Use of RTDS Real-Time Simulator for Dynamometer Control in Electrical Machine Testing.

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ABSTRACT

The use of a real-time simulator for the control of a dynamometer for testing electrical machines is described. The simulator computes the torque to be applied to the test machine using a dynamic load model appropriate to the application and computes the required control signals to get that torque by means of a feedback control algorithm. The simulator also controls the test, manages data acquisition and monitors the progress of the test for safety and institutes a shut-down procedure if a dangerous or unexpected condition develops.

Keywords: Power systems, control, hardware-in-the-loop testing, real-time simulation, dynamometer

1. INTRODUCTION

Hardware-in-the-loop testing involves the testing of a hardware device in concert with a software implementation of the system in which the hardware device is destined to operate. Such testing has the potential to provide significantly greater and more useful information than traditional hardware testing, by permitting the evaluation of both dynamic behavior and system behavior in the testing of the device. In order to reap these benefits, however, it is necessary to provide sophisticated hardware and software interfaces between the hardware device under test and the software part of the system so that the division between the two is transparent.

Testing of this type is becoming increasingly common in a number of industries. The aerospace [1] and automotive [2] industries have been primary users of this idea for testing controller hardware; development and testing of mechanical hardware such as engines and transmissions is also common [3]. Other applications include radar device and integrated-circuit development.

The Center for Advanced Power Systems (CAPS) at Florida State University has made a significant commitment to hardware-in-the-loop testing as part of its system-oriented approach to power-system research and development. The Advanced Test Facility at CAPS is being developed to test a variety of power-systems equipment at power levels up to five megawatts. As part of CAPS' extensive simulation program, an RTDS real-time simulator [4] is being employed to (among other things) implement a hardware-in-the-loop test capability in conjunction with the CAPS Test Facility. As capabilities are added to the Test Facility, they will be integrated into the hardware-in-the-loop test capability by implementing the necessary interfacing between the Test Bed and the simulator and developing the necessary control algorithms on the simulator.

The first piece of test equipment to be commissioned in the Test Facility is a five megawatt dynamometer composed of two 2.5 MW induction machines connected in tandem. This arrangement permits hardware-in-the-loop testing to be carried out either with a third (test) machine added to the end of the power train or with the two 2.5 MW motors operating by themselves, in opposition. Hardware-in-the-loop development work has been focused on preparing for pending tests involving this dynamometer. This work, centering on the development and testing of hardware-in-the-loop control algorithms for a pair of 20 hp induction machines, is the topic of the present paper.

As conceived here, the goal of hardware-in-the-loop testing is to provide highly accurate and carefully controlled dynamic testing of hardware components in an environment that closely mirrors their intended service environment. The hardware-in-the-loop control algorithms and the overall strategy for hardware-in-the-loop testing described here were developed with this goal in mind; in addition, they were developed to provide verification that this goal is met. The present approach for hardware-in-the-loop testing may be described as verifiable hardware-in-the-loop testing.

The present approach to hardware-in-the-loop testing is computationally intensive --- intentionally so. The 128-processor real-time simulator currently operated by CAPS provides the opportunity to do a great deal more than simulate the system to which the test hardware is connected. The simulator's computational capability is sufficient to perform several additional functions: run sophisticated control algorithms designed to eliminate the introduction of spurious effects from the test facility into the system being simulated, monitor the experiment for safety and implement shut-down procedures if test behavior strays too far from the expected, acquire and save test data and perform overall control of the test procedure. The real-time simulator thus becomes a complete central experimental control system for the hardware-in-the-loop test.

While the work described here focuses entirely on hardware-in-the-loop testing of rotating machinery using a dynamometer, this is only the first stage of the hardware-in-the-loop testing capability under development at CAPS. Smaller, bench-top tests are being developed involving power-system protection and control hardware; in these tests, the hardware will be interfaced to a power system simulated on the simulator and will provide appropriate control and protection signals to the simulated system. Such tests will permit the testing and tuning of hardware controllers prior to being implemented in a real system, experimentation with the potential interplay between control and protection devices in a system, etc. Large-scale equipment to be installed in the CAPS Advanced Test Facility in the near future includes controllable AC and DC experimental busses, which will permit precise, dynamic, control of the voltage fed to a test device during an experiment. These controllable busses will be interfaced to the simulator for hardware-in-the-loop work and will permit full hardware-in-the-loop control of the electrical inputs to a hardware device. For example, full-scale simulations of a ship's electrical system [5] will be integrated with hardware devices (such as propulsion motors) by means of the controllable AC bus just as dynamic load models are integrated with machines by means of the dynamometer.

