Ship Power System Control: A Technology Assessment

A. Monti, IEEE Senior Member, D Boroyevich, IEEE Senior Member, D. Cartes, R. Dougal, IEEE Senior Member, H. Ginn, IEEE Member, G. Monnat, S. Pekarek, F. Ponci, IEEE Member, E. Santi, IEEE Senior Member, S. Sudhoff, N. Schulz, IEEE Senior Member, W. Shutt, F. Wang, IEEE Senior Member

Abstract—This paper describes a multi-institution effort to demonstrate and assess newly developed control technologies for ship power systems. In comparison to land-based power systems, or even to earlier era of ship power systems, the now rapid incorporation of power electronics into ship power systems requires a complete redefinition of the control concepts. Furthermore, recent developments in control technology have re-opened debates over issues such as centralized versus distributed control. The complexity of the control problem calls for new hardware structures and new tools for control development and testing. A group of research institutions has teamed up to define a realistic power system scenario for testing several of the new control technologies.

This research will help address questions such as what level of re-configurability is reasonable to implement, how far can we push the concept of decentralized agent-based control, and what is the impact of active power management through power electronics?

Index Terms—Simulation, Control Systems, Ship Power Systems

I. INTRODUCTION

The future All-Electric warship opens new design challenges never before considered in the shipbuilding industry. The role of the electrical plant used to be minor and was mostly related to providing hotel services, air conditioning, and last but not least instrumentation. The concept of the all electric ship completely reverses this situation, making the electrical plant the backbone of the entire system, providing also propulsion, weaponry and aircraft launching. Even if commercial ships are already using electrical propulsion, the concept of the all electric warship still requires significant additional innovation. New challenges are given by such possibilities as providing energy to pulsed loads including electric guns or aircraft launchers.

These challenges can be met only if a new paradigm for the power system architecture is considered. In particular, a key to success will be the widespread application of power electronics, which will transform the process of energy conversion and distribution from a mostly passive process to an actively controlled process. Most notably, we realize that control of the power system no longer implies simply the definition of a configuration of switches but rather a more complex interaction of switches and power converter control that allocates the actual flow of power.

A group of universities coordinated through the Electric Ship Research and Development Consortium (ESRDC) are currently developing a testing scenario to verify the effectiveness of the system here envisioned. The main goal of this demonstration is to prove that the control technology is ready to support new methods of power distribution onboard the ship. The demonstration is based on a simulation testbench built on the Virtual Test Bed (VTB) platform.

The purpose of this conceptual experiment is to provide a complex simulation scenario that can be used to perform rapid verification of control concepts applied to the Ship Power System.

In the following, a short introduction to the tool is provided, then an analysis of the main questions the consortium is trying to answer is reported, and finally the procedure adopted for definition of the simulation scenario is illustrated.

II. THE VIRTUAL TEST BED

The simulation tool adopted for the experiment summarized here is the VTB. The VTB has been developed during the last nine years mainly at the University of South Carolina but with significant collaboration of institutions all around the world.

The purpose of the Virtual Test Bed project is to develop a new environment for simulation and virtual prototyping of multidisciplinary systems [1][2][3]. The term "virtual prototyping" encompasses not only simulation of the system dynamics, but also their visualization of the system dynamics via 3D solid models. Our objective is to create a multidisciplinary system description, which includes analog and digital electronics, power systems, controls, electromechanical, fluid, and thermal systems. There is a compelling need for a high-level interface that allows many types of users, from all of those disciplines, to comfortably use the

A. Monti, F. Ponci, E. Santi, and R. Dougal are with the University of South Carolina. G. Monnat, W. Shutt, and R. Hebner are with the University of Texas at Austin. D. Cartes is with Florida State University. N. Schulz and H. Ginn, are with Mississippi State University. F. Wang and D. Boroyevich are with Virginia Tech. S. Pekarek and S. Sudhoff, are with Purdue University. Corresponding author is A. Monti (monti@engr.sc.edu)
virtual prototyping tool.

The VTB attempts to solve the traditional dichotomy in modeling that universally plagues designers, allowing each designer to use an appropriate instrument for each part of the system design problem. In contrast, classical simulators limit the analysis of such systems, because only a single language can be used to specify the system.

