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Hardware-in-the-Loop Testing of a High-Speed Generator Excitation Controller

ABSTRACT

Electrodynamics Associates (EA) is developing a MW-class high-speed generator and requires testing of the corresponding excitation controller at Florida State University's (FSU) Center for Advanced Power Systems (CAPS) in a controller hardware-in-the-loop (CHIL) environment. The goal of these tests is to verify the functionality of the generator excitation controller prior to a full scale power hardware-in-the-loop (PHIL) test of the entire generator. Such tests will become feasible at FSU-CAPS in spring of 2010 as the center is currently procuring a gear system that will extend the shaft speed range of the existing 5 MW PHIL facility for rotating machinery from 450 rpm up to 24,000 rpm. This paper focuses on the CHIL testing of the primary excitation system controller, in which the secondary excitation power supply, the main generator, the prime mover, and the load were simulated on a real-time computer simulator and interfaced to the controller. Simulating the high-speed generator in real-time is especially challenging since non real-time simulation models of such rotating machines typically contain relatively small time constants which pose challenges to real-time simulation algorithms. The paper discusses approaches to overcome these challenges. In addition, the plans and considerations for PHIL testing of the generator are addressed. This setup will enable, for the first time in a laboratory setup, PHIL testing of a MW scale high-speed generator with a realistic representation of its surrounding dynamic environment.

INTRODUCTION

Controller and power hardware-in-the-loop (CHIL and PHIL) simulations are emerging approaches for advanced experimentation, whereby a piece of hardware is operated from a real-time virtual system. Signals are provided to the device under test by means of low-power analog and discrete signals and/or power amplification. The results reported here concern the first phase of CHIL tests before proceeding with PHIL of the entire Electrodynamics Associates (EA) generation system at the MW-level.

The high-speed generator under development requires verification of the functionality of the generator excitation system prior to full scale power HIL tests. The excitation system and voltage control arrangement of the CHIL experiments at Florida State University's (FSU) Center for Advanced Power Systems (CAPS) in a controller hardware-in-the-loop (HIL) environment are shown in Figure 1. The goal of these tests is to validate the control design and is comparable to previous HIL tests conducted at CAPS, see Steurer (2007) and Langston et al. (2009). Additional PHIL tests will become feasible at FSU-CAPS later this year as the center is adding a 5 MW rated gear system for its low speed 5 MW dynamometers, which will allow power HIL testing of rotating machinery at shaft speeds up to 24,000 rpm. The load for the generator will be emulated using the real-time simulator to control a 5 MW variable voltage source.

