Large Scale Simulations of a Ship Power System with Energy Storage and Multiple Directed Energy Loads

Robert Hebner
University of Texas
1 University Sta #R7000
Austin, TX 78712
r.hebner@cem.utexas.edu

John Herbst
University of Texas
1 University Sta #R7000
Austin, TX 78712
j.herbst@cem.utexas.edu

Angelo Gattozzi
University of Texas
1 University Sta #R7000
Austin, TX 78712
a.gattozzi@cem.utexas.edu

Keywords: directed energy loads, electric ship, energy storage, large scale Simulink model, simulation time

Abstract

A large scale Simulink® simulation model of the electrical power system of a ship is described. The model includes the major systems onboard, from prime movers to the actual loads, and incorporates several intermittent duty loads along with continuous duty loads. Three types of energy storage systems have been modeled: flywheels, batteries, and capacitors. Therefore, critical issues like stability, reconfigurability, fault management, and minimum rating of energy storage units can be studied.

The presence of energy storage has also allowed the study of how these systems can be used to improve the overall performance of the ship. Typical functions, for example, would include load leveling of the power bus, an uninterruptible power supply function for sections of the ship, and the potential for fuel efficiency improvement by reducing the number of turbines being run at fractional loads to fewer being run closer to their optimal specific fuel efficiency point.

Typical outputs of the simulations are presented and discussed. In addition, several challenges presented by the scale of the simulations, the software platform used, and the underlying modeling philosophy are discussed with an outlook toward future improvements both in the computing hardware and in the programming methods.

1 INTRODUCTION

For a number of years the Center for Electromechanics at the University of Texas at Austin (CEM-UT) has been engaged in the study of the electric power system of US Navy ships with direct support from the Office of Naval Research (ONR) [1, 2] or as part of the Electric Ship Research and Development Consortium (ESRDC) [3]. Much of the work has centered on the modeling and simulation of various design concepts in order to determine the best architecture that would ensure reliable electric power aboard ships, responding to the increasing pressure of fuel costs, logistics concerns, and the need to supply loads with various characteristics and requirements from continuous duty (e.g., propulsion), to highly intermittent duty loads (e.g., electromagnetic launchers). The challenges facing system designers and naval architects in regard to the electric power system of a warship are considerable. Among the most important are:

1. A combined generator power capacity only minimally larger than the total power potentially demanded by all loads
2. The likely integration of auxiliary energy storage units to supply at least some of the pulsed power loads to avoid overloading the grid
3. The probable coexistence of whole sections of the grid with different voltage and frequency characteristics
4. The ever growing density of electric power conversion stages needed to interface the various sections
5. The increased possibility of using nontraditional energy resources to supplement the more traditional ones
6. A control system design moving toward a more decentralized intelligence and decisional autonomy
7. The need for sufficient redundancies to survive the hostile environment and threats
8. Provision for adequate fault management
9. The desirability of a flexible architecture suitable for quick reconfiguration in response to possible damage
10. The need to ensure suitable power quality and stability margins in all expected configurations

In view of the above requirements, it is clear that modeling and simulation play a crucial role. Here we shall report on the efforts at CEM-UT to contribute toward a working model of a shipboard power system and some of the simulation results obtainable from it.

2 MODEL DEVELOPMENT

To address these issues, a notional electrical power system for a ship was developed and modeled in Simulink®. It must be stressed that the intent was not so much to reproduce a real system, but rather to provide a platform, albeit idealized, for evaluating alternatives and studying the interactions of the various components. It must also be said that any attempt at a detailed representation of a ship's electrical system will quickly result in a model of such complexity that it cannot be run on ordinary computer platforms. This will be discussed in more detail later. A simplified one-line diagram of the system considered is shown in Figure 1. This diagram is a conceptual rendition of the functionalities of the model but does not reproduce faithfully the level of detail of the model.

