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United States Laboratory Element Electrical Power System Verification Approach

Herb W. Wallen* and S. Johnny Fu†
The Boeing Company, Huntsville, Alabama 35824-6402

The International Space Station Product Group 3 Program Master Integration and Verification Plan (PMIVP), Appendix C—United States Laboratory (USL) Unique Verification Planning Document, provides overall guidelines for the verification of the laboratory element. Verification of the laboratory element electrical power system (EPS) focuses first on the risk mitigation activities for hardware and software integration. During this phase of the USL testing, critical predetermined electrical interfaces will be disconnected, and in a building block approach, each interface will be checked for the appropriate voltage, polarity, and the correct pin-to-pin assignment. Secondly, EPS verification objectives developed for compliance with the USL Prime Item Development Specification will be verified. This paper discusses the USL EPS architecture, key power quality requirements, and the verification approach developed to assure system stability under all operating conditions.

Nomenclature

I_L = current flowing through the power load
(s) = Laplace transform of the associated function from time domain to frequency domain
T = transfer function of the power network, equal to I_L divided by V_i
V_i = input voltage source of the power network
Z_L = load impedance of the power network at the selected interface
Z_s = source impedance of the power network at the selected interface

Introduction

THE unique requirements for the International Space Station (ISS) laboratory element electrical power system (EPS) to meet power load demands and power quality requirements present a challenge to the power system designers.[1] The system design and implementation are further complicated by the multiple interconnections between subelements of the power system, which will be assembled and integrated on orbit. The verification methods outlined in the Product Group 3 Program Master Integration and Verification Plan (PG-3 PMIVP) for the U.S. laboratory (USL) element represents a typical approach of the planned testing of the major subelements of ISS power system, and the analyses required to ensure the proper functioning of the integrated system prior to on-orbit assembling and testing.

Architecture and Requirements

The function of EPS is to generate power, store energy, and distribute power. The ISS EPS generates 160-Vdc primary power that is distributed from the power sources to a central switching location on the truss element. Primary power is routed externally along the truss element and internally within the pressurized element, and later converted to 120-Vdc secondary power. Secondary power is distributed via additional switch gear to the power loads. The power source includes four U.S. photovoltaic arrays and Russian solar panels. The primary power distribution hardware consists of cabling, and solar alpha rotary joints, main bus switching units (MBSUs), and dc-to-dc converter units (DDCUs). The secondary power distribution hardware includes secondary power distribution assemblies (SPDAs), remote power distribution assemblies (RPDAs), and cabling. Remote power controller modules (RPCMs) are used in SPDAs and RPDAs to control and monitor the power distribution and to protect the cabling from faults. The USL EPS receives the primary power from the MBSUs on the truss element and converts primary power to secondary power. Secondary power is distributed to power loads located in standoff, endcone, and rack locations inside the USL. The USL EPS also distributes secondary power to power loads outside the laboratory element. The power distribution diagram is shown in Fig. 1.

The key EPS design requirements are connectivity, power channel loading, and cable-sizing requirements. The key performance requirements are power quality including steady state and transient voltages, maximum ripple (noise) voltages at each interface in the system, and stability of the system. The interfaces in the secondary EPS as depicted in Fig. 2 are defined as interfaces A, B, and C.

Verification Process

Verification of the power system design and performance is based on the development of the verification information system (VIS). Each requirement is verified by a sequence of events defined as the verification logic network (VLN) in VIS. Each activity in the VLN may be a lower-level VLN composed of a test, an analysis, an inspection, or a demonstration with a defined verification objective (VO). The VOs also provide detailed concepts for testing and are used to generate detailed functional test plans and test procedures. VIS will show that a particular requirement is met when the VLN is completed. The VLN is completed by implementing all of the VOs in the VLN. The verification of connectivity and cable sizing follows the typical power system design analyses and inspection process. The verification of power channel loading is based on a statistical power channel loading analysis methodology.[2] This

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*Deputy Lead Engineer, Missiles and Space Division; currently at Boeing Commercial Airplane Group, 3003 West Casino Road, M/S 02-26, Everette, WA 98203.
†Team Leader, Electrical System Integration Team, International Space Station program, 499 Boeing Road, P.O. Box 240002, M/S JR-10.

