. Requirements concerning grounding, distribution wiring, isolation and reverse current are also typically covered in Power Quality documents. The importance of power quality is to improve reliability, improve stability, reduce component failures by defining operational boundaries, and define proper fault recovery.

An existing published public aerospace power quality document for high voltage direct current (HVDC) is not known to exist to the authors at the time of this publication. Most of the standards are limited to 270V on the high end, while the high voltage standards are limited to terrestrial applications. Current standards in development, such as AS7499, aim to define the performance and verification requirements between the EPS and UE in normal and abnormal operating modes. Normal operation refers to operating requirements in the absence of failures or faulted conditions, while abnormal operation refers to operating requirements during failures or faulted conditions. A generic plot of the transient voltage response in the different operating modes is shown in Figure 1[3]. Performance requirements are conventionally defined at the connection of the EPS and UE[4], as shown in Figure 2, although this can vary by standard. This paper uses the conventional definition for its studies.

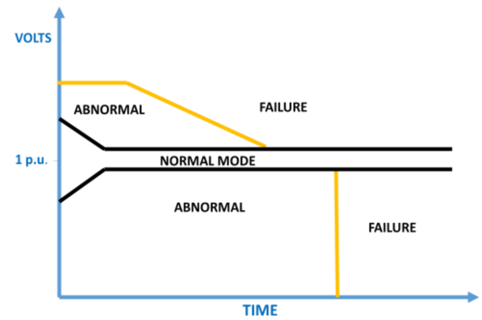


Figure 1: Normal and Abnormal Voltage Limits[3]

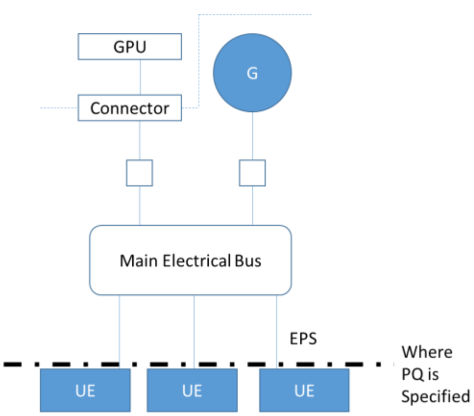


Figure 2: Power Quality Definition Interface[4]

IV. Lift-plus-Cruise Vehicle and Model Summary

This paper uses the Lift-plus-Cruise vehicle[5] as a baseline, as shown in Figure 3. The Lift-plus-Cruise aircraft power system that is simulated in this study, as shown in Figure 4, consists of a generator, one cruise motor, four lift motors, and a Power Distribution Unit (PDU) for each bus, with two busses total. Each generator and motor has an integral rectifier and inverter respectively, with the general characteristics shown in Table 1. The assumptions for this model are that the generators are Wound Rotor Synchronous Machines (WRSM) and the motors are all Permanent Magnet (PM) machines. The generators were each oversized to power the total system load in the event of an adjacent source failure, however, that operational condition is not addressed in this study. The turboshaft is controlled to operate at a constant speed to power the generators. The fan loads are modeled with torque being proportional to the square of the speed. The lift motors and cruise motors cannot operate at the same time, and the transition from lift to cruise mode is not considered for this report. The protection strategy used for the purpose of this paper consists of a directional overcurrent protection scheme shown in Figure 5, which accomplishes complete zonal protection throughout the system. Trip curves (not shown) were identified and implemented to protect the distribution feeders and branch circuits in a coordinated manner and to minimize impacts of faults to the overall operation of the system. The power system model itself was iteratively tuned to meet numerous normal operating mode requirements for an internal Power Quality Specification. Various faults were then simulated throughout the power system, and the results were documented against a target specification.