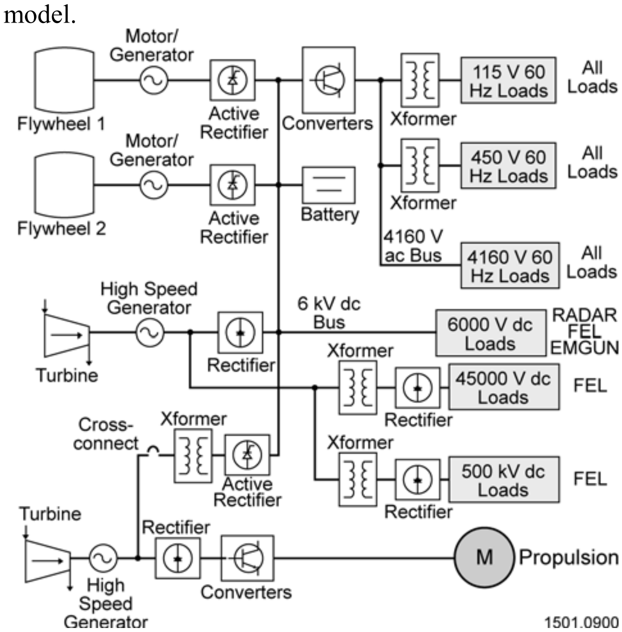

Figure 1. Functional diagram of the ship's electrical power system modeled in Simulink®

In the development of the model, a "load centered" approach was followed – first, the requirements of all loads were defined in detail and then, proceeding from them, the minimum system sufficient to adequately support the given loads with appropriate power sources was designed. The only exception to this rule is the use of two flywheel energy storage systems because there is an interest in studying the interactions among multiple units of this type and the control issues pertaining to them. The various loads modeled are:

1. Free Electron Laser (FEL)
2. AN/SQQ-90 Sonar System (SONAR)
3. Electromagnetic Railgun (EMRG)
4. Active Denial System (ADS)
5. Advanced Radar (RADAR)
6. Electromagnetic Aircraft Launch System (EMALS)
7. Laser Weapon System (LaWS)
8. Propulsion
9. Hotel

Starting from a physical description of the various loads, individual models of each load, plus a combined model for a system simultaneously supporting one instance of each load, were developed. As stated previously, the intent was to provide at least a basic system, where different possible scenarios could be simulated, and an essential framework that could easily be completed as necessary without excessive rework.

3 SIMULATION RESULTS

The Simulink® model of the system in Figure 1 was exercised under several possible operational scenarios. The model was made interactive to the extent possible with several switches and analog parameters that can be adjusted while the simulation is running, allowing the operator to change key settings dynamically, thus mimicking an actual operation of the power system of a ship in real time. Some of the typical results obtainable from the simulations are reported in Figures 2-5.