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14. ABSTRACT
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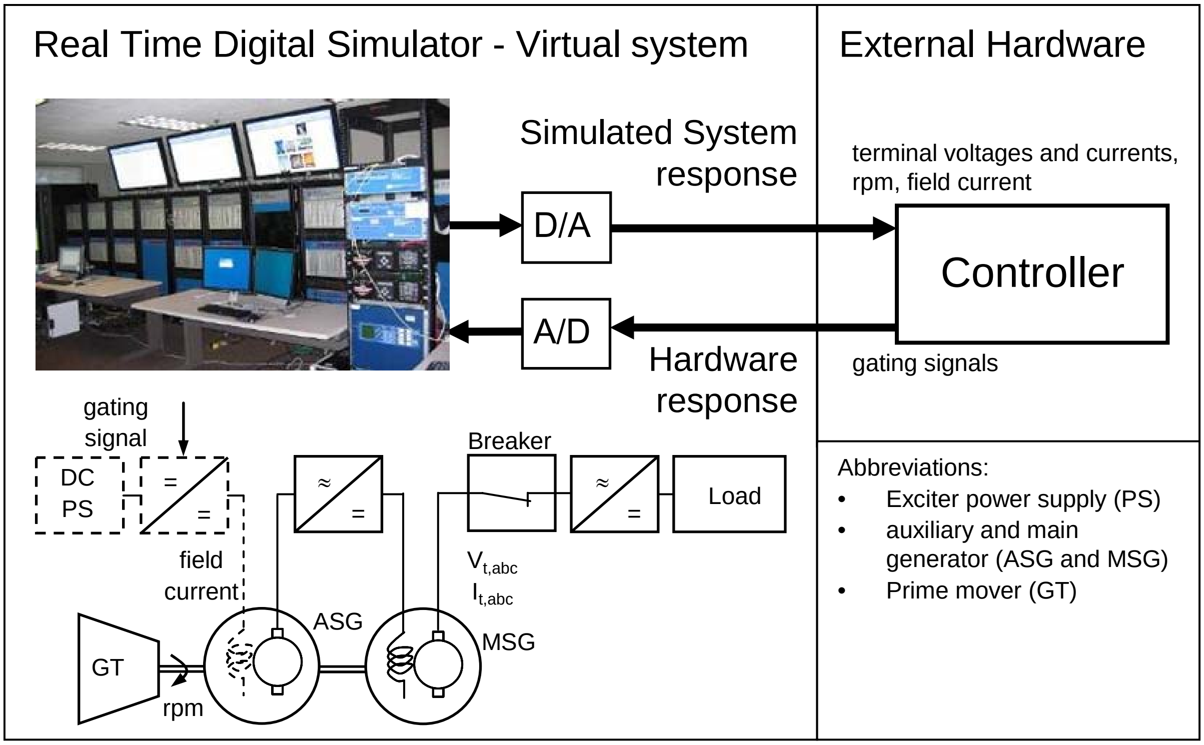

FIGURE 1. Control hardware-in-the-loop arrangement

MODELING AND SUB-SYSTEM CHARACTERISTICS

The individual system model components are shown in Figure 1 and associated challenges with respect to real-time simulation are described next.

The gas turbine model follows the guidelines given in Ballin (1988) and represents a turboshaft engine. As the model has been designed with real-time simulation in mind, no additional remarks need to be given here. The gas turbine is coupled with the synchronous generators through a gear box. For simplicity, no gear box dynamics are modeled specifically. The inertia of the gears are lumped into the gas turbine model.

The synchronous generator model of the high-speed generator follows conventional guidelines and can be found in many references, see for example Krause, Wasynczuk, and Sudhoff (2003). The important difference to common applications of synchronous generator models for utility systems is that in the target application the generator stands alone to supply a single load through a passive rectifier. In such cases very low inductances in the high-speed generator yield very small time constants under light loading conditions. This poses a challenge to real-time simulation tools. In combination with the restrictions on a minimum time step to achieve the desired real-time simulation, both integrator and differentiator based models were implemented to allow simulating and testing of loading conditions ranging from about 2% to full rated power. The minimum simulation time step is dependent upon the computational burden governed by the model details and lies typically in the range of a few microseconds to 50 µs using the real-time digital simulator (RTDS, Kuffel et al. (1995)) at CAPS. For this model the resulting time step size was 15 µs.

The integrator based model has flux linkages per second as state variables, uses currents as outputs, voltages as inputs, and allows simulation of loading conditions from about 25% to 100%. The derivative based models uses currents as inputs and approximations of derivatives of the flux linkages per second to compute the terminal voltages. This model allows simulation of the whole operating range before the minimum time step for real-time simulation leads to instabilities during simulations. The reason for the ability of the derivative based model to simulate light loading conditions of an islanded generator is due to the approximation of the derivates with a wash-out filter that effectively provides a barrier for the eigenvalues of the system. As the load decreases, and the equivalent load resistance increases, the respective eigenvalues move to the left in the complex plane. This means that the corresponding time constants decrease and the simulation time steps needs to be reduced appropriately to yield stable and accurate results.