The VTB environment addresses these challenges by supporting:

- Multi-formalism: different languages can be used to define models of the different components that compose a system. This allows an individual to build models using the preferred language within his or her discipline (in this case mechanical, electrical or chemical)
- Co-Simulation: users can use other solvers together with the main VTB solver. This means that any part of the system can be solved with the most appropriate integration step and method without affecting the solution of the rest of the system.
- High-level visualization: visualization models of the system can be easily created and linked to live simulation data. Visualization helps the user to rapidly comprehend the system performance. Visual outputs include data-driven animation of the motion of solid objects, imposition on top of the solid objects of novel representations of abstract simulation data, or simply oscilloscope-like graphs.
- Multi-resolution modeling: models have to be flexible in order to accommodate interaction with different classes of systems and then different requirements in terms of integration time-steps
- Modeling under uncertainty: a good design tool must support the engineer from the very beginning of the design when some of the parameters are still uncertain.
- Hardware in the simulation loop: A real-time extension to VTB allows performing HIL simulations.

III. MAIN GOALS OF THE DEMONSTRATION

The All Electric Ship will be the first example of a high integration of power electronics into ship systems. By this, we mean that in order to achieve the rapid dynamics of power reconfiguration the ship power systems must exploit the capability of the power electronics to allow for a rapid redistribution of energy on board.

From this perspective we can envision a set of significant questions that must be answered:

1. What hierarchical control structure should be used?
2. What kind of strategy for reconfiguration of the power system will guarantee power continuity to the most critical loads?
3. What strategies for reconfiguration of the power system will guarantee power for pulsed loads?
4. How can we guarantee the overall stability of the system?
5. Will the system maintain stability during reconfiguration?

Next we will discuss a few details for each of these questions. Concerning the control architecture, there is a significant interest in finding the right balance between centralized hierarchical control and flat distributed control structure.

The use of hierarchy is the traditional option wherein information becomes more centralized the more we proceed up the command levels. It is a typical solution for many automated industrial plants. Advances in technology, including the development of intelligent agents, has created a recent trend to investigate opportunities for distributed control schemes with flat architecture. In these schemes distributed control entities, such as intelligent agents, exchange information with their neighbors and make localized control decisions. Significant work in this direction is currently underway and applications to power systems can be found in the literature [4][5][6][7].

Two approaches surface relevant to questions 2 and 3. On the one hand it is important to guarantee enough flexibility in the power routing to provide energy to the loads under any extreme condition (including battle damage). On the other hand, it is important to improve the overall dynamics of the system to support pulsed loads such as rail guns or aircraft launchers whenever these are needed.

These two different sides of the problem call for two different approaches to the concept of reconfiguration. We will have reconfiguration in the sense of definition of the static configuration of the bus bars to support the flow of energy, and reconfiguration of the control of the intelligent loads to provide massive quantities of energy in a very short time interval. This last concept calls for an innovative application of the concept of multi-use in the sense that the same converter should be capable of operating differently depending on the specific scenario. For example an interface converter could be operating as active filter compensator or as a voltage rectifier.

All in all, the complexity of the structure creates a significant concern for stability of the power system. The system is highly non-linear and time-variant. Few attempts have been made to develop a general theory; one interesting approach is reported in [8].

These large systems that have non-linearity and time-variant characteristics have a significant degree of complexity related to mathematically modeling and demonstrating stability. In many case time-domain simulation is still one of the most widely used approaches. However

By limiting the modeling of the load to passive non-controlled components more results are theoretically achievable with standard criteria.
IV. DEFINITION OF THE SCENARIO

The first part of the effort reported here is dedicated to the definition of realistic scenarios that can be used for this first round of analysis and for future investigations for ship power systems.

Considering the list of questions reported in the previous paragraph, the authors decided to define a realistic ship power system composed of two main subsystems (see Fig. 1). A first subsystem focuses on the bus bar reconfiguration management, while the second focuses on the power electronics interaction.

As already shown in Fig. 1 this schematic is connected to the second schematic focusing on the power electronic issue. The topology selected for this second schematic has been defined according to the Ship Power System testbed available at Purdue University [10].

