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Megawatt Scale Hardware-in-the-Loop Testing of a High Speed Generator

ABSTRACT

A megawatt scale test bed for power hardware-in-the-loop experimentation with high speed generators is described, and selected results from testing of a generator are presented. The test bed includes a dynamometer and high speed gearbox used to deliver up to 5 MW to the mechanical shaft of a generator at speeds of up to 24000 rpm. A rectifier using fast recovery diodes is used to rectify the voltage at the terminals of the machine, and a 2.5 MW bi-directional DC converter is used as a dynamic load for the generator. Both the dynamometer and converter are controlled using a large scale real time simulator, enabling power hardware-in-the-loop simulation experiments to be conducted. Herein, testing is described of a new, prototype high speed generator and its associated voltage regulator using this facility. The generator has been subjected to steady-state loading at power levels above 1 MW, as well as load ramps with rates exceeding 500 kW/s. Challenges involved in the testing, as well as some of the possibilities for future tests with the setup are described.

INTRODUCTION

Hardware-in-the-loop (HIL) simulation experiments provide a flexible and often cost effective way to exercise equipment and controllers in a realistic environment prior to deployment in a real system. While controller HIL (CHIL) simulation experiments are conducted by interfacing controllers to real time simulations of the equipment at the control signal level, power HIL (PHIL) simulation experiments require the use of power actuators (e.g. dynamometers and power amplifiers) to couple the simulated equipment to the device under test. Since 2003, a dedicated facility for conducting PHIL simulation tests at the megawatt level has been established at the Center for Advanced Power Systems (CAPS) at the Florida State University. The facility has been used to conduct a number of PHIL tests ranging from a 5 MW prototype high temperature superconducting propulsion motor (Woodruff et al., 2005), to superconducting fault current limiters (Schacherer et al., 2009 and Llambes et al., 2011). While the facility provides substantial flexibility through the integration of a 5 MW, 450 rpm dynamometer, a 5 MW variable voltage source (VVS), and a large scale real time simulator, the range of rotating machinery that could be tested was limited to relatively slow speed machines due to the speed limitation of the dynamometer. As trends in the development of smaller and lighter high speed generators tend toward higher power levels, these machines become ever more appealing for applications in which size and weight command a premium, such as marine and aviation applications. In order to extend the capabilities of the CAPS facility to accommodate testing of this increasingly important class of machines, a two stage high speed gearbox was acquired through a Defense University Research Instrumentation Program (DURIP) grant and commissioned in April 2011. By allowing the low speed dynamometer to drive machines under test at speeds of up to 24,000 rpm, this gearbox enables the testing of a large group of high speed generators.

A new design for a megawatt class high speed generator operating at 15,000 rpm was recently developed by Electrodynamics Associates, Inc. (EA). The machine was targeted to be tested at the CAPS facility once the high speed gear box was installed, with a preliminary phase of the

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project to perform CHIL testing of the voltage regulator carried out in 2010. In the first phase of the work, described by Schoder et al. (2010), models for the generator and excitation power supply, along with a gas turbine and electrical load, were simulated in real time and interfaced to the controller. The firing pulses from the controller were supplied to the simulator, and the voltages and currents at the terminals and field winding of the simulated generator, along with the machine speed, were fed back to the controller. In this way, the controller was tuned and tested for a range of dynamic events with the simulated system. In the subsequent phase of the project, the actual machine and voltage regulator were brought to the CAPS facility, and testing of the machine officially began in May 2011.

In this paper, the CAPS PHIL simulation testing facility, including the dynamometer, gearbox, VVS, and the real time simulator are briefly described, along with the generator under test. The details of the PHIL test setup are then discussed, including the rectifier and torque transducer used for the experiments, and the developed real time simulation case. The conducted tests are then discussed, and selected results are presented. The paper cocludes with a discussion of the challenges and limitations of testing, as well as a discussion of more elaborate, future PHIL tests that are enabled by this setup.

