

The Utility of Wide-Bandwidth Emulation to Evaluate Aircraft Power System Performance

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ABSTRACT

The cost and complexity of aircraft power systems limit the number of integrated system evaluations that can be performed in hardware. As a result, evaluations are often performed using emulators to mimic components or subsystems. As an example, aircraft generation systems are often tested using an emulator that consists of a bank of resistors that are switched to represent the power draw of one or more actuators. In this research, consideration is given to modern wide bandwidth emulators (WBEs) that use power electronics and digital controls to obtain wide bandwidth control of power, current, or voltage. Specifically, this paper first looks at how well a WBE can emulate the impedance of a load when coupled to a real-time model. Capturing the impedance of loads and sources is important for accurately assessing the small-signal stability of a system. Secondly, this paper demonstrates the merits of a WBE for characterizing aircraft sources and loads to identify key performance parameters. The parameters can then be plugged into a simplified model that is used in simulation to identify stability problems and worst case loading conditions for power quality.

CITATION: Bash, M., Pekarek, S., and Zumberge, J., "The Utility of Wide-Bandwidth Emulation to Evaluate Aircraft Power System Performance," *SAE Int. J. Aerosp.* 9(1):2016, doi:10.4271/2016-01-1982.

INTRODUCTION

With advances in power electronics and processing technologies, load emulators with power ratings in the hundreds of kW range can now be constructed with control bandwidths that exceed 20 kHz. As a result, these wide bandwidth emulators (WBEs) have the capability to emulate a wide range of expected current or power profiles of aircraft loads. This can be attractive, since one of the issues that is often raised in the design of aircraft power systems is the stability of the integrated plant. Specifically, researchers have shown that modern power systems can exhibit instability (sustained oscillations or loss of bus voltage), when relatively slow sources are connected to highly regulated loads [1], [2], [3], [4], [5].

One approach that has been used to predict small-signal stability is to characterize the impedance (admittance) of sources (loads) and use Nyquist-based criteria to explore undesirable source/load interaction [5]. In this paper, it is shown that wide bandwidth load emulators foster such an approach. Specifically, they can be used to characterize the impedance of sources by simply commanding load currents with small perturbations. The resulting dc bus voltage and current looking into the source are measured to calculate impedance. Similarly, wide bandwidth source emulators can be used to characterize the impedance of loads by commanding small perturbations in source

voltage. In both cases, the wide bandwidth, high power emulator provides an injected signal of sufficient amplitude to better avoid signal-to-noise ratio concerns.

In addition to measuring small-signal impedance, wide bandwidth emulators can be used to emulate the admittance of aircraft loads. This can be achieved using an experimental hardware-in-the-loop (xHIL) approach in which the load dynamics are simulated in real-time and coupled to a wide bandwidth emulator to recreate the relevant dynamics.

There are several examples of load and source emulation discussed in the literature. An active load emulator with a 3 kHz bandwidth is developed in [6]. In [7], a dc-dc converter is used to emulate the dynamics of a generator-rectifier source. Therein, the authors look at how the model time step and the converter bandwidth impact the ability to emulate a given source. In [8], a high performance source emulator is developed to represent photovoltaic systems with a fast transient response of 10 μ s. Higher fidelity battery emulation is discussed in [9], and the authors include measurements of how well the emulation can recreate battery impedance.

From the existing literature, there are various approaches taken to assess how well the emulator captures relevant dynamics. In this paper, the ability of an emulator to recreate small-signal impedance is analyzed. Rather than simply measuring the emulated impedance, the paper attempts to understand how the emulated impedance can be predicted from known system characteristics. The approach is demonstrated using simulation with supporting hardware measurements. Analytical techniques are then used to provide the upper limit of the frequency range that an xHIL-based admittance emulation can be expected to match the admittance of an actual component. Understanding this upper limit and pushing it higher with high bandwidth emulation is important in understanding how well small-signal stability effects can be recreated.

When analyzing the stability of aircraft power systems, small signal stability only provides a partial answer since demonstrating small-signal stability for a range of operating points still does not guarantee that the system will be large-signal stable. An approach to predict the large-signal stability of aircraft power systems was proposed in [10]. Within the proposed approach, a simplified, behavioral model representing the dynamics between the source current and dc bus voltage is derived. The simplified model is coupled to the models of aircraft loads, and the coupled source/load model is used to predict load power commands that lead to an instability in the bus voltage. Herein, it is shown that the load emulator can be used to support and extend such an approach. Specifically, it is shown that by using the load emulator to apply step changes in load current, the behavioral, source model can be readily characterized. Subsequent to characterization, it is shown that the behavioral model can be used to establish behaviors in the power profile of loads that lead to bus voltages outside the range of MIL-STD-704F [11]. Thus, the simplified model can be used to help identify not only large-signal stability problems, but also power quality problems due to transient loading.