2. DYNAMOMETER CONTROL PROBLEM

The dynamometer-test-motor setup studied here is a matched set of 20 hp Baldor 480 V induction motors coupled together with a Magtrol TM312 torque transducer. The motors are powered by Alstom ALSPA MV3000 drives and a speed encoder is mounted on the back of each motor. The drives are connected to an RTDS real-time simulator via 16-bit, optically isolated digital-to-analog and analog-to-digital FDAC and OADC cards. Each drive provides two analog outputs and an analog input torque or speed reference; the nature of the output signals, the selection of torque or speed control mode and other drive parameters are set by the drive keypad control. The motor functioning as the test motor is operated in speed-control mode to represent the common use of such a motor in a propulsion application; the motor operating as the dynamometer is in torque-control mode to provide faster response to dynamic load variations.

The essential problem in controlling the dynamometer for hardware-in-the-loop work is illustrated in Figure 1. It is assumed that one has the desired load dynamics to be applied to the motor in the form of a model that is implemented on the simulator. This model may be thought of as providing a torque output given the speed (and, possibly, its derivatives, etc.) of the test motor. The goal is to control the dynamometer so that this desired torque appears at the torque transducer mounted on the test motor shaft.

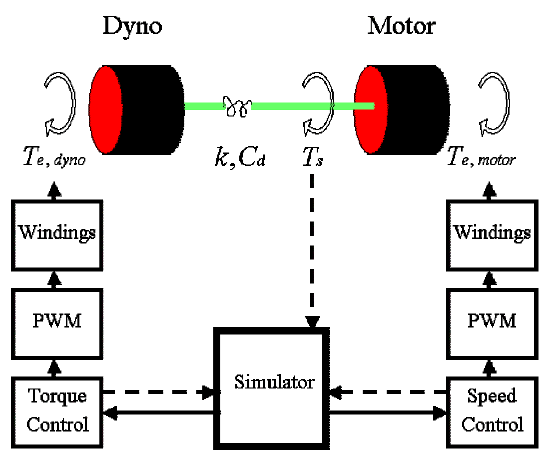

Figure 1. Dynamometer Control Problem.

Control of the dynamometer machine is achieved by means of a torque reference applied to the dynamometer motor drive. This torque reference is dynamically modified by the drive control algorithm, the operation of the pulse-width modulation converter that produces the required voltages for the dynamometer machine, the electrical windings of the dynamometer, the inertia of the dynamometer machine and the torsional stiffness and damping of the drive shaft and couplings. All of these modifying influences must be compensated for in order to accurately control the experiment so that the desired torque appears at the test-motor shaft.

Controllers have been implemented according to the scheme shown in Figure 2. Feedback from the torque transducer and from the speed reference are employed to determine a compensating offset for the torque reference supplied to the dynamometer drive. (Speed reference feedback is easier to implement than true-speed feedback due to the time delay in the latter relative to the former.) The feedback transfer functions have been determined according to such controller design strategies as pole placement, etc.; the best results to date have been found when the total torque transfer function represented by the diagram in Figure 2 is forced to be as close as possible to unity, so that the response of the system is as flat as possible. A transfer function of exactly unity is of course not possible: such a transfer function would imply that the feedback transfer functions involve unstable poles and "negative delays". Stability was maintained by rolling off the transfer function at high frequencies and accepting a small delay in the response of the system. Additional feedback from the motor speed encoders (true speed feedback) will be incoporated in the system presently.