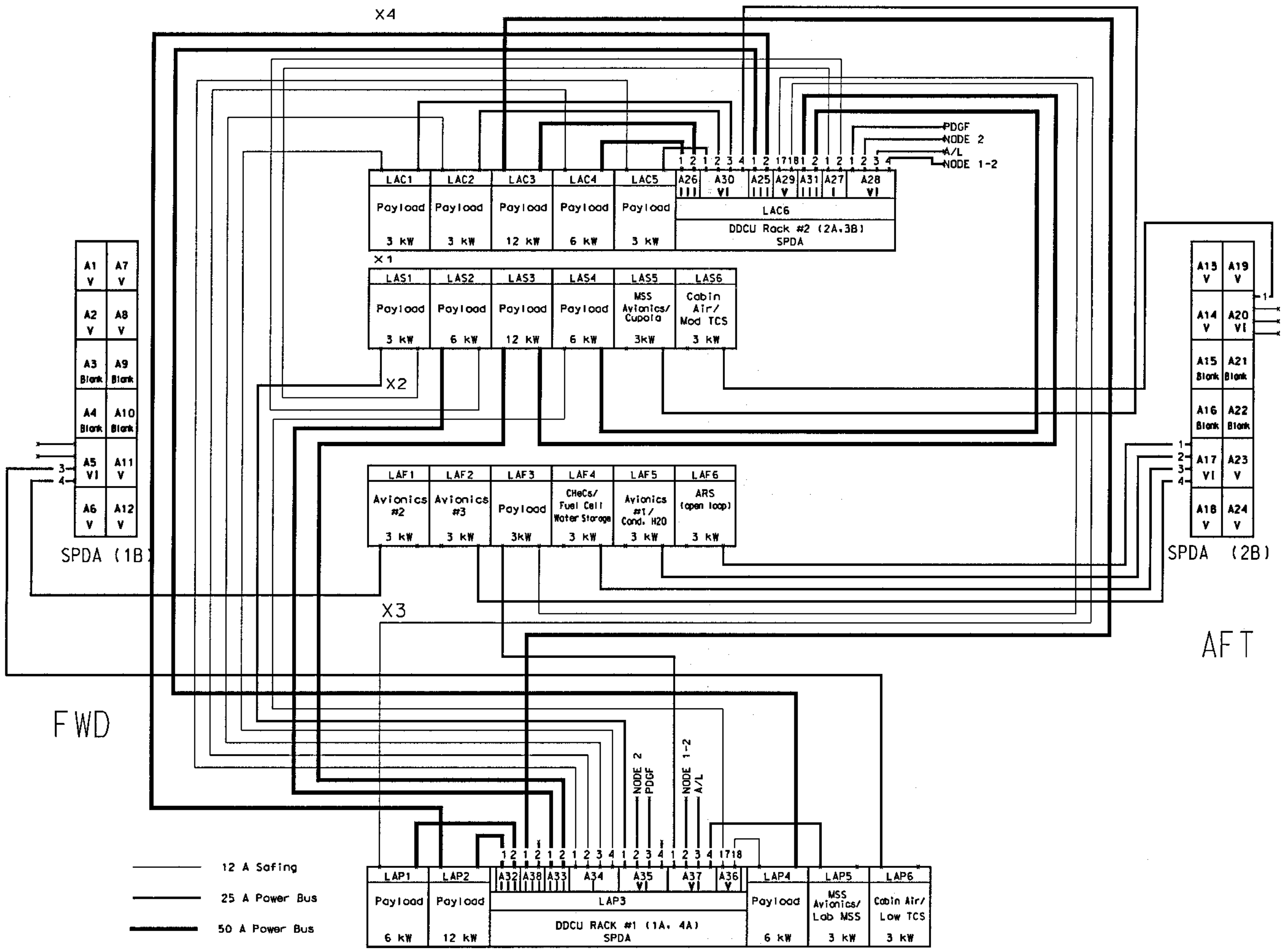

Fig. 1 USL electrical power system architecture.