OVERVIEW OF THE SOURCE-LOAD SYSTEM

The laboratory source-load system used in this paper to investigate WBE is shown in Figure 1, with key details of the source expanded in Figure 2. For cost-saving reasons, the 270 Vdc source is supplied by a permanent magnet generator connected to a passive rectifier followed by a dc-dc converter. Although this is not a configuration one would expect to see in an actual aircraft, the combined behavior of the system is representative of an aircraft source. The source connects to the load through a length of cabling. Understanding the cable impedance is important to stability-related investigations. Finally, a wide bandwidth load emulator is used to represent an array of aircraft loads.

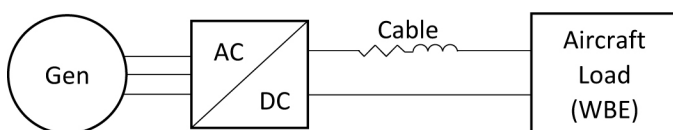


Figure 1. Basic diagram of the source-load system used herein.

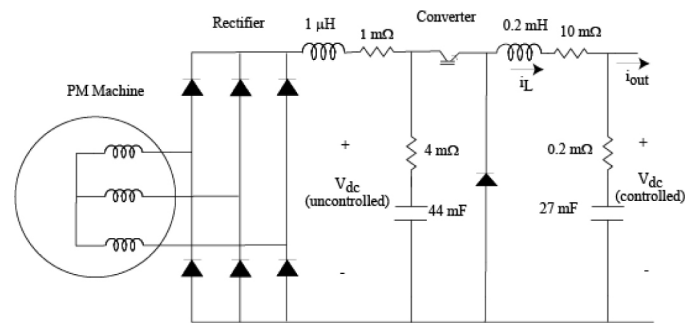


Figure 2. Details of the laboratory dc source.

The specific load emulator discussed in this paper is the DC Emulator (DCE) developed by E&M Power [12]. The DCE was originally called the Advanced Power Emulator (APE) when under development for the US Air Force. The DCE is a highly dynamic, wide bandwidth, bi-directional, dc load/source designed for laboratory testing. The original design goal for the DCE was a small-signal bandwidth of 20 kHz and a slew rate of 100% power in 1 ms. The DCE has exceeded both of these goals. In current mode, the DCE is set up to track current, power, and admittance commands. The DCE also has a fast voltage mode for wide bandwidth source emulation, as well as a low impedance voltage mode for situations where a stiffer voltage source is required. In addition, the DCE has a custom fiber interface that supports digital control at a rate of 2 MHz. The high speed control and communication is important to being able to take advantage of the wide bandwidth capabilities.

This paper utilizes both hardware and simulation results for the source-load system shown in Figure 1 and Figure 2. Detailed models of the system components have been developed and compared to hardware data under previous research efforts. The detailed model of the integrated system is developed in MATLAB/Simulink. The source model includes a traditional qd0 machine model coupled to a switch-level model of a passive rectifier and a switch-level model of the dc-dc converter. A switch-level model of the DCE is available; however, due to the high effective switching frequency, the computation time of the switch-level model is prohibitively slow. As a result, an average-value model of the DCE that has been shown to match reasonably well to the more detailed model is utilized in most simulations. The model of the source-load has proven to be a good tool for investigating the potential uses of WBE discussed in this paper.

IMPEDANCE EMULATION FOR xHIL

When considering an xHIL application, the dc load to be emulated in hardware can be represented as shown in Figure 3, where Y is the admittance (reciprocal of impedance). Using the xHIL approach, the load dynamics are emulated by a simulation running in real-time and interfacing to a load emulator. Although it can be difficult to fully capture the load dynamics within a real-time simulation, for the purpose of evaluating the load emulator, it is assumed that the real-time simulation does capture the pertinent dynamics.

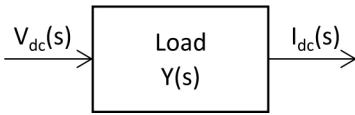


Figure 3. Block diagram of the load under test.

Coupling the real-time model to a WBE, the resulting emulated load can be represented as shown in Figure 4. As shown, the dc bus voltage is sampled and sent to the real-time model as an input. The real-time model computes the dc current based on the input dc bus voltage, and this current is sent as a command to the WBE. The asterisk in $I_{dc}^*(s)$ is used to denote a commanded or desired value. A zero order hold (ZOH) is included between the model and WBE since the model is executed at a discrete rate. The ability of the load emulator to track the command can be determined from the current regulator closed loop response, $I(s)/I^*(s)$. Although the control bandwidth of a given emulator is a key performance indicator, it is important not to forget that the load emulator's equivalent small-signal impedance will also play a role in an xHIL application. This is captured by the top path in Figure 4. From an equivalent circuit standpoint, the WBE can be viewed as a current source with an equivalent source impedance. The value of the current will be set by the load model and the WBE control response. Using the representation in Figure 4, the question of how well the load impedance is emulated can be investigated.