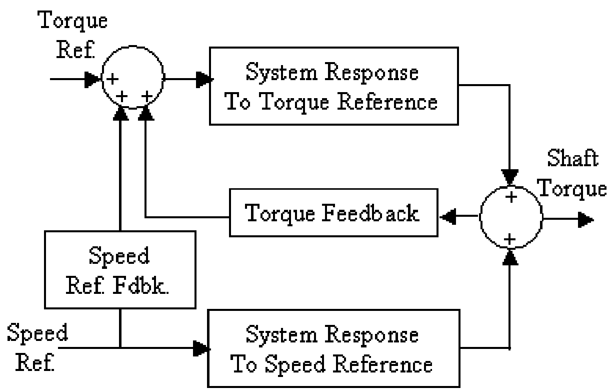

Figure 2. Control System.

In order to carry out the design of the controller, a model of the system is necessary. The model employed in the construction of the controller described in this paper involves a number of approximations, which, as will be seen, nevertheless allow good results. The shaft (including couplings and torque transducer) is modeled as a torsional spring with damping; the principle contributions to the stiffness and the damping coefficient are in fact from the couplings and the torque transducer. The motors are here modeled as perfect torque producers: the torque intended by the drive is applied directly to the mechanical equation for conservation of angular momentum of the rotor. A satisfactory model of the drive was found to be a transfer function with a constant delay and a gradual roll-off in amplitude at high frequencies. The speed control for the motor functioning as the test motor is a proportional-integral controller and is modeled as such. The combination of these approximtions results in the eighth-order transfer function for the torque reference and the sixth-order transfer function for the speed reference shown in Figure 2.

The system model described in the previous paragraph was constructed and validated through comparisons with experimentally determined transfer functions obtained from the system itself. The scripting capability of the RTDS was employed to map out the response of the torque transducer to speed and torque references with different amplitudes and oscillation frequencies. Thus, the overall transfer function of the system could be systematically determined, as well as transfer functions of those components of the system which could be isolated through the monitoring of quantities "interior" to the overall transfer function. An important example of the latter was the transfer function for the drives, which was mapped out experimentally by passing quantities such as the drive active current out through the drive analog output to the simulator. This permitted the transfer function roll-off and delay to be determined fairly accurately, which is crucial as it was found the behavior of the system, particularly near the torsional resonance of the shaft, was strongly influenced by the amount of this delay.

The success of this approach may be observed in Figures 3 and 4. Figure 3 shows the response of the original, uncontrolled, system when the requested torque is changed instantaneously from zero to 75% of rated torque. (The speed reference is held at zero.) The faster oscillations (about 32 Hz) arise from the first mode of mechanical torsional resonance in the system. The slower oscillations (about 2 Hz) are due to a resonance related to the speed control loop in the test machine. The figure shows both the true torque at the test machine shaft as given by the torque transducer and the torque given by the model. The model is seen to be fairly accurate, though it is less damped than the real system. One goal of the verifiable hardware-in-the-loop experiment is to get the true system behavior and the modeled system behavior to agree as closely as possible.

Figure 4 shows the response of the controlled system to the same step change in requested torque. The response of the model follows the step change very well, which is to be expected since the controller was designed using the model. The actual system response is good, but not as good as the model; this reflects, in large part, the deviation of the model from the true system behavior. The actual system response oscillates once in the first third of a second about the requested torque before reaching close to its final value. It is expected that improving the predictive capability of the model will improve this performance further, as will introducing true speed feedback (from the motor speed encoder outputs).

3. DYNAMIC LOAD MODELS

Two load models will be used to demonstrate the performance of the dynamometer control algorithm described here under actual experimental conditions with realistic dynamic loads. The load models are similar in behavior: the first represents the hydrodynamic loading a ship propulsion motor would experience when connected to the propellor shaft of a ship and the second represents the loading experienced by a generator connected to a wind turbine.