Because the switching frequency for the main generator's excitation power supply was on the order of 10 kHz, the power supply was modeled as a small time-step environment subsystem using a time-step size of 1.5 μs. The voltage applied to the exciter field winding was filtered to remove the high frequency components before being applied to the field winding of the model in the large time-step environment, which employed the 15 μs time-step size. The excitation reference signal is based on the outer loop rms-voltage controller with a bandwidth of several 100 Hz.

Another challenge for both the real system and the simulated model concerns the load interface which is an uncontrolled three-phase rectifier. The rectifier may be connected through a short cable to the generator terminals and supplies a constant dc power load with a corresponding cut-off frequency of several kilo-hertz. As the frequency of the generator ac output voltages and currents is on the order of 1 kHz, fast transients are involved in current commutation between the phases. However, since modeling of these transients is not of interest for tuning of the exciter system to control the desired rms value of the voltage at the generator terminals, a dynamic average-value model has been implemented instead of the detailed switching-based model Krause, Wasynczuk, and Sudhoff (2003) with harmonics neglected.

MODEL VALIDATION

As the need for real-time execution of the virtual system model required sub-system models to be either implemented differently from conventionally used models or simplified, significant model validation efforts were undertaken. The results from both sub-systems and overall real-time model were compared to results obtained from high-fidelity non real-time switching models.

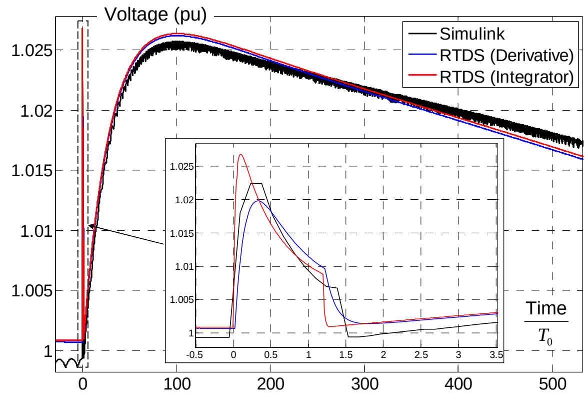

FIGURE 2. Comparing results for terminal rms-voltage using different model implementations: Detailed switching-based model in Simulink (offline simulation), RTDS using derivative-based generator models, and RTDS using integrator-based generator models

The results shown in Figure 2 compare simulation results for offline (non-real-time) and real-time simulation results. The offline implementation uses a detailed switching and integrator based implementation in Simulink (The MathWorks (2010)). The real-time results using the RTDS compare derivative and integrator-based approaches. Both axis are shown in per unit using nominal voltage and fundamental period as base quantities and demonstrate that the rms-voltages at the generator terminals match reasonably well. The inset figure shows the initial transients in more detail and a closer look reveals that the derivative-based approach yields slightly slower and the integrator-based slightly faster transients when compared to the off-line, i.e., much lower simulation time step, results.

REAL-TIME EXPERIMENTS

The goal of the tests was to verify operation and tune the two cascaded control loops to stabilize the terminal voltage at the desired rms reference value while limiting the field current to a chosen maximum value. The control board was connected to the real-time simulator using available A/D and D/A interfaces, as in Figure 1. The controller supplied the gating signal to the simulated power supply receiving feedback of the excitation field winding current and the currents and voltages at the terminals of the generator. A number of dynamic tests were carried out in which step changes in the load were applied and the ability of the controller to regulate the terminal voltage was assessed. Additionally, tests were conducted to ensure proper operation of protection functions for over- and under-frequency, over- and under-voltage, and voltage imbalance conditions.

