LARGE-SCALE SIMULATION OF NAVAL POWER SYSTEMS FOR DESIGN OPTIMIZATION

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Abstract – The use of large-scale simulations to accurately predict the behavior of the complex, closely coupled power systems characteristic of the all-electric ship is described and the application of such simulations to the systematic optimization of power systems and control systems is discussed. Simulations of a two-generator, two-motor system with PWM drives are coupled with a gradient-based line-search optimization strategy to determine the gains on a motor controller and on a simple ship-wide control system to minimize both motor speed error and generator speed error. The same search strategy is employed with simulations of a series PWM converter configuration to permit determination of an inter-converter filter that gives the most accurate reproduction of a target waveform at the filter output. The results of even these relatively simple test cases show clearly the necessity of large-scale simulations for understanding and designing electric-ship power systems and the potential utility of optimization techniques in concert with the large-scale simulations to enhance the performance of electric ships.

I. INTRODUCTION

The challenges presented to ship designers by the Integrated Power System concept are many and complex and are, to a large degree, unprecedented in power-system work, in that they lie in the closely coupled nature of the system. This is in sharp contrast to the very loosely coupled systems typical of utility grids and thus the design intuition, practices and tools of the past are not fully adequate to this new task.

One tool for meeting these new challenges is the large-scale simulation of ship power systems. Such simulations employ high-performance computers, detailed representations of the full power system and sophisticated models of electrical and control components to predict quickly and accurately power-system behavior. The information derived from these simulations has many applications: some obvious, some yet to be developed.

The simulation application discussed here is the design optimization of ship power systems. The complex and closely coupled nature of all-electric ship power systems means that components and sub-systems cannot be designed and optimized without consideration of their behavior in the full system. The incorporation of many new components, such as permanent magnet motors, and new control systems, such as hierarchical control systems for reconfiguration, means that the limited design intuition and experience currently available for these innovations must be rapidly augmented. Detailed simulations coupled with optimization techniques can help meet these needs.

Such simulations are being developed for systems representative of those being considered for the Navy's DDX. Containing multiple generators, twin PWM-driven motors and various representations of service and weapons loads, these systems may be run through scenarios to permit thorough evaluation of their performance. Optimization techniques can be applied so that, over a series of repeated runs with different electrical or controller parameters, performance may be improved.

Presented here are optimizations of motor controller parameters in ship systems (with realistic representations of propulsion loads) to improve the accuracy with which the motors follow command

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requests, of PWM-drive filter parameters to improve waveform fidelity and of a rudimentary example of a high-level system-wide controller to improve speed and quality of system response to abrupt commands. The results presented in this work show clearly that the combination of optimization techniques and sophisticated, detailed, large-scale simulations of electric-ship systems will be an important tool for Navy ship design.

II. LARGE-SCALE SIMULATION FOR ELECTRIC-SHIP DESIGN

Many areas of engineering have embraced large-scale computation as a primary tool of analysis and design. Developments in computer hardware and in algorithm design have made it possible for designers of airplanes, for example, to perform detailed simulations of the aerodynamic and structural characteristics of a proposed design prior to laboratory and wind-tunnel testing. These computations routinely involve hundreds of thousands, even millions, of variables. Applications such as shape optimization of airfoils to achieve minimum drag with specified lift are becoming increasingly practical.

The computational analysis of power systems has not yet reached this level. However, the success of computational methods in other areas provides a large body of potentially applicable techniques, as well as strong encouragement that large-scale computations can be of material assistance in meeting the design challenges the electric ship presents.

To fully predict the behavior of a power system and its associated control system at the level of accuracy and detail required for design applications, large-scale time-domain computations must be performed. That is, models of individual power-system and control-system components are coupled together through the electrical-network equations and the whole system evolves time step by time step. Most of the existing software platforms for performing power-systems computations [e.g., 1,2,3] are targeted at personal computers, which severely limit the complexity of the systems that can be studied and the number of different simulations one can perform to try options, test parameter values, etc.