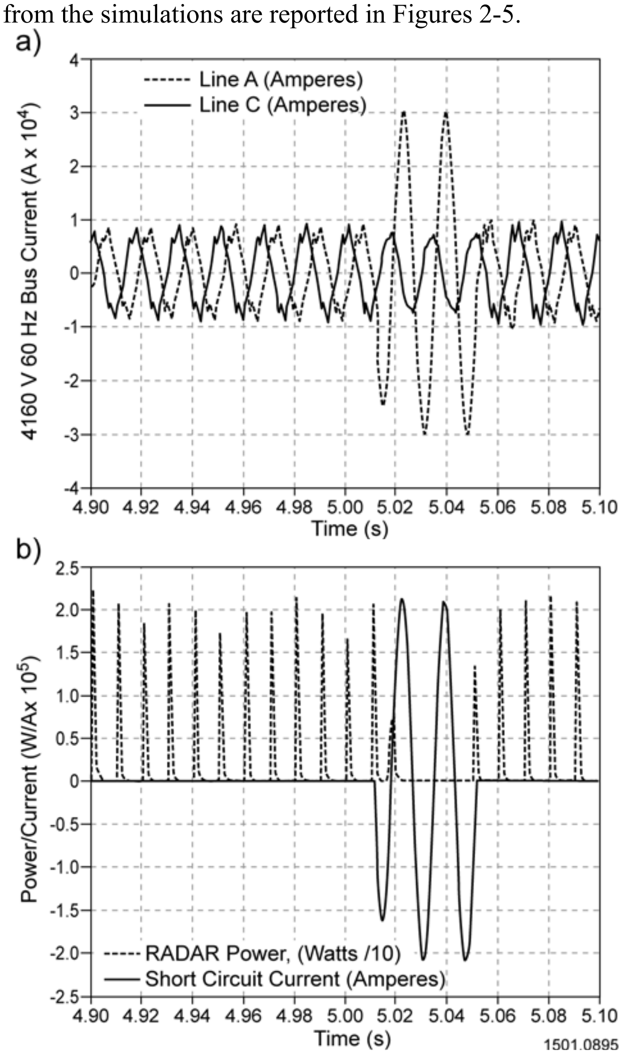

Figure 2. Some effects of a momentary line-to-line short circuit on the 450 V, 60 Hz, bus