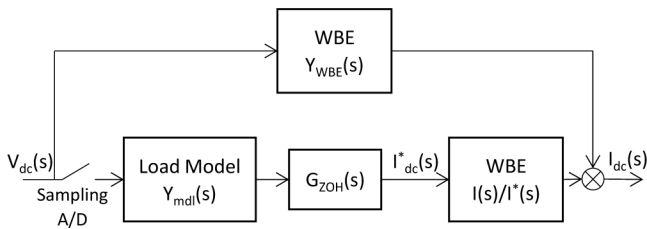


Figure 4. Block diagram of the emulated load (WBE coupled to a real-time model).

From Figure 4, neglecting the discrete nature of the real-time model, the equivalent transfer function for the emulated load can be written as,

$$Y_{emulated} = Y_{mdl}(s) \frac{I(s)}{I^*(s)} + Y_{WBE}(s) \quad (1)$$

Looking at the first term, it can be seen that the load model admittance is directly affected by the closed loop current regulator response ($I(s)/I^*(s)$) of the WBE. As discussed in the overview section, the DCE is used herein as an excellent example of a WBE. The closed loop response of the DCE from both hardware measurements and simulation is shown in Figure 5. The bandwidth of the emulator is found to be about 40 kHz. When using the DCE to closely emulate load dynamics, the goal would be to maintain as much accuracy as possible, or at least, to understand where the accuracy starts to degrade. With this in mind, the modeled load admittance will begin to be affected when the closed loop gain deviates from 0 dB and the closed loop phase deviates from 0 deg. As for all emulators, this deviation happens well before the 3 dB point. At -3dB, the phase error is greater than 90 degrees. In terms of emulating a load for stability purposes, the phase plays an important

role, and thus, understanding potential phase error is important. At 4 kHz, the phase error is about 5 degrees and the magnitude error is about 4% (0.37 dB). The phase error increases to 10 degrees at about 7.8 kHz with a magnitude error of 10.5%. The acceptable level of error for high accuracy emulation is likely in the range of 4-7 kHz, depending on the exact application. This highlights the importance of the wide bandwidth emulation, since phase typically starts to roll off about a decade before the 3 dB point.

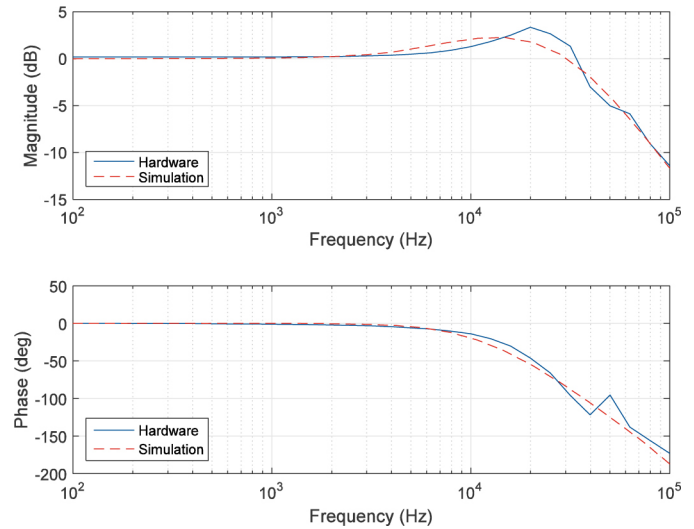


Figure 5. Closed loop current regulator response of the DCE.

As mentioned, Figure 5 includes both hardware and simulation results. For the hardware measurements, the DCE was supplied by the laboratory source shown in Figure 2 with roughly 7 uH of cable inductance. Sinusoidal current commands of 14 A-rms were used. The simulation measurements were performed using an ideal 270 V source and sinusoidal current commands of 7.07 A-rms. The closed-loop current response is affected by the characteristics of the source and cabling. However, based on several hardware and simulation measurements, the DCE maintains its ability to closely track current out to the 4 kHz range.

In addition to the emulator control dynamics, the discrete rate set by the model time step will also play a role in the emulation (G_{ZOH} in Figure 4). The DCE can support high rates of communication via analog I/O or a digital fiber interface. Measured bus voltage is updated every 1 μ s and commands are read every 0.5 μ s. Assuming measured bus voltage is read from the DCE, a minimum discrete rate of 1 μ s is possible. The achievable model time step will depend on the complexity of the model being run and the computation capabilities of the real-time hardware. To analyze how various discrete rates affect the emulated system, the first term in Eq. (1) can be reevaluated including the sampling and ZOH as follows,

$$Z \left\{ \frac{I(s)}{I^*(s)} G_{ZOH}(s) Y_{mdl}(s) \right\} \quad (2)$$

Setting Y_{mdl} to 1, the impact of the discrete rate on just the closed loop transfer function can be investigated. Discrete rates of 0.5 μ s and 1 μ s are compared to the continuous case in Figure 6. As shown, the 1 μ s case is more accurate than the 0.5 μ s case.