PHIL Simulation Testing Facility at CAPS

The 5 MW PHIL test bed at CAPS, described by Steurer et al. (2010), is illustrated by Figure 1. The facility includes a 5 MW dynamometer set, making use of two 2.5 MW, 450 rpm induction machines that can be operated in tandem to supply or absorb up to 5 MW of mechanical power on the shaft of a rotating machine. The dynamometer is also designed for 3 pu overload torque for short periods of time, enhancing the capability for acceleration of machinery. The facility also makes use of a 5 MW VVS which serves as a power amplifier with an effective bandwidth of approximately 1.2 kHz. The VVS can be operated as a single 5 MW unit to produce arbitrary AC waveforms with fundamental frequency components ranging from 40 to 400 Hz and up to 4.16 kV in magnitude. Alternatively, the VVS can be operated as a 2.5 MW AC amplifier and a separate 2.5 MW DC amplifier rated for 1.2 kV. In both configurations, the VVS operates as a fully bidirectional amplifier, allowing power to be either supplied or absorbed. A commercial real time digital simulator (RTDS) (Kuffel et al., 1995) is used for simulation and control with the test bed. The RTDS executes electromagnetic transient simulations in real time using time-step sizes on the order of 50 μs, with the capability to simulate converters in small subsystems with time-step sizes on the order of 2 μs. The simulator provides substantial I/O capabilities for interfacing with the dynamometer, VVS, and the device under test. In the context of PHIL simulation tests, the RTDS serves several functional roles, including monitoring and real time display of measured quantities, simulation of systems to be emulated, control of the power actuators, and protection. Thus, these components provide mechanical and electrical actuation, along with simulation and control, to facilitate PHIL simulation experiments at a megawatt scale.

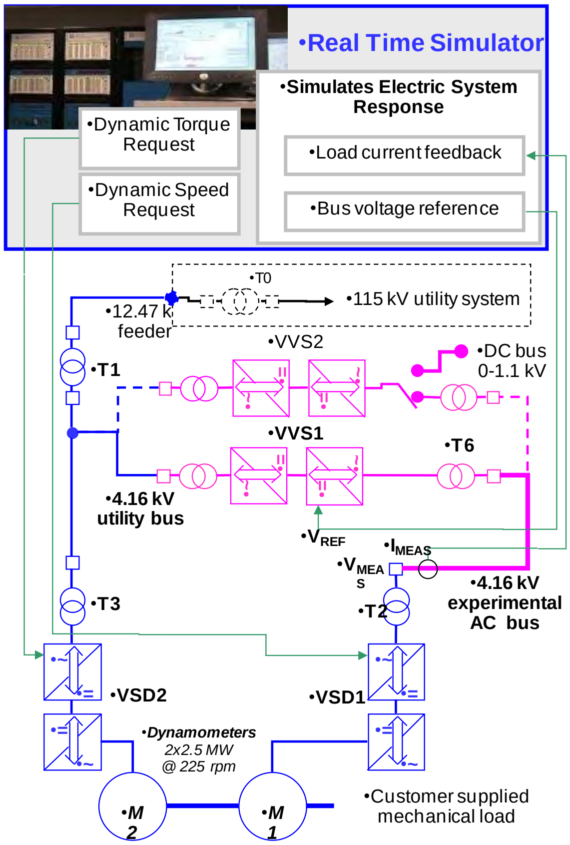

Figure 1 CAPS PHIL Testing Facility

The most recent enhancement to the CAPS PHIL test facility is the addition of a 5 MW, high speed gearbox, purchased through a DURIP grant and installed in 2011. The gearbox is an epicyclic, two-stage design, constructed such that the center line of the output shaft of both stages remains centered on the test bed mounting rails and in-line with the output shaft of the existing dynamometer. The gearbox was designed and built by Lufkin (France) to match the available overload capabilities of the dynamometer (3 pu torque at near zero speed and 2 pu torque at base speed of 225 rpm for 1 minute). The gear ratio for the first stage is 1 : 8.087, resulting in a nominal maximum output speed of 3600 rpm. The second stage has a ratio of 1 : 6.548, resulting in a maximum speed of 24,000 rpm on the high speed shaft.

High Speed Generator

The machine tested, shown in Figure 2, is a 15,000 rpm, oil cooled generator designed for 1.2 MW continuous and 2.5 MW intermittent power. The generator is a two-stage machine composed of a brushless DC exciter and main generator, weighing 390 pounds (an alternative housing is also available, which reduces the weight to 330 pounds). The machine is designed to nominally supply 620 V at 1.5 kHz fundamental frequency, and is rated for up to 2.45 kA current. The rated torque for the machine is 1591 N·m.