The need to do more extensive simulation work than is possible with these PC-based systems, plus the desire to perform extensive hardware-in-the-loop experiments with its 5 MW test facility, led the Center for Advanced Power Systems (CAPS) at Florida State University to purchase a four-rack, 128-processor, real-time simulator from RTDS, Inc. [4]. Power and control systems constructed of library component models and user-defined models are solved in real time on racks of processors functioning in parallel. A scripting language permits a high level of control of simulations performed in batch mode and is used to implement the parameter surveys and the gradient search algorithm employed in the work reported here.

III. DESIGN OPTIMIZATION

The ability to accurately and quickly predict the detailed behavior of closely coupled power systems such as that of a Navy electric ship opens up significant possibilities for enhancing the design of these systems. The possibility considered here is that of design optimization, where optimization algorithms are applied to systematically manage design trade-offs and arrive at the best design satisfying design constraints.

The optimization applications described in this paper are part of a research program to explore and develop the applications of optimization coupled with large-scale power-system simulations to electric-ship design. It is believed these applications will soon begin to find their way into ship design, as the problems faced by designers are sufficiently great to make whatever effort is involved in adopting such new techniques worthwhile.

The optimization problems discussed in this paper illustrate two types of parameter optimization: optimization of parameters in power-system controllers and optimization of component values in the electrical system itself. In each case, the first step was a detailed parameter survey, where thousands of simulations were performed in batch mode to evaluate the performance of the system using various parameter combinations. Once this survey had given an overall picture of the dependence of system performance on the parameters, a gradient-based optimization technique was employed to zero in more accurately on the best combination of parameters.

The optimization technique employed here is a line-search method [5] chosen for its simplicity and robustness. During each iteration, the gradient of an objective function with respect to each of the parameters is found by finite differencing and used to determine the direction of steepest descent. A line search is then conducted along this direction for the point minimizing the objective function; this point is used as the starting point for the next iteration. The procedure terminates when the line search yields a change in position smaller than a specified tolerance. Several means are employed to minimize the effect of the “roughness” in the surface defined by the objective function caused by numerical errors and by the noise and complexity of the system being simulated: the finite-difference determination of the gradient is sampled twice and averaged and is monitored to ensure that the change in the objective function exceeds a pre-determined noise threshold, and the line search involves a binary-search component as back up in case the gradient determination is erroneous. Together, these precautions produce a fairly robust algorithm that has also been applied to a STATCOM control system [6].

Optimization in power systems based on time-domain simulations has been fairly rare, particularly for complex systems. A recent example [7] employing PSCAD/EMTDC used a simplex algorithm. Control-system optimization is much more active, with a good deal of recent work in new approaches such as genetic and evolutionary algorithms [e.g., 8]. These algorithms are well worth investigating in power-systems applications [9], too, but many power-system problems can take advantage of the highly developed and efficient gradient methods used extensively in other areas of engineering and the effective use of objective-function information that they entail.

IV. MOTOR AND SHIP CONTROLLERS

The control-system optimization problems considered here center around the control of an electric-ship system during a maneuver in which the propulsion motor speed is ramped down, then back up to the original speed. This is considered first as a local motor-control problem, then as a ship-wide control problem involving feed-forward control to the generators.

The power system used in these examples is the current stage in CAPS' development of a DD(X)-like baseline simulation for the RTDS, to be used for research into the simulation, power-system and control aspects of electric-ship design. The present system involves two conventional 13.8 kV, 36 MW synchronous generators, two 36.5 MW conventional induction propulsion motors with PWM drives and their associated local or component control systems. Without auxiliary generators, the system is of course under-powered and thus makes a useful example for illustrating the potential of ship-wide control.

