Electric Ship Technologies

By **STEINAR J. DALE**, *Life Fellow, IEEE*

ROBERT E. HEBNER, *Life Fellow, IEEE*

GIORGIO SULLIGOI, *Senior Member, IEEE*

I. INTRODUCTION

Although electric propulsion for marine ships goes back more than 100 years, the modern age of electric propulsion and electric ships emerged with the retrofit of *Queen Elizabeth 2* in 1988 when the shipping industry began to introduce electric propulsion as a solution to improve fuel efficiency and reduce carbon emission. Electric ships also resulted in improved controllability of the vessels during ship maneuvering and docking. All this became possible with the development and advancement of semiconductor switching devises. Most cruise ships today are all-electric, meaning that they have electric propulsion in addition to electric distribution for hotel loads. Many cargo ships, icebreakers, and smaller supply/service vessels are also going to electric propulsion. Cruise ships, liquefied natural gas (LNG) carriers, and drilling vessels with dynamic positioning systems have taken advantage of the power plant model where electricity can be produced at any time with optimum running of the prime movers, and scheduling the plants based on the loads of the ship. The key drivers for the commercial ship business to convert to all-electric ship propulsion include environmental requirements and cost of operation leading to the need for reduced fuel consumption and reduced environmental emission; increased efficiency of the prime movers (generators) because they can be run at optimum speed; better efficiency of the electric propulsion motors at lower loading and speed; improved dynamic response and fuel savings resulting from the use of energy storage; reduced weight, size, and footprint of the electrical equipment; more flexible equipment placement, resulting in increased space for payloads, e.g., more cabins in a cruise ship; reduced manpower through more automation and better safety management systems; and reduced lifecycle costs through reduced maintenance.

This special issue provides a comprehensive treatment of the history of electric ship propulsion, the present status of both commercial and military electric ships, and the ongoing research that will lead to the fully integrated all-electric ship.

Because these advantages all come with challenges, the adoption of electric ships has tended to be both opportunistic and targeted. The challenges are broad.

- All energy for a ship is stored in fuel. Good engineering is needed to determine when it is cost effective to provide additional energy storage for the electrical energy produced by the fuel.
- Low-speed, high-torque electric motors tend to be large.
- Power electronics require large volumes, particularly due to the passive components. The use of wide-bandgap semiconductor systems to increase the frequency and so reduce the size of the passive components is an emerging approach to address this challenge.
- The cable plant is large.

So, while the use of electric ships is growing, this is very much an emerging application benefitting from the maturation of a range of new technologies.

These drivers are also important to electric naval combatants, but the biggest drivers are the need to accommodate multimission capability and the increasing loads in future combatants, such as electrokinetic energy weapons (electromagnetic rail gun) and high-power sensors such as advanced radars and lasers. These new electric loads are likely to rival or surpass the propulsion load of a warship in the next 25 years. Thus, the generation capacity of these ships can exceed 100 MW to meet the load requirements. The U.S. Navy has a long history in electric navy ships. The U.S. Navy commissioned the first electric ship in 1913, the *USS Jupiter* (which was a collier), followed by the *USS New Mexico*, the first Navy electric propulsion combatant in 1918, and with the *USS Jupiter* recommissioned as the first Navy aircraft carrier, the *USS Langley* in 1922. In 2010, electric ships propulsion was deployed in combatants by the navies of Great Britain, The Netherlands, Germany, France, Italy, Greece, Morocco, and Australia. The U.S. Navy commissioned the LHD-8 Amphibious Assault ship in 2010 with a hybrid electric drive, and three surface combatants of the DDG-1000 Zumwalt class destroyers are under construction with electric propulsion and a single unified electrical system—the integrated power systems (IPSs).

The electric ships with electric generation, IPSs, and dynamic loads will surpass the land-based microgrids in terms of automation, control, and design for reliability and will be the ultimate "smart grid" in complexity. Moreover, the underlying technology has commonality with emerging land-based microgrids, modern control theory, and advanced electrical machines.

This special issue has broad appeal, as it will cover a cross section of core and multidisciplinary issues of interest to the IEEE and marine community.

II. ISSUE OVERVIEW

This special issue of the PROCEEDINGS OF THE IEEE on the topic of Electric Ship Technologies comprises 13 invited papers from the world leaders in the field.

The invited contributions include "History and state of the art in commercial electric ship propulsion, integrated power systems, and future trends" by Hansen and Wendt and "History and the status of electric ship propulsion, integrated power systems, and future trends in the U.S. Navy" by Doerry *et al.* These two "global" overview papers on commercial and military development and applications of electric ships set the stage for introduction, overview, and status of the details of several ship system technologies, and include early-stage ship design methods ("Early-stage design for electric ship" by Chalfant), hybrid propulsion systems ("Hybrid electric drive for naval combatants" by Alexander), IPSs ("Integrated power systems—An outline of requirements and functionalities for ships" by McCoy), advances in power conversion ("Advances in power conversion and drives for shipboard systems" by Wang *et al.*) and converter controls ("Control architecture for high power electronics converters" by Ginn *et al.*), propulsion motor technologies ("Motors for ship propulsion" by Kirtley, Jr. *et al.*), and ship and motor development in Japan ("Electric propulsion motor development for commercial ships in Japan" by Yanamoto *et al.*), dynamics of load and integration of storage ("Dynamic load and storage integration" by Hebner *et al.*), power flow control and IPS network stability ("Power flow control and network stability in an all-electric ship" by Cupelli *et al.*), electric power for ship–shore connection ("Shore-to-ship power" by Sulligoi *et al.*), and finally the role of modeling and simulation in the design and verification of IPS concepts ("Role of power hardware in the loop in modeling and simulation for experimentation in power and energy systems" by Edrington *et al.*).