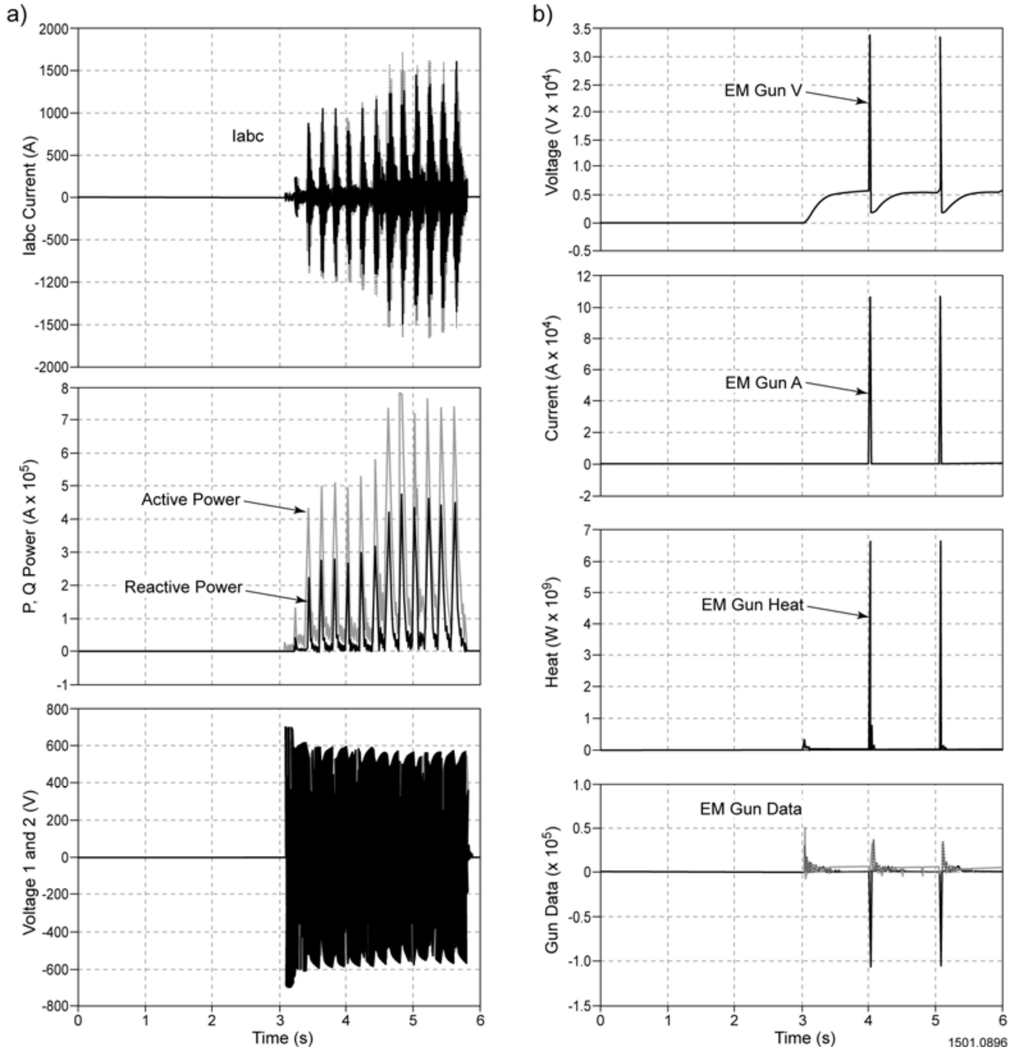

Figure 3. Some operational details of the ADS and EMRG systems

The plots shown are indicative of the many different outputs that can be obtained from the simulations, and, in fact, several others have been generated from simulations run under different conditions [4, 5]. The outputs of these simulations can be related back to component stress levels, the required redundancies, the needed infrastructure and supporting equipment, as well as the most suitable control strategy.

The presence of several energy storage units also allowed the study of how these systems can be used profitably, when not needed to handle the intermittent loads, to improve the overall performance of the ship. Typical "steady state" functions, for example, include load leveling of the power bus, operation as an uninterruptible power supply for sections of the ship, and fuel efficiency improvement by reducing the number of turbines being run at fractional loads to fewer being run closer to their optimal specific fuel efficiency point.

The one simulation that is of great interest at the present time, is the study of transients associated with the cross-connect option shown in Figure 1, where operational power to support large directed energy loads is now supplemented by the turbine normally dedicated to providing propulsion.

The model developed is working correctly, but has one major limitation – in most of the cases, the simulation time is quite long, forcing the disabling of some of the features of the complete system in order to obtain results in a reasonable amount of time. Even with these reduced models, however, the ratio of simulation time to simulated time tends to be quite large. It is not unusual to run simulations where one second of simulated time results in 24-48 hours of simulation. This forces not only the simplification of the model, as mentioned above, but also the unnatural compression of events into short time intervals that do not reflect actual real life operations.

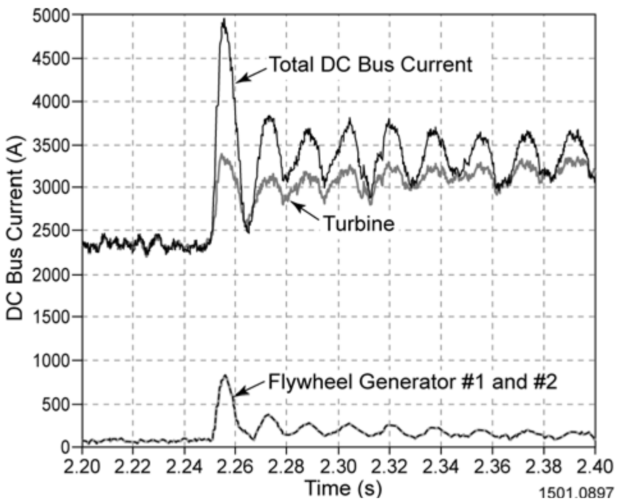

Figure 4. Effect of starting a large induction motor across the line on dc bus currents: note the reduction of the shock on the turbine due to the two flywheel generators (blue and green lines overlap)