This system has provided valuable insight into the process of developing and working with a ship-system simulation at this level of detail. Work is under way to add numerous features to the system to make it more representative of DD(X) possibilities. These include models for auxiliary generators, permanent-magnet, superconducting and enhanced induction propulsion motors, AC and DC zonal distribution systems, pulse-power loads and energy sources and more sophisticated and realistic models of local and ship-wide control systems. These enhancements will provide a system-simulation capability that will be an invaluable tool for many aspects of power-system and control-system research.

The generators are modelled in terms of Park's equations with a single rotor damper winding and parameters typical of modern conventional machines. An industrial gas-turbine model is currently being employed pending the completion of aero-derivative gas turbine models typical of naval prime movers. Voltage regulation is by means of a PID controller. A load-balancing system attempts to drive each generator's real and reactive power towards the average value by providing offsets to the voltage-regulation and speed-governor set points.

The induction propulsion motors are also modelled by Park's equations and again typical parameters were chosen. The PWM drives are modeled by a single level of ideal switches and are controlled by a standard triangle-wave firing algorithm. Switching frequency is 1000 hz. The propulsion load is modeled using equations for rate of change of linear momentum of the ship and angular momentum of the propellor, with hydrodynamic effects represented by empirically determined coefficients (the model used here follows [10]).

Ship-system simulations of anything other than steady-state operation require some form of motor control to tell the motor drive what voltage is required to get the desired motor speed or power. A general-purpose cascade motor controller has been developed at CAPS and is used in the present system. The controller has a total of five control loops, all of which are currently PI controllers. The inner control loops are the d- and q-axis current loops, whose outputs are the corresponding voltage references supplied to the motor drives. The current references are provided by torque and rotor-flux loops. The flux reference is set to a constant in the current version of this controller. The torque reference is the output of a speed loop; the speed reference is provided by a pre-set speed program. With the two current loops sharing gains, there is a total of eight control-loop gains that have to be determined in order to build an efficient controller. The motor-controller arrangement is shown in Figure 2. It is likely a production controller would make do with fewer loops; the idea here is that the optimization process should be able to determine whether loops are necessary or not. It is expected that being able to design effective controllers without making use of prior experience will be useful in the design of controllers for novel devices, such as superconducting motors.

To illustrate controller optimization, a simple speed program is used which involves ramping down from steady-state forward cruise at two-thirds power to a propellor speed just short of regeneration, holding, then ramping up to the original speed. In a real design application, one would select a suite of performance scenarios, determine appropriate performance criteria for each scenario and their relative weightings and then determine a design that optimizes over the suite.

Initial parameter values were determined by trial and error; the goal was simply a controller that wasn't so unstable the simulation of the speed program couldn't be completed. Then an extensive parameter survey was conducted which improved performance to the point shown in Figure 3. The gradient algorithm, using the rms error between the speed and the speed reference as the objective function, improved performance further. Figure 4 shows the motor speed follows the reference quite closely.

The work described in the previous paragraph was originally carried out before the present ship system was implemented, instead involving simulations of a one-generator, one-motor PWM-drive system with adequate generator capacity and fully tuned governor and voltage regulator. Once the optimization process had tuned the controller to the behavior of the system, the controller could rely on the power it needed to follow closely the speed reference. This is not the case with the two-generator, two-motor system: application of the same optimization procedure to the motor controller in this system yields the performance shown in Figure 5. The motor speed lags the reference throughout the maneuver.

Figure 6 shows the electrical speed (in rad/s) of one of the generators. The rather large excursions from the nominal value of 376.991 rad/s do suggest the generators are responsible for the motor controller’s performance and would of course be unacceptable in normal operation even if there were no motor-performance consequences.

The use of this system provides a clearer demonstration of two points. First, large-scale simulations of these closely coupled systems as complete entities are required to properly evaluate their performance. The interaction between components won’t usually be as dramatic as that shown in Figure 6, but it will be there and it will make designing components like motor controllers as if they were isolated from the rest of the system risky. Second, ship-wide control of these closely coupled systems may be beneficial and in some cases necessary. It is reasonable to ask whether some form of feed-forward control could mitigate the effects of marginal generator capacity in the system considered. Or, more practically speaking, if one or more generators on a ship are lost, can ship-wide control maintain a higher level of overall ship performance than would otherwise be possible? Some preliminary results with a very rudimentary control system suggest this could be the case.