Figure 3: Lift-Plus-Cruise Aircraft

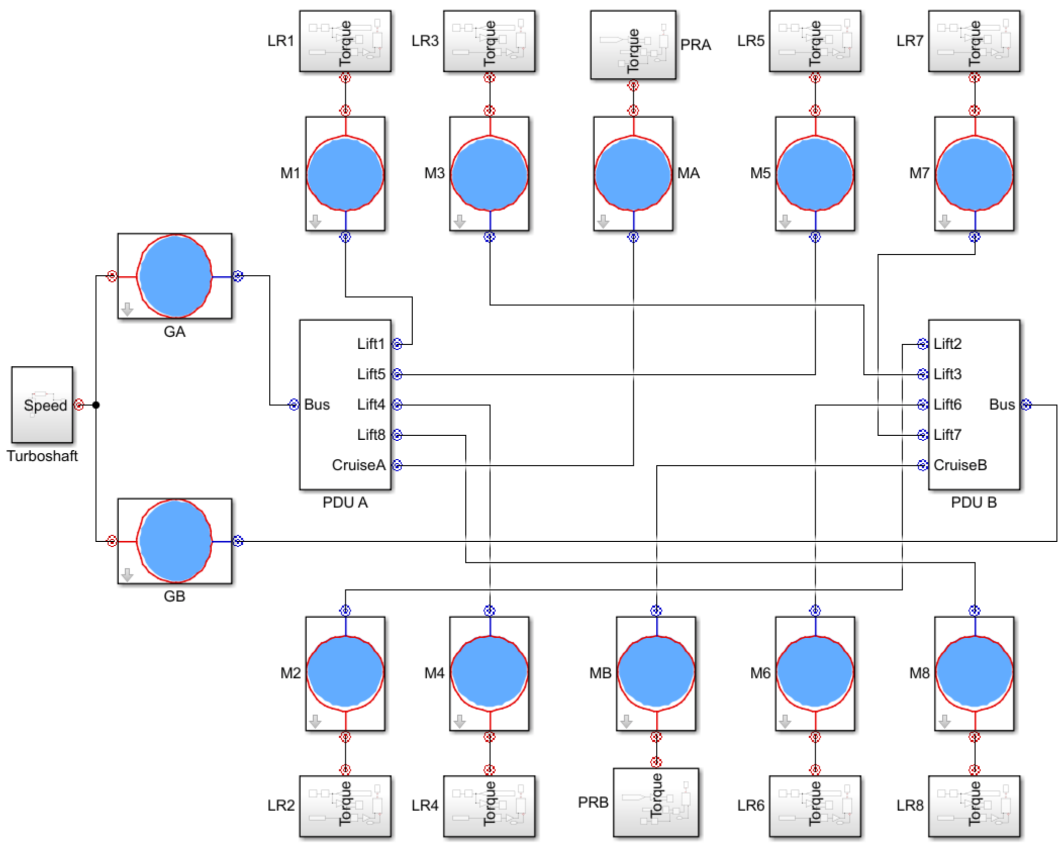


Figure 4: Lift-plus-Cruise Aircraft Electrical Architecture Model

Table 1: Machine and associated Power Converter Parameters

	Generator	Lift Motor	Cruise Motor
Count on Aircraft	2	8	2
Machine Type	Wound-Rotor Synchronous	Permanent Magnet Synchronous	Permanent Magnet Synchronous
Rate Power (HP)	1000	98.6	423
Rated Torque (N m)	1978	668	2366
DC Voltage (V)	650	650	650
Rated DC Current (A)	1147	113	485
Speed (RPM)	3600	1050	1273
Control Objective	DC Voltage	Speed	Speed

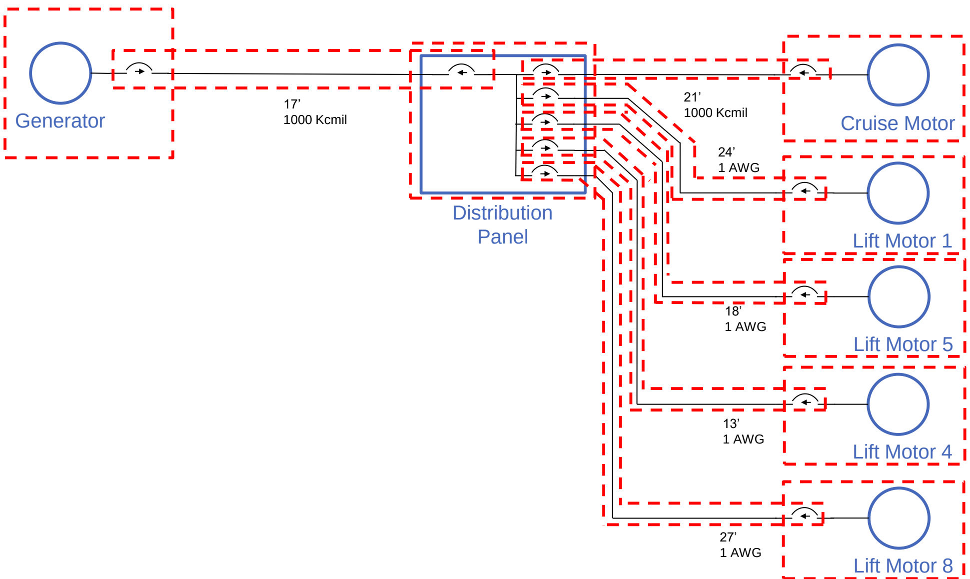


Figure 5: Lift-plus-Cruise Directional Overcurrent Protection Scheme with Protection Zones (dashed red) (Power Electronics and Filtering not shown)