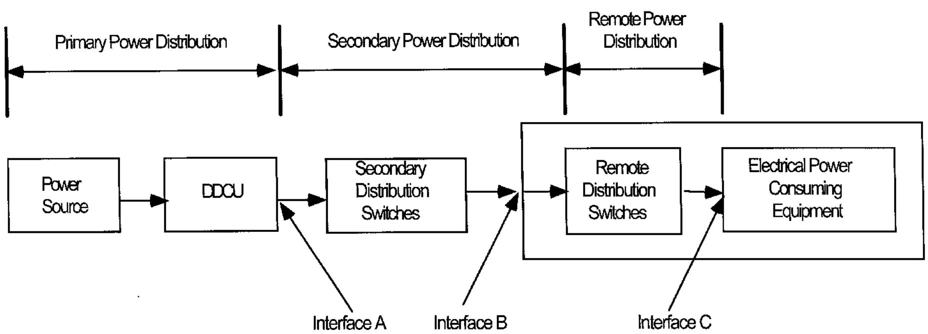

Fig. 2 Electrical power system interface.

methodology is developed using a mathematical algorithm based on probability theory and the convolution integral. Results from the mathematical model provide the optimum power channel loading and the match between power supply and demand.

USL power channel loading analysis has been updated periodically during the USL EPS design process.[3] Design analyses[3] also addresses the selection of RPCM and cable sizing to ensure system protection against faults. Therefore, the discussion in this paper will focus on power quality verification. Figure 3 shows the top-level VLN to verify the compliance of power quality. The success criteria for the VOs at each interface are derived from the performance requirements. For example, a VO may state that at interface A, the transient voltage shall be below 155 Vdc, the steady-state bus voltage shall be between 120–126 Vdc, the ripple voltage shall be less than 3 V peak-to-peak, and the minimum phase and gain margins calculated from the source impedance divided by the load impedance shall be 30 deg and 3 dB.

Stability Verification

Because of the multiple-level power conversion in the EPS, system stability becomes a critical design and performance consideration. The secondary power feeds many power loads that convert 120 Vdc to 28 V, ±15 V, ±12 V, ±5 V, etc., to feed specified electronics equipment. Power converters regulate output power to provide stable and constant output independent of input voltage variations. To maintain constant power, the power converter input impedance exhibits the characteristics of negative dynamic resistance. Negative resistance in an electrical network is a source of instability if the system is not properly damped, as determined by the design of load

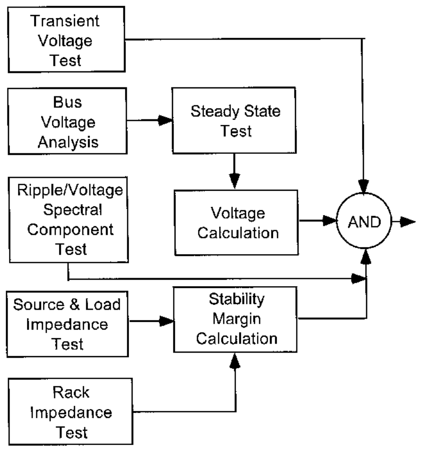

Fig. 3 Lab EPS top-level power quality VLN.