The feed-forward system is shown in Figure 7. In a fashion similar to the load balancing system, the feed-forward system controls the generators through offsets to the governor and voltage-regulation set points. The offsets are determined using an estimate of the increase (or decrease) in required power computed as the filtered derivative of the product of the speed reference and the motor torque. The governor and voltage offsets are the outputs of separate PID controllers whose inputs are the power increase; the PID gains are determined through optimization. (While it is helpful to describe the process this way, the derivative followed by the integral, being the identity, does not have to be computed.) An offset is also applied to the speed reference provided to the motor controller, primarily to provide a mechanism for avoiding instability by delaying the speed commands (via a single-pole transfer function) long enough to give the generators a chance to act. The generator speed error is applied to the single-pole transfer function and to a PD controller (all of whose parameters are determined in the optimization procedure) to find this motor speed-reference offset.

Parameter surveys and gradient searches were performed on the ship system with feed-forward control implemented, using a weighted sum of the rms motor and generator speed errors as the objective function. At this point only the feed-forward system parameters were optimized; the motor-control parameters were held fixed. The resulting performance is shown in Figures 8 and 9. While the motor speed shows oscillations suggesting an instability barely under control, the excursions taken by the generator speed have been noticeably reduced. It is important to note that the objective function has been reduced by 40% over the value of the run of Figures 5 and 6 through the use of the feed-forward control. The optimization has been effective; the problem with the motor speed performance is related more to the need for an objective function that penalizes motor-speed oscillations more severely. The effect of alternative weightings and objective functions is being investigated. In general, the correct choice of objective function is crucial to developing an optimum solution that truly reflects the desired performance; how to do this for electric-ship applications is an important topic for research.

Finally, a gradient search was performed with all 17 parameters of the feed-forward and motor controllers varied simultaneously. The weighting of the objective function was also changed to de-emphasize the generator speed error relative to the motor speed error. The benefits of simulating and tuning the system as a whole are clear from the results (Figures 10 and 11). Motor speed variation is smooth and significant motor speed-reference offset is required only at the very end of the simulation to minimize the sharp dip in generator speed. The extent of generator speed variation has been reduced from 90 rad/s to 10 rad/s.

The need for simulation and analysis of the system as a whole is clear: the characteristics of the motor and its controller were heavily influenced by the behavior of the generators and vice versa. The only tool for accurately predicting and fully understanding the behavior of such systems is large-scale computation. Coupled with optimization strategies, it can be a powerful one for electric-ship design.

VI. PWM FILTER

As an example of the use of large-scale simulations in the optimization of electrical systems themselves, some preliminary results are described for the sizing of filter components in a PWM converter system. The filter lies between two PWM converters connected in series, the planned arrangement for the 5 MW controllable AC bus at the CAPS test facility when used to provide controlled voltages to a motor drive under test. The controllable bus will play the role of a ship's generator bus, its reference waveform supplied by the CAPS real-time simulator based on the current drawn by the test device and a real-time simulation of a ship's generators and loads.

The initial purpose of this simulation work is to develop some insight into what fidelity in reproducing a desired waveform is possible and what electrical and control problems need to be solved. Detailed simulations like that described here provide a viable design tool for understanding filter performance and voltage-controller performance under, for example, the effect of the nonlinear current response of a motor drive.

The configuration simulated is shown in Figure 12. The trial filter configuration used involves inductors in series and a shunt resistor-capacitor circuit ("LCL"). The AC bus converter is a low-voltage PWM unit with a 3000 hz switching frequency, modeled similarly to the PWM drives of the ship system discussed earlier. An output transformer brings the voltage up to the 4160 V used by the test facility and provides isolation from the high-voltage PWM motor drive it supplies. The motor is a 5 MW conventional induction motor driving a ship propulsion load model. In a motor test at the CAPS facility, such a load would be provided by the facility's dynamometer. While the CAPS test facility is supplied by the neighboring utility substation, the simulation uses a 100 MW generator to provide a stiff, but not ideal, voltage source.