V. Power Quality Analysis Results

The PCKA model contains MATLAB® scripts and Simulink® models that represent the Lift-plus-Cruise system. These scripts were run with the Simulink model to generate the system performance plots for normal and abnormal system operation. Steady-state, transient voltage response, and small-signal stability were simulated and analyzed under normal operation. Hard (low impedance) faults were introduced to analyze abnormal voltage response for the tuned system and identify performance improvements for the next design iteration. Voltage transients less than ten micro-seconds in duration were ignored and filtered out, as they are considered outside the range of typical power quality studies in addition to being outside the accuracy of the model.

A. Steady State Voltage Analysis

The internal specification used for the design of this aircraft model was such that the steady-state voltage limits of the EPS at the any UE terminal was between 0.93 and 1.04V per unit for a regulated bus. This results in a voltage range of 604.5 to 676Vdc under full-load and no-load conditions respectively. Figure 6 below demonstrates that the EPS provides a steady-state voltage of 649.1Vdc to the UE under full-load, and 650Vdc to the UE under no-load, meeting the internal specification. At no-load, where no voltage drop occurs across the distribution system, the EPS maintains the 650Vdc regulated output of the generator/rectifier. At full-load, only a 0.9Vdc drop occurs across the distribution system due to the short conductor lengths. Larger vehicles with longer distribution runs, or vehicles with less accurate source regulation may produce different results closer to the steady-state limits.

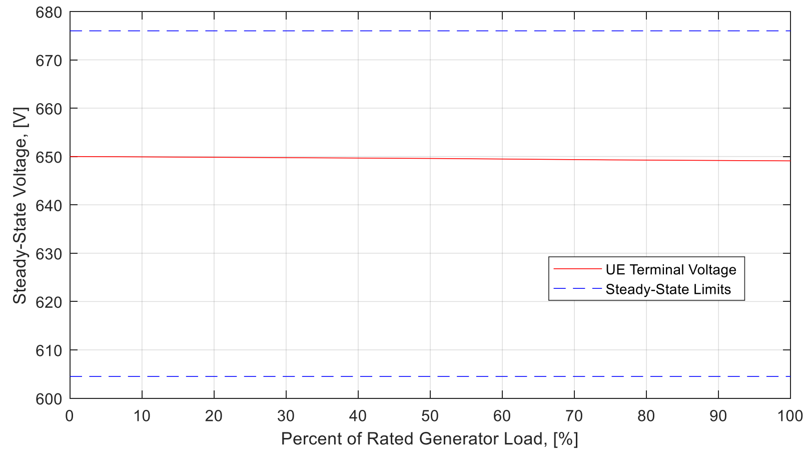


Figure 6: Worst Case Steady-State Voltage from No-Load to Full-Load

B. Transient Voltage Analysis

The internal specification used for the design of this aircraft model was such that the transient voltage limits of the EPS remain within the limits defined in Figure 7. The verification mechanism for these limits is such that a resistive step-load increases and decreases of 50% of nominal power are applied at 10 percent and 45 percent of rated output power. The worst-case results of these step-load tests are shown in Figures 8 and 9, verifying that the EPS meets the internal specification. In the case of the transient under voltage, the voltage hits a worst-case 608.3Vdc within 1msec, and stays within the steady-state limits over the duration of the entire transient. In the case of the transient overvoltage, the voltage hits a worst-case 699Vdc within 1msec, and recovers within the steady-state limit of 676Vdc within 5.5msec. The overall performance of the vehicle EPS was well within the worst-case limits prescribed by the internal specification. The peak transient response magnitudes and response times may vary from vehicle to vehicle, and degrade based on longer distribution lines, slower generator/rectifier response & bandwidth, and less restrictive filtering across the power system.