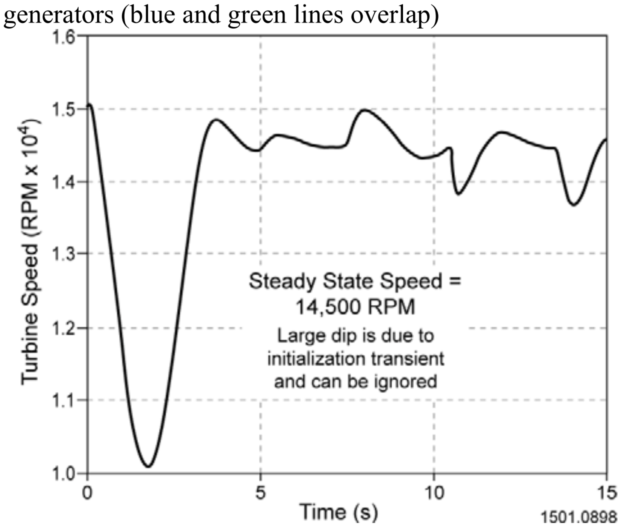

Figure 5. The effect of large load fluctuations on the turbine prime mover

Obviously, all these constraints may affect the interactions among the various components, making the study of the potential issues much more difficult to interpret.

An additional goal of this development was to provide a graphical user interface (GUI) to demonstrate the ability of this model to be converted into a top-level training tool for Navy personnel, supported by a realistic representation of the ship power system. A preliminary GUI was indeed developed within MATLAB, but had to be abandoned because it was slowing down the execution time even more.

4 OPTIONS FOR SIMULATION IMPROVEMENT

It is clear that we have reached the limits of what can be expected from the tools used so far, and that new approaches must be found to make the simulations more useful. At the present time, for a simulation run on a 64-bit dual core desktop computer with 3.16 GHz clock and 3.93 GB of RAM, the ratio σ, defined as

$$\sigma = \frac{simulation\ time}{simulated\ time},$$

is typically in the range of 100,000. Fully realizing that this ratio is a function of the problem being solved, one concludes that this value is not out of the ordinary, as it has been reported that in the microprocessor simulation arena typical values for σ are on the order of 300,000 or more [6]. Thus, one concludes that the problem is quite general and of current interest. All this, obviously, implies that improvements in σ values of 3-4 orders of magnitude are necessary to achieve a tolerable level of performance, and that enhancements of 6 orders of magnitude are needed to realize levels suitable for a real time simulator. It is unlikely that these upgrades can be attained simply by faster processors in the foreseeable future.

It is also clear, however, that as one searches for possible solutions to the speed bottleneck, the simulation will probably become less general and more dependent on either the hardware or the software platform. In view of this, we decided to approach a potential solution gradually, trying to maintain as broad a usefulness as possible of the tools developed so far. With this in mind, some of the options we are actively exploring are described in a general order of desirability, beyond the trivial one of waiting for faster computers, an option on which one has no control.

4.1. Expanded Use of Multi-rate Techniques

Multi-rate simulation methods have been demonstrated to achieve sizable gains in program execution time [7]. In fact, our own model is already running as a dual rate simulation. Plans to expand the application of multi-rate techniques to our model are currently under way.

MATLAB-Supported Multi-core Calculations

Multi-core desktop computers are now common (CEM-UT is replacing older computers with quad-core machines), but the availability of multiple cores per se does not help in speed of execution. In order to exploit the multi-core capability, the software must also be designed to run on multiple cores. MATLAB/Simulink® has recently introduced a software version suitable for parallel computations through the use of its Parallel Computing Toolbox [8]. Although this approach is by far the simplest way to gain some speedup and we are currently pursuing it very actively, preliminary investigations seem to suggest that the gains are modest, perhaps a factor of 2 or 3 [9]. This is because the speed gain is not proportional to the number of cores and is subject to saturation after a critical number of cores is exceeded.

4.2. MATLAB-supported Calculations on Computer Clusters

MATLAB now offers the ability to run its code on computer clusters using its Distributed Computing Server [10]. This is a more powerful tool than the previous one, but also more complex. As in the case of multi-core calculations, here also the speed gain is not proportional to the number of computing units in the cluster. Thus, it is difficult to predict the incremental gain from this approach, but probably speedup ratios of 10:1 could be achieved [9]. At the present time, we are pursuing this path in cooperation with the Texas Advanced Computing Center (TACC) at the University of Texas at Austin (UT) which houses Ranger, the world's largest computing system as of this writing [11].