Figure 2 High Speed Generator

Test Setup

The general configuration of the test setup is illustrated by Figure 3. The dynamometer is coupled through the high speed gear box to the shaft of the generator. A torque transducer rated for 2000 N·m and 22,000 rpm constructed by HBM (Germany) is used to measure the torque and speed on the high speed shaft. A flexible coupling with shear section, constructed by Coupling Corporation of America, is used to couple the torque transducer to the generator shaft.

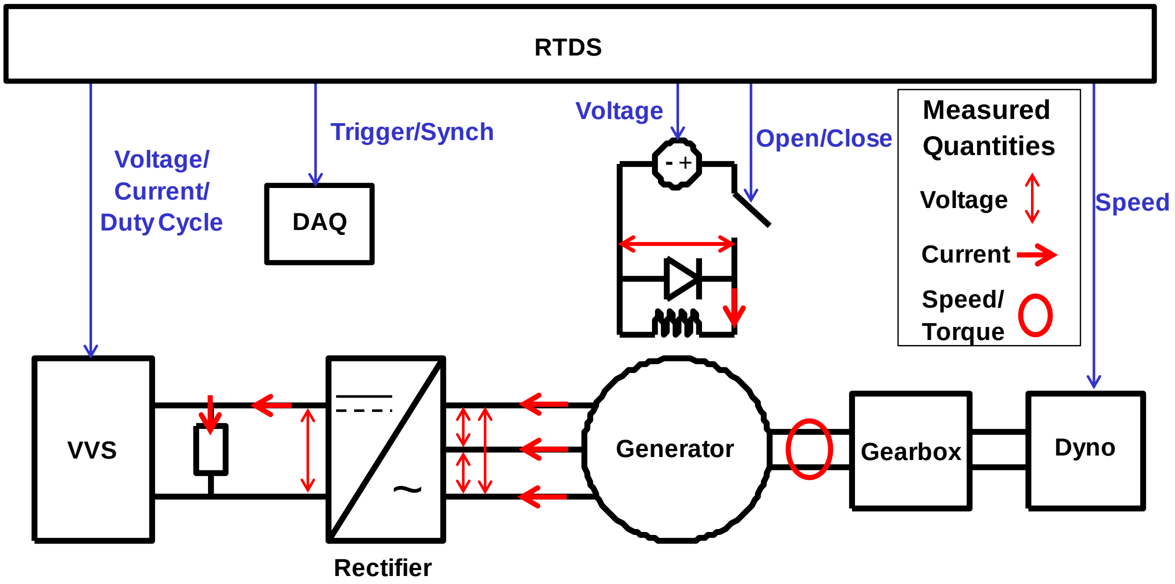

Figure 3 Test Setup

Because the fundamental frequency at the generator terminals is too high for the VVS to act as an AC load, a rectifier is used to interface the generator with the VVS, with the VVS operating in DC mode to serve as a dynamic load. The primary advantage of using the VVS as a load in the experiments (as opposed to a resistive load bank), is that the loading on the generator can be continuously and dynamically controlled, allowing emulation of a wide range of loads and load characteristics. A secondary advantage is that, since the load power is regenerated, only the power losses in the components are dissipated. Again, due to the high fundamental frequency of the generator voltage, a standard, 60 Hz rectifier could not be used for this application. Instead, a 3 MW, 1.2 kV rectifier was constructed for use in the testing by IXYS Long Beach using fast recovery diodes. In order to provide a small base resistive load in the event the VVS was tripped offline, a 2.6 Ω resistive load bank is placed in parallel with the VVS on the DC bus, providing about 125 kW of load with the generator operating at 440 V.

Two different modes of operation were used for excitation of the generator over the period of testing. For some tests, a controllable voltage source was used for manual adjustment of excitation, while in other tests the voltage regulator and controls developed by EA were used to regulate the terminal voltage of the machine. In both cases a switch, controlled by the RTDS case, was placed in series with the exciter field winding of the machine along with a parallel freewheeling diode, as illustrated in Figure 3. This setup allows the machine to be immediately de-excited if a problem is detected during testing.