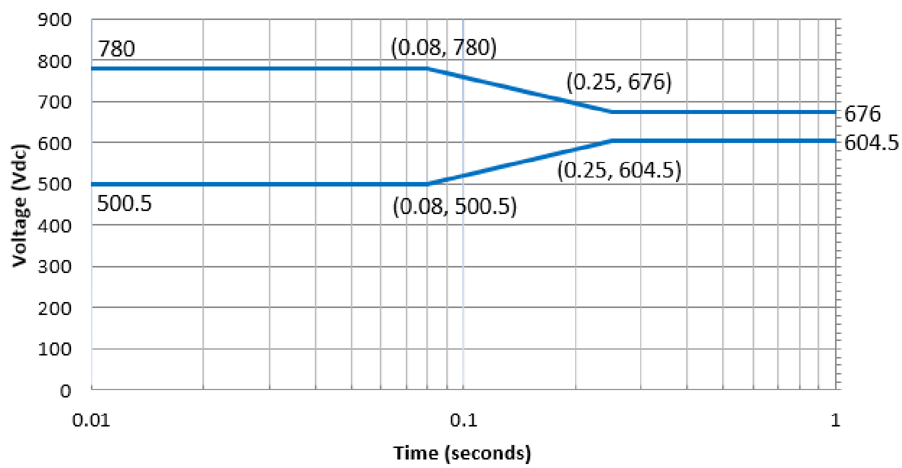


Figure 7: EPS Normal Transient Response Upper and Lower Limits

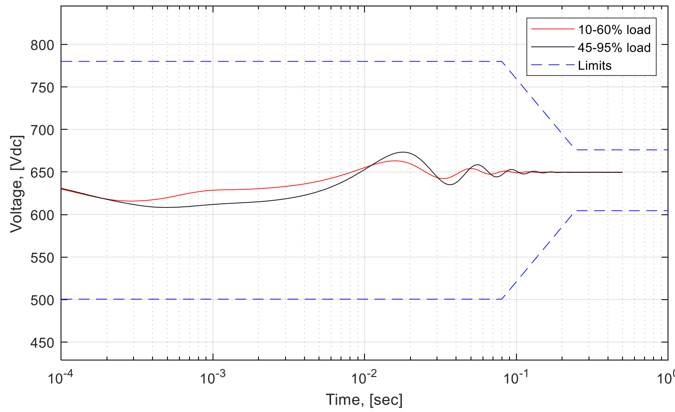


Figure 8: EPS Worst Case Transient Voltages, Step-Load Increase at Cruise Motor Terminals

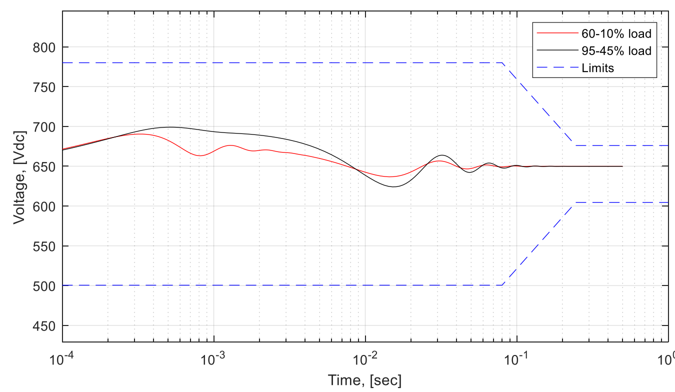


Figure 9: EPS Worst Case Transient Voltages, Step Load Decrease at Cruise Motor Terminals

C. Small Signal Stability

The small signal stability of each load with regard to the source can be assessed by using the analyzing the Nyquist plot of the ratio of source impedance Z_S to the load impedance Z_L[6]. The internal specification used for the design of this aircraft model, as shown in Figure 10, is such that when $|Z_S/Z_L|$ exceeds -3 dB (0.707), the phase of $|Z_S/Z_L|$ cannot enter the Forbidden Zone over the span of frequencies from 30 Hz to 100 kHz. Figure 11 demonstrates that the cruise motor, and individual load motors meet the internal specification under full-load. For informational purposes only, the source and load impedances at the cruise motor, and Lift Motor 8 are provided in Figure 12. The target stability specification was met based on an iterative process of modifying the controller gains of the generator and power electronic converter control loops for low to mid frequency impedance shaping, and input and output filter design changes for the mid to high frequency impedance shaping.