The simulation fits on a single rack of the RTDS (as did the ship-system simulation). In order to accurately represent a wide range of waveform harmonics in the PWM converters at the switching frequencies projected for this equipment, the simulations were not run in real time. Tests showed a time step of three microseconds gave results independent of time step. With the time required for the machines to reach a steady state, each simulation takes about an hour to run.

Described here are some preliminary results in an attempt to design a filter with as close to flat response as possible in the desired frequency band while still filtering out higher-frequency switching effects. Once the best design is found for this open-loop operation, a feedback controller will be designed to improve the characteristics of the system further.

A search through ranges of parameters was conducted first, then the best results of this search were used to initiate the gradient search scheme. The objective function measures the rms error between the requested and actual waveforms. Results are shown in Figure 12 for a target waveform with fundamental and 5th, 7th, 11th, 13th and 17th harmonics, each with an amplitude of 9% of the fundamental. In keeping with the goal of determining performance limits, the modulation index, in terms of the fundamental, is one and so the harmonics drive the target waveform significantly past that point. The choice of harmonics is consistent with a filter pass band of 1000 hz, which is perhaps reasonable given the 3000 hz switching frequency of the converter. Performance of the filter is fairly good, with the exception of the almost complete loss of the seventh harmonic. This and other aspects of the behavior of the system at the limits of its performance are under investigation.

While the data produced by the gradient search algorithm indicates it has reached a minimum in the objective function, more testing has to be done to determine whether this is truly the global minimum, representing the best possible filter design of this configuration, or whether it is only a local minimum in the objective function, or possibly even a false minimum created by numerical inaccuracies. It is also necessary to test a wide variety of reference waveforms to ensure the filter design gives satisfactory performance for the widest possible range of experiments that might be performed with the controllable AC bus. A progression of increasingly sophisticated feedback controllers will be developed, as were the motor and ship controllers of the previous section, to improve the performance and versatility of the converter.

VII. CONCLUSIONS

The results presented here for optimization of both power- and control-system parameters provide some preliminary evidence that optimization strategies coupled with large-scale system simulations can have a useful role to play in the design of all-electric ships. The next step is to build on these results through employing more refined optimization strategies in concert with more detailed and realistic simulations to address both general design considerations and specific issues raised by electric-ship designers.