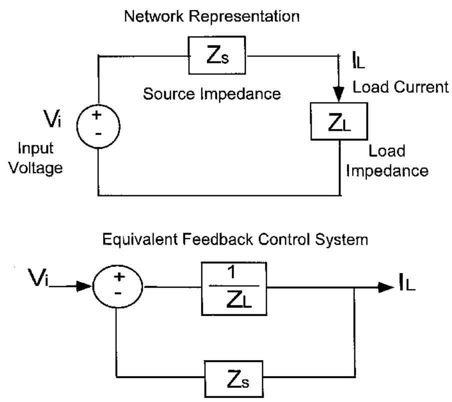

Fig. 4 Equivalent network representation for stability analysis.

converter, input filter, and the characteristics and configuration of the interconnecting cables. Stability criteria is developed by applying the Nyquist stability criteria to the equivalent feedback control system of an electrical network as shown in Fig. 4. The closed-loop transfer function of the electrical network is shown in Eq. (1):

$$T_{(s)} = \frac{I_{L(s)}}{V_{i(s)}} = \frac{1}{Z_{s(s)} + Z_{L(s)}} = \frac{1/Z_{L(s)}}{1 + Z_{s(s)}/Z_{L(s)}} \tag{1}$$

The network is stable if and only if the polar plot of $Z_{s(s)}/Z_{L(s)}$ at any interface in the network does not encircle $(-1, 0)$. The phase and gain margins of that interface is defined relative to $(-1, 0)$ and provide the indication of the stability of the system.

From the theoretical derivations stated earlier, the stability of USL EPS requires the analyses of source and load impedance at each interface in the EPS network. At each interface to the power loads external to the USL element, the source impedance will also be measured. The source impedance will be analyzed with the input impedance of the external network, which will be connected on orbit but verified independent of the USL element. The stability will be determined by the same methodology as other EPS interfaces inside the USL element. A state-space network impedance model is being developed for each power bus. The model will be linearized at each bus operating condition. The system eigenvalues provide the first indication of system stability. Furthermore, the model will be used to predict the phase and gain margins at different interfaces for operating conditions beyond the test scenario. The impedance test methodology will be illustrated by measuring the input impedance of a single power load. The same test procedure is applicable to each interface of the network under a variety of load operating conditions.

Impedance Measurement

A variety of test support equipment will be used for impedance measurements. A network impedance analyzer connected to a power breakout box will be used to conduct source and load impedance measurements. These measurements will consist of gain vs frequency plots and phase vs frequency plots for the frequency range of 100 Hz to 100 kHz as shown in Fig. 5. Each plot with its associated numerical data will be used to analyze the phase and gain margins at the interfaces defined in Fig. 2. When testing a fully integrated power bus, power breakout boxes are connected to each designated interface location where impedance measurements are made. The breakout boxes are connected in series with actual power loads [e.g., racks, orbital replacable units (ORVs), etc.] or simulated loads (resistive load bank). Interface cables provide connectivity for all of the previously mentioned hardware.

The system currently selected to be used in acquiring impedance data is the venable model 350 system. This system is integrated with a standard personal computer and the following equipment. Frequency response analyzer starter system: model 5060A frequency response analyzer, model 350 software, and IEEE-488 controller card. Input/output impedance measurement set: high power amplifier, injection transformer for use with dc current up to 100 amps, accuracy within 1% of magnitude and 1 deg for phase up to 100 kHz. Performance verification program: calibration lab software used to check and adjust the calibration of the model 350 frequency response analyzer.

Figure 6 shows a test setup for measuring the output impedance of the source and the input impedance of the load.[4] In this configuration the injection transformer along with a

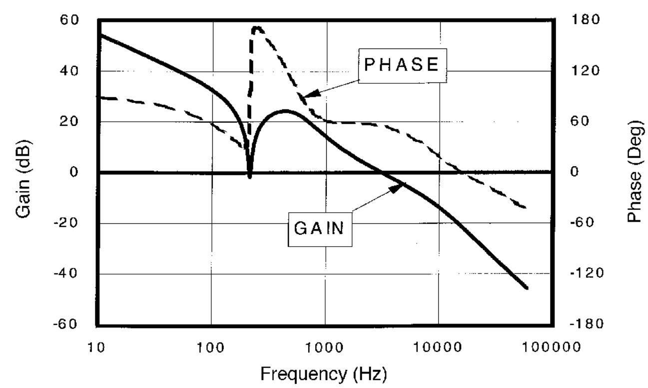

Fig. 5 Sample impedance measurement plot.