As illustrated by Figure 3, a number of quantities are measured and provided to the RTDS for monitoring, control, and data capture. These include the torque and speed at the high speed shaft, the voltages and currents at the terminals of the machine, and the voltages and currents at the exciter field winding. Additionally, the voltage and current at the DC terminals of the rectifier and the current into the resistive load bank are used. Due to the high fundamental frequency of the generator and the presence of harmonics, the maximum sampling resolution of the RTDS (dictated by the simulation time-step size of 30 μs that was used) was not sufficient for many data recording purposes. For this reason, many of the measured quantities are also provided to a dedicated data acquisition system, which is able to sample at 1 μs resolution. Measurements of oil flow and temperatures within the machine are also provided to the data acquisition system at low time-scale resolution for monitoring and logging purposes. Accelerometers were also installed on the generator for monitoring of vibrations by EA.

As illustrated by Figure 3, the RTDS case provides several control signals to the test setup, including the dynamometer speed reference and the excitation voltage reference (for tests in which manual excitation is used). A signal from the RTDS is also used to open and close the series excitation switch. The RTDS case also provides a reference signal to the VVS, which is interpreted by the VVS differently depending on the mode of operation. For these tests, three different modes of control for the VVS were used. In the normal, closed-loop voltage control mode, the RTDS sends a voltage reference, and the VVS controls maintain the reference voltage at the terminals of the VVS. Because there were initially concerns about possible interactions between the VVS voltage controls and the voltage regulator used to maintain the terminal voltage of the generator, the VVS was operated in a "bypass" mode for the initial tests involving the generator voltage regulator. In this mode, the RTDS essentially provides a duty cycle to the VVS in order to effectively achieve an open-loop voltage control for the VVS. In the third mode of operation, the outer voltage control loops of the VVS are bypassed, and a current reference signal is sent from the RTDS to the VVS inner current control loops, operating the VVS as a current sink. Thus, the reference signal from the RTDS to the VVS can serve as a voltage, duty cycle, or current reference. A trigger signal is also provided from the RTDS to the data acquisition system to allow high resolution captures to be synchronized with test events. Although a crash of the RTDS system was not encountered during testing, where possible, the signal levels were defined in a way to cause a shutdown of the experiment in the event of an RTDS case failure. In the event of such a failure, the RTDS analog output signals revert to zero volts. Thus, the series excitation switch is configured to close with a high value from the RTDS, so that a failure of the case would result in de-excitation of the machine. Similarly, the speed reference for the dynamometer is configured to bring the machine to a stop in the event of a case failure.

The RTDS case serves a number of functional roles in the context of the test setup, supporting simulation, monitoring, control, and primary protection. The RTDS case is the primary means of controlling the experiment, presenting an interface to the operator for controlling dynamometer speed, VVS voltage or current, excitation voltage, triggering plot captures, etc., as well as displaying real time information on monitored quantities and status of protection elements. The case makes use of instantaneous voltages and currents to compute and display root mean square (rms) and filtered quantities, as well as power. The interface also allows the operator to take short captures and plot the instantaneous quantities. A script was written to maintain logs of trending data during the tests, writing all reference and metered values to a file at 1 s resolution. This slow speed trending data was used during tests to quickly generate plots such as saturation curves or torque-speed characteristics, monitor time spent above a given power level, or for other general purposes. The trend logs also served as general records for diagnostic purposes after the completion of tests. A number of protection elements, including over-voltage, over-current, over-speed, and over-torque were also implemented. Operator adjustable thresholds and pickup times for warnings and trips are provided for each of the protection elements. Warning thresholds, which are only used to alert the operator, were generally set more aggressively than the actual trip thresholds in order to notify the operators of the possibility of an impending trip. The trip thresholds, however, are used to initiate various protection actions, such as unloading of the machine, de-excitation of the machine, or bringing the machine to a stop. A single-click option for initiating a "graceful" shutdown of the experiment, by de-exciting the machine and gradually ramping the machine speed to zero, was also added to the RTDS case interface. Furthermore, an external switch was added in the experiment control room to allow any of the test participants to trigger the RTDS case to initiate this shutdown. A number of other protection measures, such as fuses, breakers, and limits in the dynamometer drives were put in place for the tests, but the RTDS protection implementation was used as the primary and preferred method to shut down the experiment in the event of a problem.