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IX. ACKNOWLEDGEMENT

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FIGURES

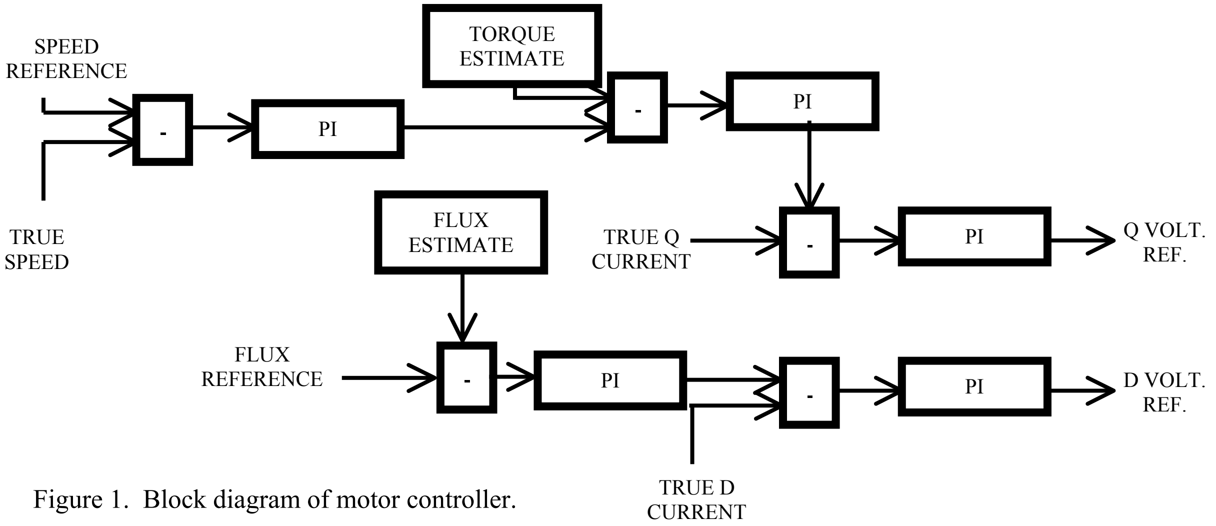

Figure 1. Block diagram of motor controller.

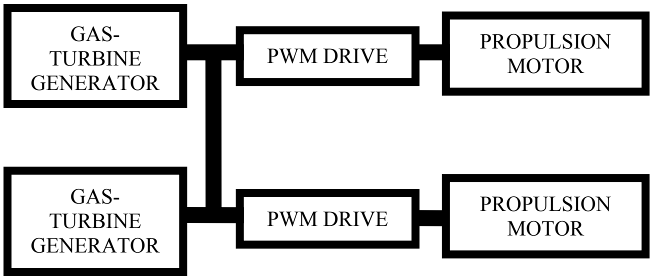

Figure 2 Layout of basic ship system.

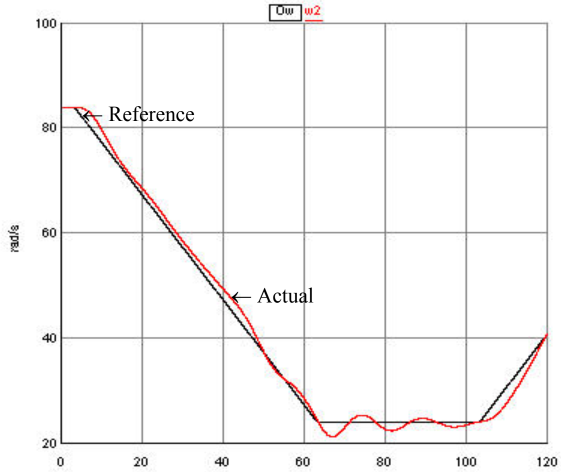

Figure 3. Motor controller performance after parameter sweep. (Here and throughout, motor electrical speed in rad/s is shown.)

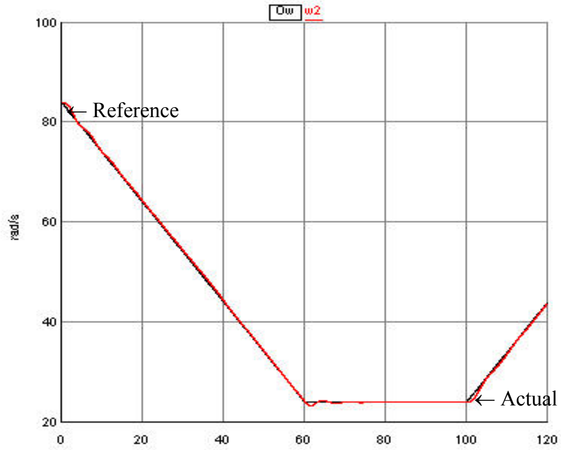

Figure 4. Motor controller performance after gradient search.