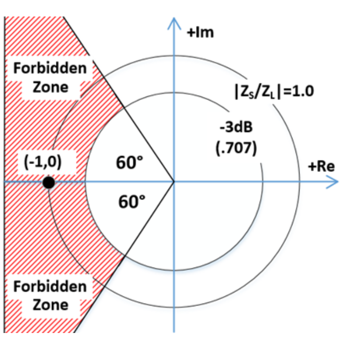
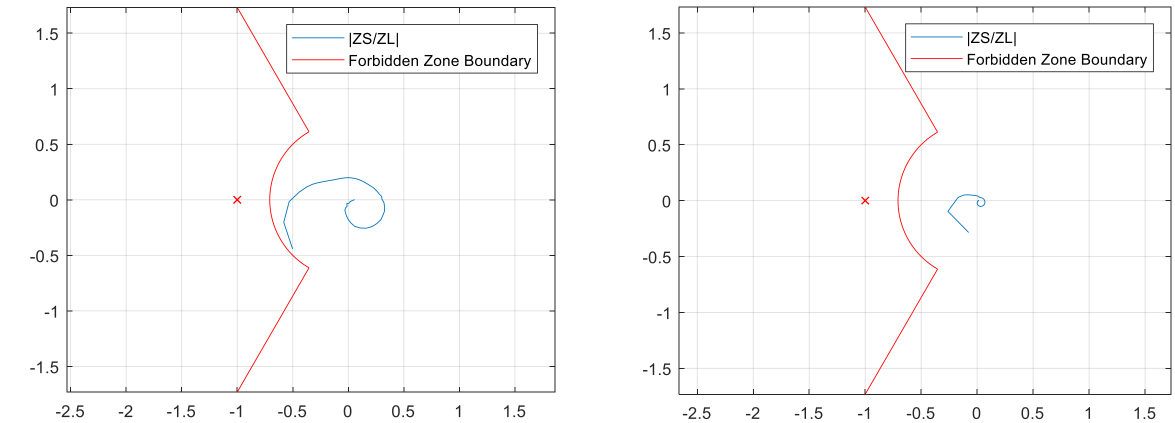
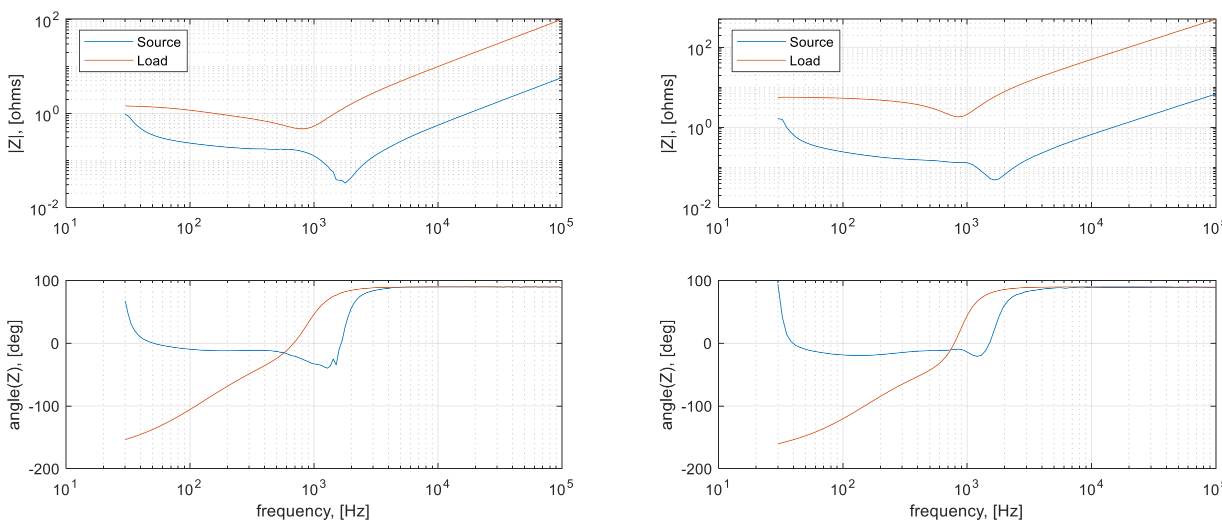


Figure 10: Nyquist Stability Criteria



(a) **(b)**

Figure 11: (a) Nyquist Stability for the Cruise Motor (b) Nyquist Stability for Lift Motor 8



(a) **(b)**

Figure 12: (a) EPS and UE Input and Output Impedances at Cruise Motor (b) EPS and UE Input and Output Impedance at Lift Motor 8