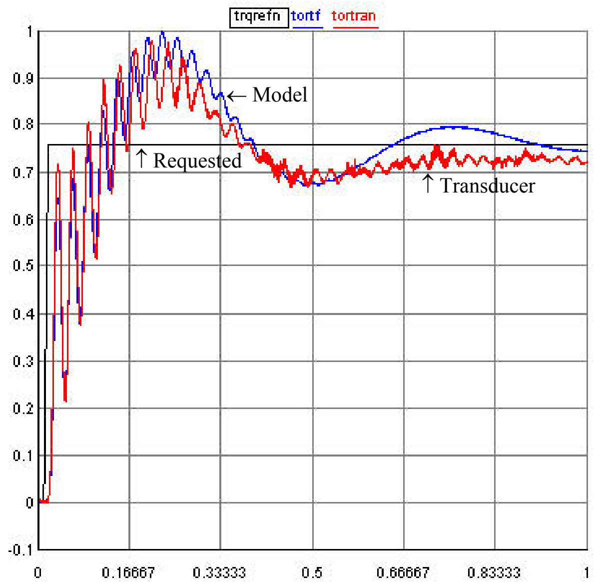

Figure 3. Response of Uncontrolled System to Step Change in Requested Torque.

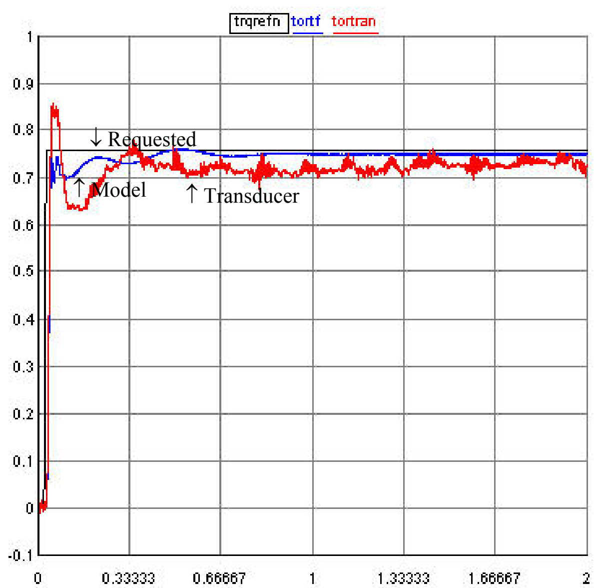

Figure 4. Response of Controlled System to Step Change in Requested Torque.

The ship propulsion load model is based on a pair of equations describing conservation of linear momentum of the ship and angular momentum of the propellor [6]:

$$
\begin{aligned}
\mu M V' &= n_{PROP}\,(1-t)\,T_{PROP} - R_{\mathrm{water}} - R_{\mathrm{ice}} \\
\frac{2\pi}{60}(J_{PROPELLER} + J_{WATER} &+ J_{SHAFT}/2)\,N'_{PROP} \\
&= Q_{SHAFT} + Q_{DAMP} - Q_{LOSS} - Q_{PROPELLER} - Q_{ICE}
\end{aligned}
$$

Here, M and V are the mass and velocity of the ship and the terms on the right-hand side of the first equation represent the thrust of the propellor and the water and ice resistance of the ship (the data used in the model for the present study is that of the United States Coast Guard Cutter *Healy*). In the second equation, the moments of inertia and the speed derivative of the propellor appear on the left and on the right appear the torques due to the motor, shaft damping, bearing losses, hydrodynamic propellor torque and ice-breaking, respectively. The various thrusts and torques required for the right-hand sides of these equations are described by non-dimensional coefficients which are determined empirically, usually using towing-tank data. It is important to recognize that these empirical coefficients depend both on the angular speed of the propellor and the linear speed of the ship, so the two equations must be solved simultaneously.

The load equations are programmed into the simulator using standard control blocks in such a way that the speed of the test motor is the input and the instantaneous motor shaft torque is the output. Quantities such as the speed of the ship are available in the simulation of the load, but play no direct role in the hardware interface.

The wind-turbine load model is similar in many respects to the ship-propulsion load model and may be considered a special case of it. In the case of the wind turbine, the speed of the wind is assumed given (at least for the purposes of the load model; the wind speed could come from a wind-speed estimator in the wind-turbine control system) and so no equation like that for ship motion is necessary.