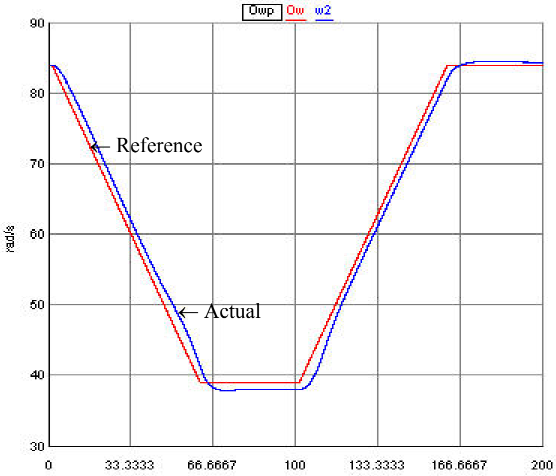

Figure 5. Optimized motor controller performance in two-generator, two-motor system.

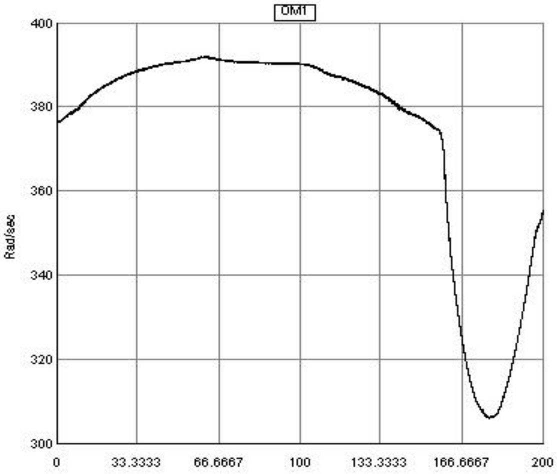

Figure 6. Generator electrical speed during speed program of Figure 5.

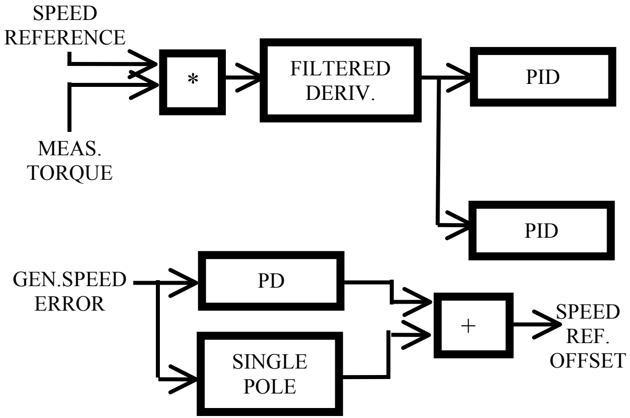

Figure 7. Feed-forward control system.

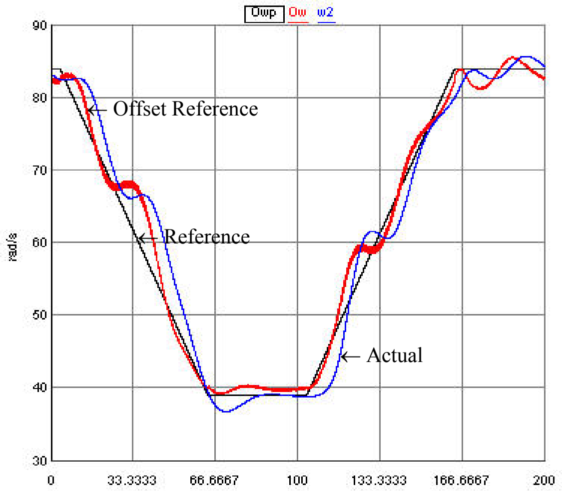

Figure 8 Motor controller performance with optimized ship controller.

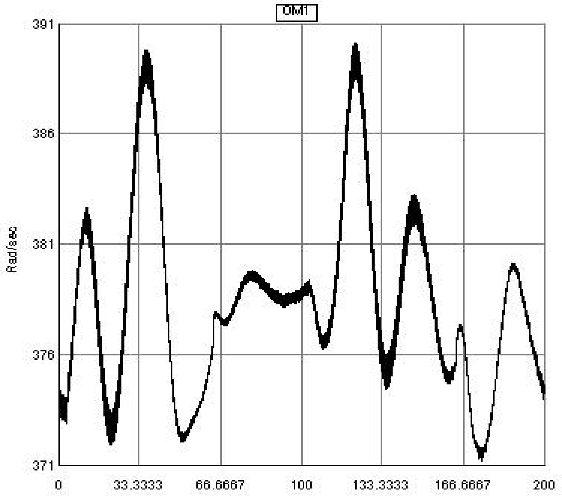

Figure 9 Generator electrical speed during speed program of Figure 8.