D. Abnormal Voltage Response

The internal target specification used for the design of this aircraft model was such that the worst-case abnormal transient voltage limits of the EPS remain within the limits defined in Figure 13, after isolation of a faulted branch circuit. The verification mechanism for these abnormal limits is such that hard faults (with fault impedances ~1/10th rated load) were introduced at the various branch circuits, and the worst case voltage at the nearby parallel loads was compared to the specified limits. Various fault scenarios and overall power system responses were observed and measured, however, only the response at the standardized EPS/UE interface location was practically addressed. Two examples of the abnormal response are presented. In one test case, as seen in Figure 14, a fault is introduced and cleared on the branch circuit feeding Lift Motor 8. The voltage response at the inverter input for Lift Motor 4 is displayed. The second case presented, as seen in Figure 15, inserts a fault onto the branch circuit feeding Lift Motor 4, and measures the voltage response at Lift Motor 8. The abnormal response for both test cases was approximately the same. At the initiation of the fault, the terminal voltage at the non-faulted inverter drops to approximately 384Vdc. The fault is then isolated by the corresponding circuit breakers on that branch circuit, at which time the voltage overshoots to approximately 679Vdc at 1.6msec. The voltage quickly returns to the steady-state limits thereafter.

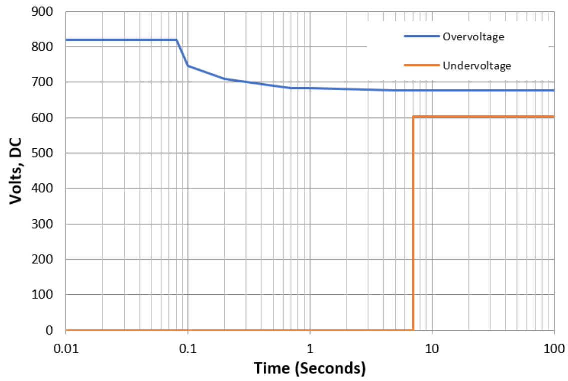


Figure 13: Abnormal Voltage Response Target Performance Window at EPS/UE Interface

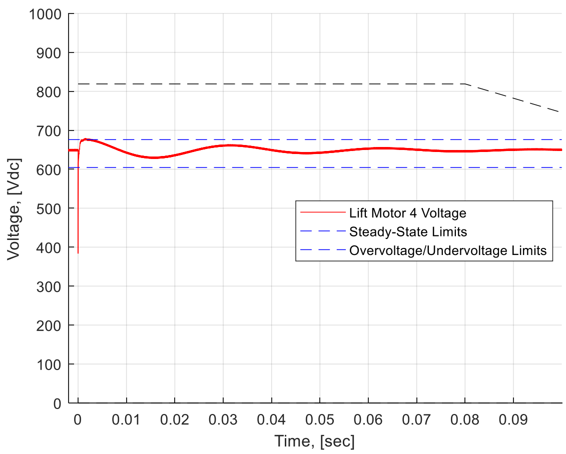


Figure 14: Abnormal Voltage Response at Lift Motor 4 Inverter Terminals during and after Fault Initiation and Fault Isolation on the Lift Motor 8 Branch Circuit

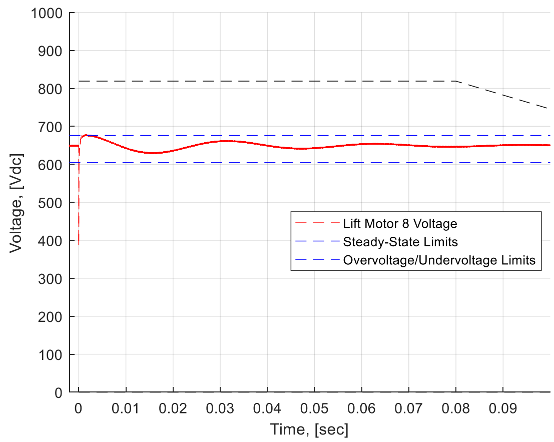


Figure 15: Abnormal Voltage Response at Lift Motor 8 Inverter Terminals during and after Fault Initiation and Fault Isolation on the Lift Motor 4 Branch Circuit

VI. Conclusion and Future Work

This paper summarizes the results of several power quality studies for a high voltage UAM Lift-plus-Cruise vehicle. The vehicle EPS and UE were scaled, sized, and iteratively designed to meet generic, but historically reasonable, power quality performance requirements for normal operation. The current performance of the power system during abnormal operation was documented against internal specifications for hard faults on the lift-motor branch circuits, although future studies and possible system modifications still remain. These studies include the insertion, detection, and isolation of soft (high impedance faults), as well as the addition of a cross-tie across the main power busses to allow for a single generator to supply power to all of the loads in the event of an additional source failure. The final system performance that meets the internal specifications for normal and abnormal operation will be presented in a future paper. These results can be used as a point design for informing future Power Quality Standards.

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