V. PARTNER CONTRIBUTIONS

One of the main strengths of the research experience reported here is the collaboration of many different schools with different backgrounds and expertise. It is worthwhile here to briefly summarize the main goals of each partner in this experience.

The University of Texas is focusing on the analysis of algorithms for power system reconfiguration. The main goal is to test the impedance-based algorithm for optimization of the power bus configuration.

Florida State University is focusing on the application of the agent-based controls for determining dynamic reconfiguration algorithms.

Mississippi State has two main areas of work for this demonstration. Area one relates to active filtering including VTB modeling and control algorithms for PEBB based filters. The second area involves reconfiguration strategies for the
ship power system and its protection systems. The power system reconfiguration work involves optimization, agent-based controls and control of distributed generation sources using the Virginia Tech UCA concept. Additional work is being done to investigate adaptive protection strategies to adjust for different power system configuration.

The University of South Carolina is providing modeling support and it is also performing research related to the concept of intelligent load, with intent to look at the agent technology as a way to make power converter based loads smarter.

Purdue University is the developer of the reference test bed with which the model will be compared. They are providing support in the model development process and will be active in validation of the testbed.

Virginia Tech focuses on developing the UCA technology and will provide UC hardware, software and modeling support for system-level testing in other institutions.

VI. FUTURE DEVELOPMENTS

The effort described here has been performed during the last nine months. The group of universities will deliver the main results of this first phase in late September.

However, the group has already put together a three-year plan of demonstration with the goal of increasing the reliability of the results, and increasing the role of the hardware validation process and the use of Hardware in the Loop (HIL) platform.

A pictorial view of this evolution is shown in Fig. 4.

The final goal is to simulate the complete system in Hardware in the Loop configuration applying the Real Time Digital Simulator (RTDS) available in the Center for Advanced Power Systems (CAPS) facilities at Florida State University.

VII. CONCLUSION

This paper has summarizes an on-going collaborative effort performed by a consortium of universities working to advance the state-of-the art for the control systems within the all electric ship platform. Work to date has developed a virtual test platform for the assessment of different control approaches for the ship power system. Using the diversity of expertise at the six involved universities we will investigate, test and demonstrate the many facets of the challenges related to control strategies. This three year assessment plan will provide a multi-dimensional investigation of control system structures, reconfiguration capabilities and system stability characteristics.

ACKNOWLEDGMENT

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

Fig. 4: The three-years plan for the control assessment

REFERENCES

Antonello Monti (M. 1994) received the M.S. degree in Electrical Engineering from the “Politecnico di Milano” in 1989 and the Ph.D. still from the “Politecnico di Milano” in 1994. From 1990 to 1994 he worked in the research laboratory of Ansaldo Industria at Milan. From 1995 to 2000 he was Assistant Professor at the Department of Electrical Engineering of “Politecnico di Milano”. Starting from August 2000 he is Associate Professor at the Department of Electrical Engineering at the University of South Carolina.

Ferdinanda Ponci (M. 2000), received her master degree in Electrical Engineering from Politecnico di Milano in 1998 and the Ph.D. from Politecnico di Milano in 2003. During 2000 and 2001 she served as Visiting Researcher at the Department of Electrical Engineering at the University of South Carolina, where she is currently serving as Assistant Professor.

Roger A. Dougal earned the Ph.D. degree in electrical engineering at Texas Tech University in 1983, then joined the faculty at the University of South Carolina. Dr. Dougal has received the Samuel Linman Distinguished Professor of Engineering award, and has been honored as a Carolina Research Professor. He is a Senior Member of the IEEE. Prof. Dougal is the director of the Virtual Test Bed project, which is developing an advanced simulation and virtual prototyping environment for multidisciplinary dynamic systems.

Herbert L. Ginn III (M. 96) received the M.S. and Ph.D. degrees in electrical engineering from Louisiana State University, Baton Rouge, in 1998 and 2002, respectively. In the fall of 2002 he joined the Department of Electrical and Computer Engineering at Mississippi State University as an Assistant Professor. His research interests include power phenomena and compensation in non-automated systems and power electronics applications in power systems.