4.3. Third Party-supported Parallel MATLAB Calculations

This is certainly an option [9], but we are not actively pursuing it at this time, as our preference is to remain within the same software support structure for the time being.

4.4. Field Programmable Gate Array (FPGA) Assisted Processing

In this option, external processors designed around FPGAs are used to assist the main computer in speeding up the most intensive time-consuming calculations. This option has become technologically viable because of two recent developments:

1. FPGAs, which have been traditionally fixed-point devices, are now being used also with floating-point operations
2. More powerful FPGAs reduce the traditional penalty of latency due to data being exchanged between processing units that used to negate the superior speed of the FPGA devices [12]

This approach requires serious consideration as the speed of FPGAs holds the promise of large gains in terms of computing times [7]. By the same token, this choice also requires serious investment of design time on the part of the programmer.

We have used FPGAs made by Xilinx Inc. [13] in the context of generating the driving pulses for electric power converters [14]. Therefore, it has seemed natural to explore this option within the Xilinx family of devices and capabilities with the assistance of the manufacturer. At the same time, it has also seemed opportune to explore the possibilities being opened by National Instruments (NI), as it also has moved into the area of FPGA co-processing [16], especially in view of the extensive experience gained over the years with NI's main product – LabVIEW. It must also be noted that UT has been among the leaders in the development of FPGA co-processing and has considerable expertise in this regard [16].

As of this writing, it appears that FPGA-assisted processing is a viable alternative and one that has the chance of realizing the largest gains, as both hardware and software become inevitably more powerful, but one that is probably not yet at a sufficiently advanced level of maturity for general use [17].

4.5. New Proprietary Code Development

This option would allow the full exploitation offered by parallel processing, being essentially custom made, but is also believed to require substantial research and development, especially if one hopes to develop a general purpose program applicable to a large variety of possible cases. This alternative is probably the least desirable, although it is recognized that it has been tried in well defined cases resulting in application specific programs [18].

5 CONCLUSIONS

The large scale Simulink® model, developed by CEM-UT, of the electric power system of a ship was described. The model includes the major system components with a sufficient degree of fidelity that critical issues like stability, reconfigurability, fault management, and minimum rating of energy storage units can be studied.

Various types of energy storage systems were incorporated, as well as several intermittent duty loads, along with continuous duty loads. Typical outputs of the simulations were presented.

Execution time was identified as a major challenge presented by the scale of the simulations, the software platform used, and the underlying modeling philosophy. Current developments at CEM-UT and plans for the near future for a possible solution to this issue were outlined with consideration of feasible improvements both in the computing hardware and in the programming methods.

REFERENCES

[1] Herbst, J.D. and A.L. Gattozzi. May 2008. "ONR Megawatt Power Module for Ship Service." Final Report to ONR, Grant #N00014-06-1-0886.

[2] Herbst, J.D., A.L. Gattozzi, R.E. Hebner. Feb. 2009. "ONR Megawatt Power Module for Ship Service:

Volume 1: Program Technical Report, Volume 2: MatLab Simulation User's Manual, Volume 3: Rolls Royce Documentation." Final report for ONR Contract N00014-07-C-0361.

[3] Ouroua, A., L. Domaschk, and J. Beno. 2005. "Electric ship power system integration analyses through modeling and simulation." IEEE Electric Ship Tech. Symp., (Philadelphia, PA, July 25-27). 70-74.

[4] Hebner, R., J. Herbst, and A. Gattozzi. 2010. "Intelligent microgrid demonstrator." Electric Machines Tech. Symp., (Philadelphia, PA, May 19-20), to be published.

[5] Hebner, R., A. Gattozzi A., K. Cohn, and W. Colson. 2010. "Analysis of the power quality impact of multiple directed energy loads on an electric ship power system." 23rd Annual Solid State and Diode Laser Technology Review, (Broomfield, CO, June 15-18), to be published.