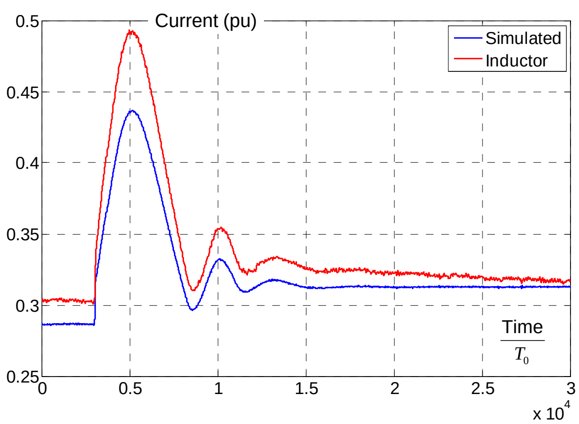

FIGURE 3. Comparison of simulated exciter field winding current and actual current through the load inductor (normalized scales and filtered for clarity)

In order to test the ability of the controller hardware to dynamically deliver current, CHIL tests were also conducted in which the controller was used to control current through a load inductor specifically designed to mimic the characteristics of the exciter field winding. For these tests, the controller received feedback of the voltages and currents at the terminals of the simulated generator, as usual. However, the controller received feedback for the exciter field current from current probes measuring the current into the load inductor. The voltage of the external DC power supply and converter (the components drawn with dashed lines in Figure 1) for the controller hardware was supplied to the simulation to adjust the simulated power supply voltage for consistency. Comparisons of the measured current through the inductor with the simulated exciter field current showed reasonably good agreement, as illustrated by Figure 3 for a scenario in which the load power was abruptly increased by 0.2 pu (the time axis is again normalized by T0, the period of the fundamental component.) The offset in steady-state values is due to neglecting the temperature dependence of the field winding resistance. Thus, the resistance of the inductor, which does exhibit this temperature dependence, is lower than the resistance modeled in the simulation (which represents the hot resistance), leading to a lower current in the simulation. The corresponding generator speed trace is shown in Figure 4. While not truly a PHIL experiment, this approach provided a relatively simple means to test the ability of the controller hardware to drive the necessary current under dynamic conditions.

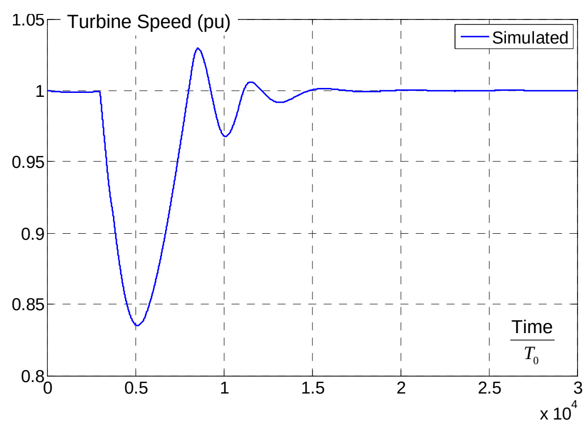

FIGURE 4. Generator speed for CHIL test (normalized scales)

FUTURE PLANS FOR POWER HARDWARE IN THE LOOP TESTING

The plans for the next phase seek to use the upgraded PHIL facility to test the entire high-speed generator system. The corresponding arrangement of laboratory equipment, hardware under test, and the real-time simulator is shown in Figure 5.

The gear box links the high and low speed shafts in two conversion steps. The gear box is rated at

5 MW and will allow use the full dynamic range of both the dynamometers and the variable voltage source (VVS). For this phase of testing only the load and the prime mover will be simulated. The simulated prime mover will be interfaced to the generator through the two dynamometers, and the load will be interfaced through the VVS. For this work, the VVS is intended to be operated in dc mode and interfaced to the generator through a diode rectifier. This approach will facilitate testing of the generator under realistic conditions reflecting the dynamics of the prime mover and load.