The RTDS case was also developed to support a simulation mode of operation, which serves as a method to test and debug controls, as well as a means for familiarizing the operators with the case interface. A simulation model of the entire PHIL test setup (dynamometer, gearbox, generator, rectifier, VVS, etc.), including delays, harmonic distortion, and sensor noise was implemented as part of the RTDS case. When executed in the simulation mode, all measured quantities are taken from the simulated setup, instead of the actual sensors, and reference values are sent to the simulated actuators and equipment. In this way, the same controls and protection functions that are used for the actual tests can be used with the simulated environment to control a mock experiment. This feature provided invaluable benefits over the testing period, through enabling testing and debugging of newly requested and added controls, as well as providing a means to train and familiarize operators with the added controls.

Startup Sequence

With the test setup as described above, the general startup procedure begins with the dynamometer at rest, the VVS off-line, the excitation voltage at zero, and the excitation switch in the open position. The machine is then ramped up to the desired speed, stopping at regular intervals to monitor vibration. Once at rated speed, the VVS is brought on line, sourcing current into the resistive load bank, and the DC voltage is brought to a value well above the desired line-line voltage for the machine. This procedure ensures that when the machine is excited, the rectifier diodes will be reverse-biased and the machine will not source current. The series excitation switch is then closed, and the machine is then excited, bringing the terminal voltage to the desired level. At this point, the VVS voltage can be slowly ramped down, and the machine will begin to source current. The current supplied by the machine initially flows into the load bank, reducing the contribution from the VVS. As the VVS voltage reference is further reduced, the VVS begins to sink current. In this way, the load on the machine can be dynamically controlled by adjusting the VVS voltage.

Testing

A large number of simulations and analyses were conducted in preparation for testing to study possible failure scenarios and the impact of uncertain model quantities such as stray inductance and capacitance. Several modifications to the planned test setup were made, and a test readiness review was conducted in April 2011, prior to the commencement of testing. Testing proceeded cautiously through an initial set of tests aimed at successively proving each part of the test setup. Spin tests, with no excitation, were first conducted with the generator in order to ensure that vibrations were within acceptable limits at the desired rotational speeds. These tests were followed up by open-circuit excitation tests (using manual excitation), and then with load bank tests, in which the generator sourced current through the rectifier into the resistive load bank. These tests were useful in proving operation of the rectifier with the high fundamental frequency of the generator, as well as obtaining initial measurements of the harmonic distortion and torque oscillations caused by the rectification process. Subsequent tests focused on verifying the use of the VVS as a DC load for the machine. In order to characterize the sensitivity of changes in load to changes in the VVS voltage, initial tests were conducted with the VVS operating in “bypass” mode (which uses an effective duty cycle as the reference for the VVS) and with manual generator excitation. Once this sensitivity was assessed, tests with the normal, closed-loop voltage control were conducted. At this point, actual load testing with the generator was conducted, and the generator was successfully loaded to 1 MW for over five minutes in multiple tests, operating with a terminal voltage of 430 V at 11,000 rpm. The generator was also tested at levels of 1.2 MW for over five minutes at 500 V and 13,000 rpm, and was loaded to over 1.4 MW at 500 V for a short duration in another test. Thus, a number of tests were conducted demonstrating the capabilities of the generator to deliver power, and a substantial amount of data was obtained. In the second major thrust of the testing, ramps in the load power were to be applied, using the voltage regulator developed by EA to maintain the terminal voltage of the machine. Again, the tests were approached cautiously, as there was concern about possible control interactions between the VVS voltage controls and the generator voltage regulator. Thus, for the initial tests, the VVS was again operated in the duty cycle reference mode, and a simple current controller was implemented as part of the RTDS case, making use of a feed-forward control with a proportional-integral (PI) controller used for correction. In order to reduce the risk of instabilities due to interactions between the current controller and the voltage regulator, an additional protection element was added to the case which would disable the closed-loop current control and slowly unload the machine if a current threshold was exceeded. The current controller was largely tuned in simulation, making use of a model that had been refined with data collected from the previous tests, but final adjustments were made to the controls during testing. This current controller was used to achieve ramp rates of up to 1 kA/s, and was used for a range of tests. However, in order to improve performance, the VVS controls were modified to allow a current reference to be sent directly to the inner current control loops that were part of the normal VVS controls. This solution yielded superior performance, and was used to obtain ramp rates of up to 3.5 kA/s, the highest rates called for in the test plan. Some of the results from this test are illustrated in Figure 4, Figure 5, and Figure 6, which show the reference and actual DC load current for the generator, the RMS voltage at the terminals of the generator, and the corresponding power supplied by the generator, respectively. A large number of these ramp tests were conducted, beginning with smaller steps in current levels, and slower ramp rates, progressing toward the more aggressive tests. Through these tests, the voltage regulator could be tested and tuned for a wide range of dynamic changes in load.