[6] Chiou, D., H. Angepat, N. Patil, and D. Sunwoo. 2009. "Accurate functional-first multicore simulators," IEEE Computer Architecture Letters, 8, no. 2, (July-Dec.): 64-67.

[7] Crosbie, R., D. Word, J, Zenor, R. Bednar, N. Hingorani. 2009. "High-speed real-time multi-rate simulation." Conf. Grand Challenges in Modeling and Simulation, (Istanbul, Turkey, July 13-16).

[8] The MathWorks: http://www.mathworks.com/products/parallel-computing/description1.html, (May 7, 2010).

[9] Samsi, S., V. Gadepally, and A. Krishnamurthy. 2010. "MATLAB for signal processing on multiprocessors and multicores." IEEE Signal Processing Magazine, 27, no. 2, (March): 40-49.

[10] The MathWorks: http://www.mathworks.com/products/parallel-computing/description5.html, (May 7, 2010).

[11] TACC at UT: http://www.tacc.utexas.edu/resources/hpc/#pwreblades, (May 12, 2010).

[12] Starbridge Systems: http://www.starbridgesystems.com/hypercomputing/overview/, (May 6, 2010).

[13] Xilinx Inc.: http://www.xilinx.com/, (May 12, 2010).

[14] Williams, A., A. Gattozzi, and R.F. Thelen. 2007. "Applications of an auxiliary resonant commutated pole converter." 22nd IEEE Applied Power Electronics Conf. and Expo., (Anaheim, CA, Feb. 25-Mar. 1). 661-665.

[15] National Instruments: http://sine.ni.com/nips/cds/view/p/lang/en/nid/11834 (May 12, 2010).

[16] Chiou, D., D. Sunwoo, H. Angepat, J. Kim, N.A. Patil, W. Reinhart, and D.E. Johnson. 2008. "Parallelizing computer system simulators." IEEE Intl. Parallel & Distributed Processing Symp., (Miami, FL, April 14-18). 1-5.

[17] Mills, A.R., B. Apopei, A. Zammit Mangion, H. Barron-Gonzales, P. Gunetti, H. Thompson, and P. Garbett. 2010. "Heterogeneous hardware technologies for accelerating complex aerospace system simulations." IEEE Aerospace Conf., (Big Sky MT, March 6-13). 1-10.

[18] Uriarte, F.M., K.L. Butler-Purry. "A partitioning approach for parallel simulation of AC-radial shipboard power systems." IEEE Trans. Power Systems, to be submitted.

BIOGRAPHIES

Dr. Robert E. Hebner is the Director of the Center for Electromechanics at the University of Texas at Austin. The Center develops advanced energy technology and teams with companies to get the technology to market. Previously, he was acting Director of NIST with an annual budget of about $750 million. He worked in OMB on the technology portions of the Administration's 1990 budget and at DARPA to advance semiconductor manufacturing. He has extensive experience in measurement systems needed to support global trade and in developing government technology programs to stimulate the economy. He is a fellow of the IEEE.

John D. Herbst joined the Center for Electromechanics in 1985. He is currently the Principal Investigator for research programs involving high power rotating electric machines and power converters. Prior to his current position, Mr. Herbst served as Principal Investigator for the ONR Megawatt Power Module for Ship Service program, an effort to explore high speed generators and energy storage flywheels to reduce fuel consumption on the DDG51 class of Navy warships. He was also Co-Principal for the Advanced Locomotive Propulsion System (ALPS) project, a $30M effort to demonstrate an advanced hybrid electric propulsion system for high speed passenger locomotives.

Dr. Angelo L. Gattozzi joined the Center for Electromechanics at the University of Texas at Austin in 2000. His main focus has been on power modules for the electric gun program, resonant converters for high speed motors/generators with flywheel energy storage, design of special generators for energy harvesting from sea waves, and modeling the electric system with energy storage of the DDG51 class Navy destroyer and of some Army Tactical Operating Centers including renewable energy resources.