4. SAFETY MONITORING

In the present experiments, the safety monitoring function of the simulator as controller of the hardware-in-the-loop test was limited to monitoring the torque read by the torque transducer and setting the dynamometer torque reference to zero if the transducer reading exceeded a pre-defined threshold (in this case 130% of machine rated torque). This monitoring function was particularly useful when probing experimentally the lightly damped 32 Hz shaft resonance present in this system and when testing new --- and potentially unstable --- control algorithms.

More sophisticated safety monitoring that will be implemented on this system as a prelude to implementation on the five megawatt CAPS Test Facility dynamometer includes having an entirely separate simulation of the hardware system running simultaneously with the experiment; the outputs of the software and real systems are monitored and when they differ by an amount determined in advance to be significant the simulator will shut down the experiment.

5. TEST CONTROL & DATA ACQUISITION

In the tests described here, and in the corresponding tests to be conducted in the 5 MW CAPS Test Facility, the simulator will control the speed reference to the test motor as well as the control signals for the dynamometer. This central control of the entire test by the simulator permits a more coordinated conduct of the experiment, a higher level of safety monitoring (since a controlled shut-down can involve the test machine as well as the dynamometer) and the potential for feedforward control of the dynamometer based on test motor behavior not yet observable.

Since the 20 hp motor set that is the subject of this paper is used primarily for the development of dynamometer control algorithms, data acquisition other than of control signals (transducer output, etc.) is not a major concern. In the course of actual hardware tests, however, the simulator will provide one means for data acquisition. The 16-bit analog simulator input cards provide a convenient and accurate means for acquiring data that may be stored by the simulator to disk.

6. RESULTS

Some simple results will be shown for the two cases represented by the dynamic load models described in Section 3.

The principle reason for doing dynamic dynamometer testing of a marine propulsion motor (as opposed to testing at steady-state conditions) is to evaluate the behavior of the test motor when subjected to the types of loads it would see when under maneuvers at sea. One of the more dramatic of these maneuvers is the crash astern or crash back maneuver, in which the ship's propulsion system goes from forward power to reverse power as rapidly as possible (such as for collision avoidance). A version of this maneuver is shown for the present system in Figures 5 and 6. Figure 5 contains the torque requested by the load model, the actual torque measured by the transducer and the shaft torque predicted by the model when the system is uncontrolled. The speed reference for the test motor has been ramped from positive 70% of rated speed to negative 70% of rated speed. It is clear that the test in no way reflects the true dynamics of the situation due to the significant difference between the requested and actual torques. The model does, however, represent the actual torque reasonably well. The principle features of the actual torque in the uncontrolled case are the offset, primarily due to the dynamometer rotor inertia, and the noise present in the signal, which is primarily due to the 32 Hz shaft vibration.

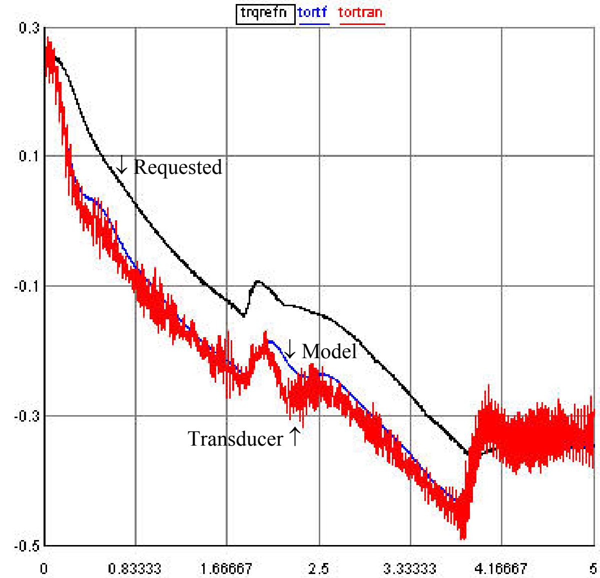

Figure 5. "Crash Astern" Maneuver in Uncontrolled System.