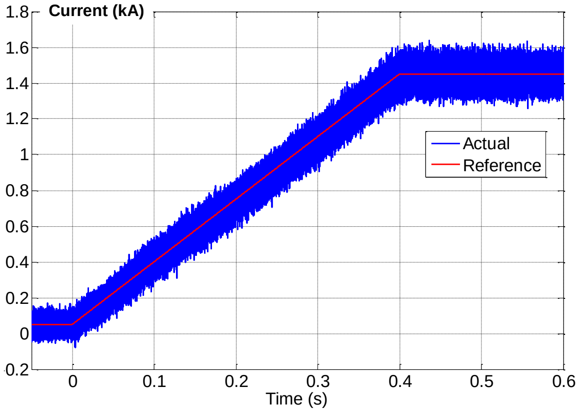

Figure 4 Reference and Actual DC Current for Load Ramp Test

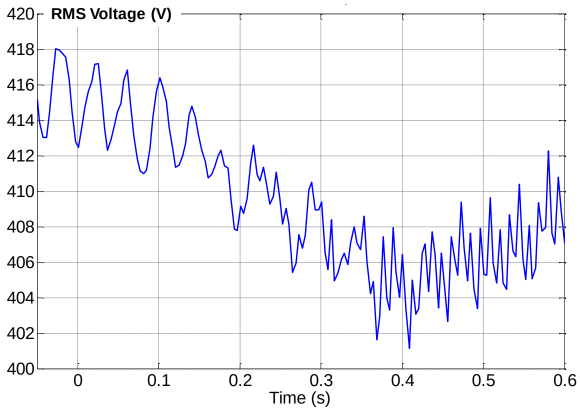

Figure 5 RMS Voltage at Generator Terminals for Load Ramp Test

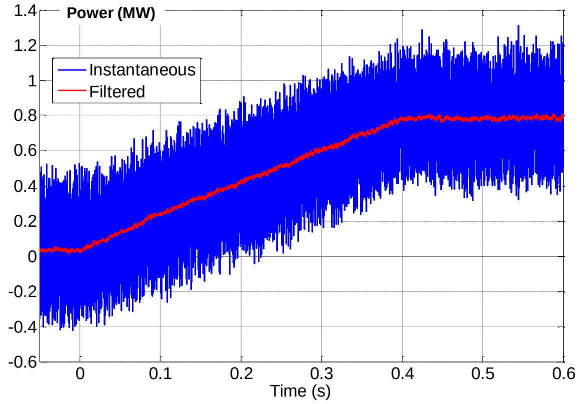

Figure 6 Power Supplied by Machine for Load Ramp Test

Conclusion

Herein, a megawatt scale test bed for conducting PHIL simulation experiments with a high speed generator was described, and tests with a high speed generator were discussed. Though the testing process was not without challenges and obstacles, the generator was successfully tested at 1.2 MW for over five minutes, and the performance of the machine and voltage regulator was established for changes in load of up to 750 kW with ramp rates of up to 1.9 MW/s (3.5 kA/s). However, a number of challenges are presented in PHIL testing of high speed generators at the megawatt level. One challenge is to provide high power for the range of speeds over which these machines are intended to operate. In the case of the enhancement of the CAPS 5 MW test bed for accommodation of high speed generators, a two-stage gearbox was acquired to accommodate speeds of up to 24,000 rpm, but the dynamometer is not able to deliver the full 5 MW shaft power over the full speed range due to the torque limitations. For the tests discussed herein, this was not a limitation, but the need to accommodate a wide range of operational speeds is a challenge. Additionally, due to the high speeds and power levels, other difficulties include accurate measurement of torque and speed on the high speed shaft, requiring rather specialized equipment, and the construction of a protective enclosure for the device under test. Further, providing a dynamic load using a VVS is challenging due to the high fundamental frequency associated with the machine. The solution chosen in this case was to use a rectifier at the terminals of the generator and a DC VVS as the dynamic load. Again, however, the high fundamental frequency is inappropriate for standard, 60 Hz rectifiers, necessitating the use of a specialized rectifier constructed with fast recovery diodes. Additionally, accommodation of 6- or 9-phase machines would require a separate rectifier. As with any specialized equipment, lead times for delivery can be substantial and must be accounted for in schedules. As with accommodation of a range of speeds, coping with different voltage levels is also an issue, as current limitations for the VVS will limit the power capabilities at lower voltage levels. While the system emulation aspect of the PHIL experiments was limited for the testing conducted during this phase of the work, a substantial amount of ground work for experiments involving more elaborate emulation has been done through these tests. The ability to dynamically and finely control the load on the machine using a DC VVS connected through a rectifier at the megawatt level with a fundamental frequency above 1 kHz is a significant building block in this framework. Although ramp rates above 3.5 kA/s were not tested with the generator, the test bed is