Noel N. Schulz received his B.S.E.E. and M.S.E.E. degrees from Virginia Polytechnic Institute and State University in 1989 and 1990, respectively. She received her Ph.D. in EE from the University of Minnesota in 1995. She has been an Associate Professor in the ECE department at Mississippi State University since July 2001. Prior to that she spent six years on the faculty of Michigan Tech. Her research interests are in computer applications in power system operations, including artificial intelligence techniques. She is a NSF CAREER award recipient. She has been active in the IEEE Power Engineering Society and is serving as Secretary for 2004-2005. She was the 2002 recipient of the IEEE/PES Walter Fee Outstanding Young Power Engineer Award. Dr. Schulz is a member of Eta Kappa Nu and Tau Beta Pi.

George Munnar, Jr., earned a B.S. degree in electrical engineering at the University of Texas at Austin in 2004, then joined the staff at Applied Research Laboratories: University of Texas at Austin (ARL-UT). George was a nuclear electrician on the submarine U.S.S. Taung (SSN 639) and afterwards worked in semiconductor manufacturing for seven years while earning his degree.

David A. Carter is an Assistant Professor of Mechanical Engineering at Florida State University. He joined the Department of Mechanical Engineering at FAMU-FSU College of Engineering in January 2001, after receiving his Ph.D. in Engineering Science from Dartmouth College. He leads the Power Controls Lab at the Center for Advanced Power Systems. He teaches courses on control and dynamic systems. His research interests include Distributed Control and Reconfigurable Systems, Real-Time System Identification, and Adaptive Control. In 1994, he completed a 20-year U.S. Navy career with experience in operation, conversion, overhaul, and repair of complex marine propulsion systems. He is a member of the American Society of Naval Engineers.

Enrico Santi received the Dr. Ing. degree in electrical engineering from the University of Padua, Italy in 1988 and the M.S. and Ph.D. degree from Caltech in 1989 and 1994, respectively. He worked as a senior designer engineer at TESLAco from 1993 to 1998, where he was responsible for the development of various switching power supplies for commercial applications. Since 1998 he has been at the University of South Carolina, where he is currently an Associate Professor in the electrical engineering department. He has published several papers in power electronics and modeling and simulation and holds two patents. His research interests include switched-mode power converters, advanced modeling and simulation of power systems, modeling and simulation of semiconductor power devices, control of power electronics systems.

Fred Wang is an associate professor and technical director at the Center for Power Electronics Systems (CPES) of Virginia Tech. Prior to joining CPES in 2001, he worked in General Electric Company from 1992 to 2001 as an application engineer, a senior development engineer, and a R&D manager. He was a research scientist and an instructor at University of Southern California from 1990 to 1992. He earned his B.S. from Xi An Jiaotong University, China in 1982, his M.S. and Ph.D from University of Southern California in 1985 and 1990, all in electrical engineering.

Dr. Dushan Boroyevich received his Dipl. Ing. degree from the University of Belgrade in 1976 and his M.S. degree from the University of Novi Sad in 1982, both in Yugoslavia. He received his Ph.D. degree from Virginia Tech in 1986. Between 1986 and 1990 he was an assistant professor and director of the Power and Industrial Electronics Research Program in the Institute for Power and Electronic Engineering, at the University of Novi Sad, and later, acting head of the Institute. In 1990 he joined The Bradley Department of Electrical and Computer Engineering at Virginia Tech, Blacksburg, Virginia, as associate professor. He is now co-director of the NSF Engineering Research Center for Power Electronics Systems and professor at the department.

Dr. Sven Pekarek received his PhD in Electrical Engineering from Purdue University in 1996. From 1997-2004 Dr. Pekarek was an Associate Professor of Electrical and Computer Engineering at the University of Missouri-Rolla. He is presently an Associate Professor of Electrical and Computer Engineering at Purdue University, and is the co-director of the Energy Systems Analysis Consortium. As a faculty member, he has been the principal investigator on a number of successful research programs including projects for the Navy, Airforce, Ford Motor Co., Motorola, and Delphi Automotive Systems. The primary focus of these investigations has been the analysis and design power electronic based architectures for future military power and propulsion systems. He is an active member of the IEEE Power Engineering Society, the Society of Automotive Engineers, the Small Motor Manufacturers Association, and the IEEE Power Electronics Society.
Fig. 5: A view of the power system implementation in VTB

Fig. 6: A simplified single phase view of the same system