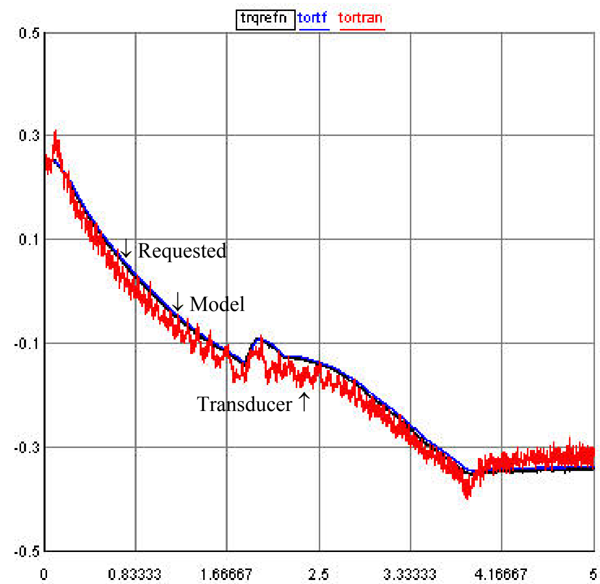

Figure 6. "Crash Astern" Maneuver in Controlled System.

The controlled case is shown in Figure 6 and the results are much improved. The offset has been largely dealt with and the vibration noise has been significantly reduced. The problem of a small dc error seen in the response to a step change may be seen here and there is the overshoot in response to abrupt changes in the requested torque (at the beginning and end of the maneuver, for example) that was also seen in the earlier case.

In the case of wind-turbine generator testing, a major area of interest is the design of controllers that will extract maximum power as the wind speed changes (eg., [7]). An initial experiment with the dynamometer configured for emulating a wind turbine is shown in Figure 7. A series of wind gusts (Figure 7a) results in a corresponding series of step changes in torque. The ability of the dynamometer to follow these successive step changes is shown in Figure 7b.

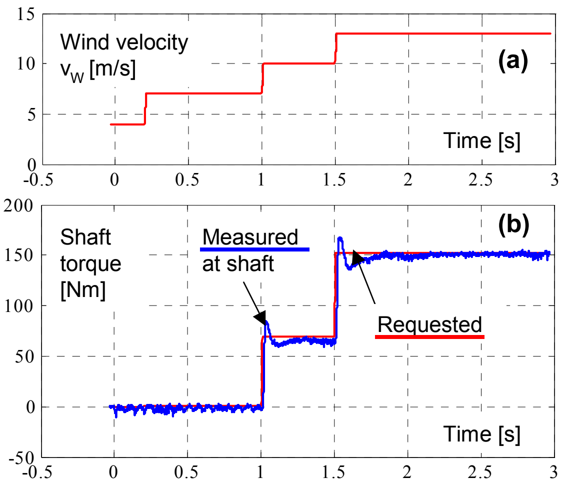

Figure 7. Wind-Turbine Emulation Test.

7. CONCLUSIONS

The results presented in this paper clearly demonstrate the feasibility of using the RTDS real-time simulator to control and monitor a dynamometer hardware-in-the-loop experiment. The implementation of two related dynamic load models for applications to ship propulsion motors and wind-turbine generators was described. A control algorithm for compensating for dynamometer and shaft dynamics was presented and was seen to significantly reduce the effect of these dynamics on the results of the test. The use of the simulator for safety monitoring, test control and data acquisition was also briefly discussed.

The control algorithm described here is being modified to include true-speed feedback and more accurate models of the system. It is expected that the control algorithms and system models for hardware-in-the-loop testing will be the subjects of continuous development as new hardware is introduced for testing and as new and more accurate tests are required for the hardware.

The accuracy of hardware-in-the-loop experiments such as those described here and the degree to which they are faithful to the real system under consideration may be verified through the use of simultaneous software simulations of different representations of the system. The model results presented in this paper are an example of a model representation of the actual hardware-in-the-loop test system. Discrepancies between it and the actual hardware-in-the-loop results are used to understand and minimize testing inaccuracies. Simulations of the real system (such as of a test motor coupled directly to the ship propulsion model) will provide a further basis for comparison and a further means for understanding the validity of the hardware-in-the-loop test and how its accuracy may be improved.

8. ACKNOWLEDGEMENT

This work was supported by the Office of Naval Research through grant number N00014-02-1-0623.

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