capable of obtaining much higher rates of change of current. Although ramps in machine speed at extreme rates were not conducted as part of this test, the successful use of the gearbox and the ability of the dynamometer to tightly regulate the speed of the machine during fast load dynamics also demonstrate one of the key aspects of the framework. The successful use of a real time simulation model for control, monitoring, and protection of the device under test provides the additional piece needed for the PHIL simulation framework. Future PHIL simulation experiments with the test bed could involve emulation of particular dynamic loads of interest, as well as emulation of a gas turbine used as the prime mover for the generator. The test bed offers the flexibility to dynamically control the speed of the machine, as well as the load, from a real-time simulation platform, facilitating a wide range of possibilities for emulation of a dynamic environment for the device under test. Additionally, this allows such experiments to be conducted in a safe, controlled environment in which limits of operation can be set and experiments can be quickly and gracefully stopped if abnormal behaviors or conditions arise. Thus, while this approach certainly presents challenges and difficulties, the potential benefits of PHIL simulation experiments with high speed generators can be substantial.

REFERENCES

Kuffel, R., J. Geisbrecht, T. Maguire, R. P. Wierckx, and P. G. McLaren, “RTDS-a fully digital power system simulator operating in real time,” in Proc. 1995 IEEE Conf. on Communications, Power and Computing, WESCANEX, vol. 2, pp. 300-305.

Llambes, J. C., D. Hazelton, J. Duval, M. Albertini, S. Repnoy, V. Selvamanickam, G. Majkic, I. Kesign, J. Langston, M. Steurer, F. Bogdan, J. Hauer, D. Crook, S. Ranner, T. Williams, and M. Coleman, "Performance of 2G HTS Tapes in Sub-Cooled LN2 for Superconducting Fault Current Limiting Applications, *IEEE Trans. Applied Superconductivity*, Vol. 21, Issue 3, Part 2, 2011, pp. 1206-1208.

Schacherer, C., J. Langston, M. Steurer, and M. Noe, "Power Hardware-in-the-Loop Testing of a YBCO Coated Conductor Fault Current Limiting Module," *IEEE Trans. Applied Superconductivity*, Vol. 19, Issue 3, Part 2, 2009, pp. 1801-1805.

Schoder, K., J. Langston, M. Steurer, S. Azongha, M. Sloderbeck, T. Chiocchio, C. Edrington, A. Farrell, J. Vaidya, and K. Yost, "Hardware-in-the-Loop Testing of a High Speed Generator Excitation Controller," Proc. 2010 ASNE Electric Machines Technology Symposium, Philadelphia, PA, May 19-20, 2010.

Steurer, M., C. S. Edrington, M. Sloderbeck, W. Ren, and J. Langston, "A Megawatt-Scale Power Hardware-in-the-Loop Simulation Setup for Motor Drives, "*IEEE Transactions on Industrial Electronics*, Vol. 57, Issue 4, pp. 1254-1260, 2010.

Woodruff, S., H. Boenig, f. Bogdan, T. Fikse, L. Petersen, M. Sloderbeck, G. Snitchler, and M. Steurer, "Testing a 5 MW high-temerature superconducting propulsion motor," Proc. 2005 IEEE Electric Ship Technologies Symposium, 2005, pp. 206-213.

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