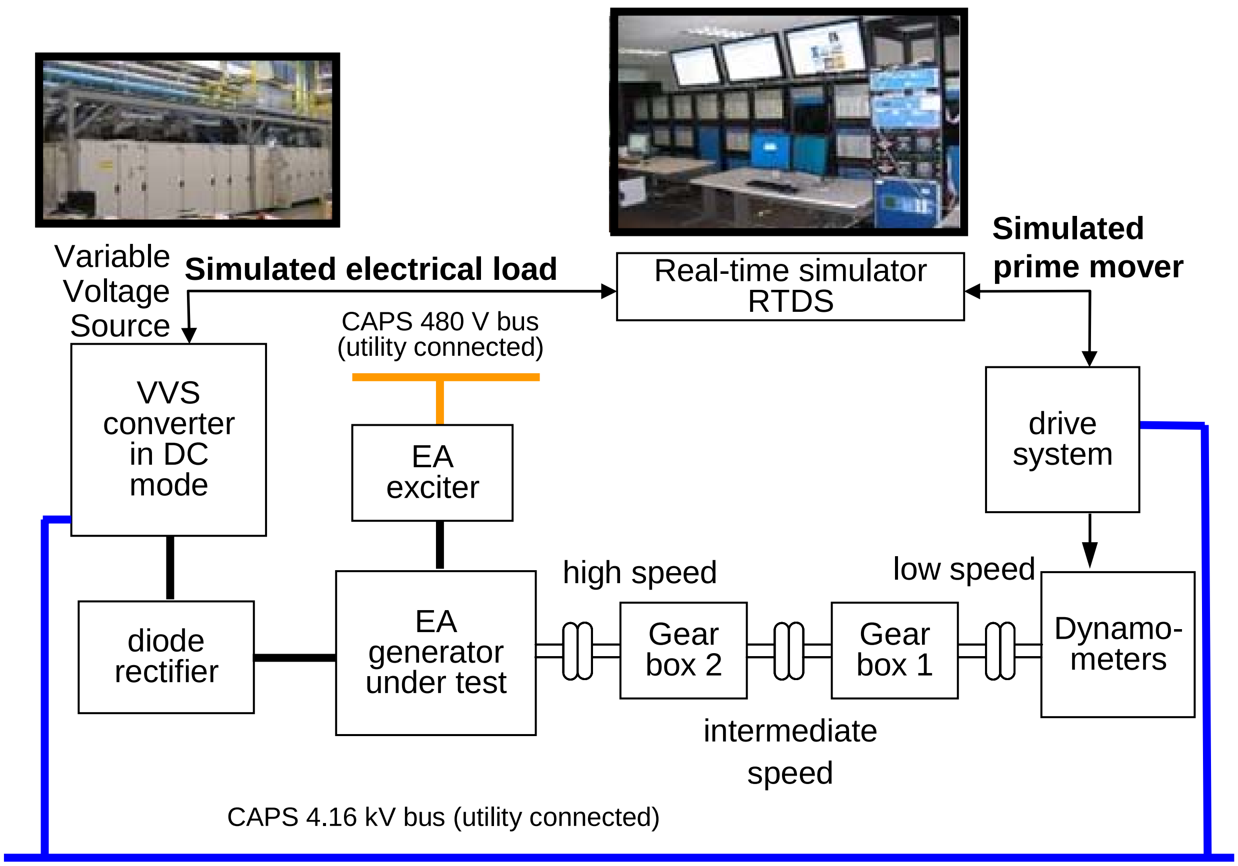

FIGURE 5. Proposed PHIL testing arrangement

CONCLUSION

The first phase of control hardware in the loop experiments in evaluating a high-speed generator system with a local load proved challenging due to the computational demands posed by the high frequency output of the generator. In addition, restrictions due to the minimum simulation time step necessary to achieve real-time simulation require careful consideration in both model details and implementation strategy. The burdens encountered and solutions found have been discussed. In conclusion, the current modeling and simulation approach allows testing of voltage controllers and excitation systems of high-speed generators. The proposed MW scale power hardware in the loop testing arrangement for the entire generator system has been outlined. In the future, additional work will be required to improve the ability of real-time simulation tools to accommodate ac output of high-speed generators with frequencies significantly above 400 Hz.

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