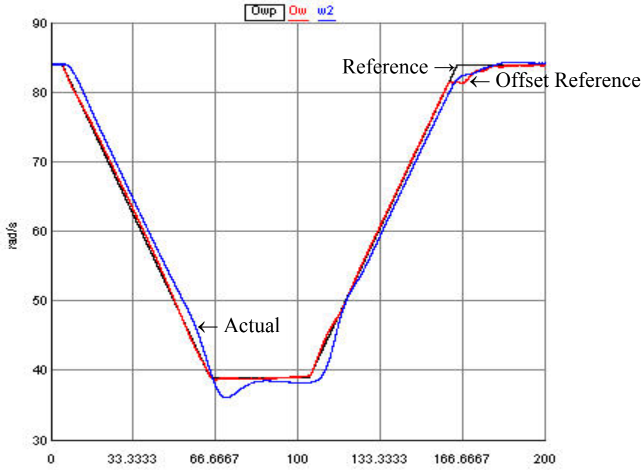

Figure 10. Motor controller performance when motor and ship controllers are optimized simultaneously.

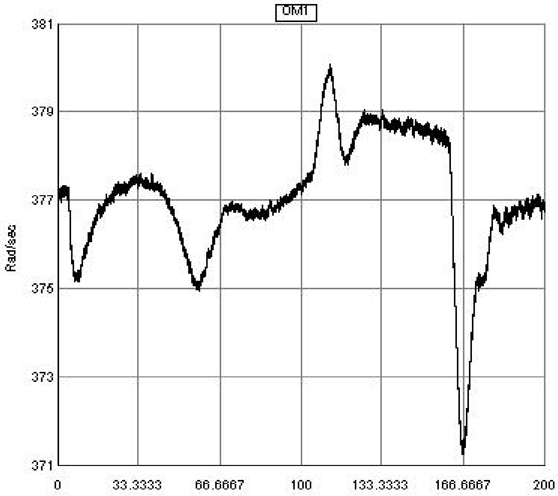

Figure 11. Generator electrical speed during speed program of Figure 9.

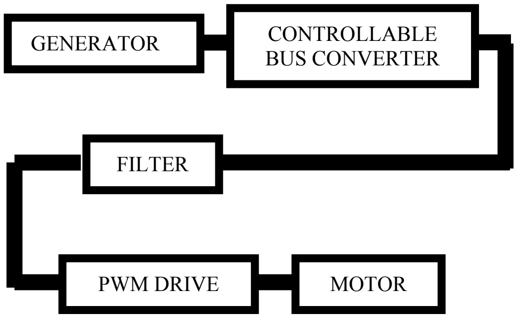

Figure 12. Layout of series converter system.

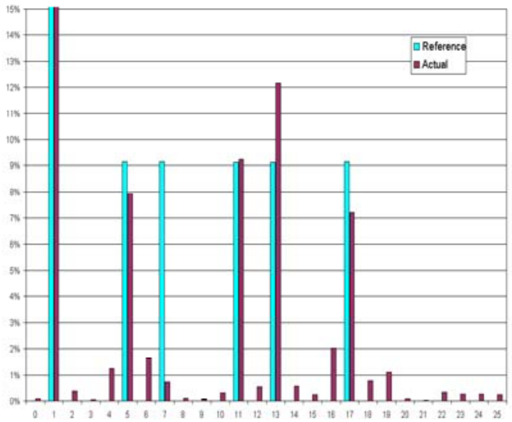

Figure 12. Voltage spectra for reference and actual waveforms.