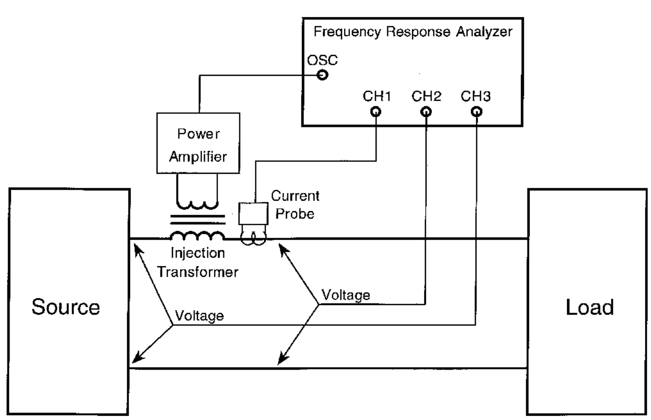

Fig. 6 Impedance measurement technique.

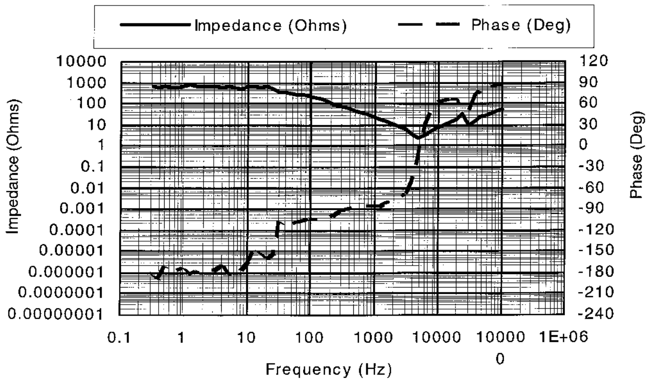

Fig. 7 Prototype VTR input load impedance measurement.

current probe used to measure the current will be packaged in the power breakout box. Power source output impedance is measured at CH3/CH1. Load input impedance is measured at CH2/CH1. The scale factor and the direction of the current probe have to be accounted for in scaling the measurement data. The data for the unit that the current probe is pointing away from need to be inverted (negative) to be accurate. The data for the unit that the current probe is pointing to will be correct (positive) as measured.

In USL test setup configurations, any measurement of load input impedance with respect to the source, the power transfer cable in the lab will be included in the input impedance measured. The selection of the cable contributes to the overall stability of the lab EPS. Figure 7 shows a plot of the impedance vs frequency of the prototype video tape recorder (VTR) input load impedance, as measured by the model 350 system without the cable effects.

Conclusions

The key design and performance requirements, and the verification approach for the ISS laboratory element EPS are summarized in this paper. The methodology of system stability verification, including the theoretical development, analyses, test methods, and instrumentation are discussed. The stability concept based on linear control theory verifies the power system stability at the operating conditions and is commonly referred to as the small-signal stability. The phase and gain margins analyzed from the impedance measurements provides the margins of stability at a particular operating condition. These analyses will be augmented by transient test data, such as the system response to a large step load change, to ensure overall power system stability. At the completion of assembly and checkout, the EPS will be tested as part of the U.S. laboratory element integrated testing.[5] These tests and their associated analysis will be used to satisfy all EPS verification objectives needed to closeout the EPS verification logic network and ensure that the USL EPS will function as specified when the USL is on orbit as a central ISS element.

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