The first paper (Hansen and Wendt) shows that the potential for the beneficial use of electric ships has been recognized since the early success in harnessing electricity. For modern commercial ships, the main reason for going to electric propulsion is the potential for fuel savings compared to conventional mechanical propulsion systems. Icebreakers were early adaptors of electric propulsion because of the superior performance of the electric-driven propeller. The development and improvements in converter technologies and the integrated power system using direct current (dc) distribution and energy storage allowed multiple energy sources to meet the increasing electric loads, and opened the application of several vessel types such as all-electric ferries using batteries, and drilling ships with advanced positioning systems.

The U.S. Navy has been maturing electric ship technologies over several decades (Doerry *et al.*). The electric ship technologies have been introduced into auxiliary ships (e.g., oilers), the latest aircraft carriers, the Gerald Ford class, and the Zumwalt class destroyers with the first warship IPS. This development is driven by the development of electricity-based weapon systems, such as lasers, radars, rail guns, and electromagnetic launch and retrieval systems for aircraft carriers.

Early-stage ship design concepts present the designers with the tools to integrate emerging technology with proven approaches. In ship design, the decisions of greatest impact are made early in the design stage when the greatest uncertainty about the final product is present. Chalfant reviews the Navy ship design process and introduces ship design tools that are collaborative and makes more information available from various design groups to facilitate an integrated approach to modern ship design, including the hull form, the propulsion system, the integrated power system, heating and cooling requirements, etc. Hybrid electric drive developments for high-performance naval combatants are presented by Alexander. This paper also reviews the backfitting of the hybrid drive to existing power generation and ship architectures, as well as the potential benefits of fuel savings and emission reduction.

The concept of an integrated power system is introduced by McCoy, where he describes the various IPS architecture options available to the ship designers and the benefits afforded by the IPS, including reduced operating cost, flexibility in arranging major loads and generation, including weapon loads, and provides superior reliability and survivability of the total ship.

Power electronic converters are key enablers for the modern all-electric ship. Wang *et al.* introduces some of the key advances made in power electronics with a focus on ship electric power applications. The potential impact from the emerging wide-bandgap technologies such as SiC and GaN devices is described, and the impact includes higher efficiency increased power density and smaller size, allowing medium-voltage class drives and converters for alternating current (ac) and dc systems as well as solid state transformers.

Modern power electronic devices require control and protection systems that can be upgraded and with added new features without impacting adjacent control architectures and the converter hardware. Ginn *et al.* discuss the hierarchical control architecture in high power electronic converters and define partitioning strategies, functions, and parameters that must be handled. The common control layers include hardware control layers for the power hardware, switching control layers for managing the switching logics and sequences, converter control layers for the common converter functions, and the application control layer and system control layers.

Several ship types, such as icebreakers and cruise ships to ferries, tankers, and marine drilling platforms are taking advantage of fuel flexibility and improved maneuvering ability by adopting electrical propulsion. The issue is included in three papers that discuss the various types, advantages, and developments of electric propulsion motors for ship applications. Kirtley *et al.* describe the features of several major classes of motors that are suitable for ship propulsion, such as dc (commutator) motors, induction motors, synchronous motors, doubly fed machines, and superconducting motors. Yanamoto *et al.* discuss the electric propulsion development in Japan that aims at special purpose vessels, such as ice breakers and arctic observation ships, with the focus of this development on superconducting motors on achieving high efficiency and size reduction.

Modern technology combined with the desire to minimize size and weight of a ship's power system has resulted in renewed interest in the integrated power system to facilitate the support of various dynamic/variable loads that may require peak loads in excess of the available generation capacity on the ship. Hebner *et al.* describe the developments and applications of several energy storage technologies such as batteries, capacitors, and rotation machines to facilitate ride through capability for gas turbines, and applications of these to stabilize the ship IPS during transients resulting from the dynamic loads, including insight into when to stage gas turbines versus energy storage.

The evolution of computing and telecommunications provides the opportunity to control the ship power system with heretofore unachievable levels of control. Cupelli *et al.* compare the various approaches to power flow control and network stability of integrated ship power system. A "smart" ship power system achieved through power electronic technologies and controls and "smarter" generation through the power electronic interface is described to achieve the power flow control and network stability in a ship IPS with medium-voltage dc distribution.

Environmental conditions increasingly require that ships in port reduce emission from the generators. Sulligoi *et al.* review the rules, principles, and technologies for providing electric power to the ship when in port from a shore-based connection, such as a port substation.

In a range of fields, new designs are increasingly being evaluated through a combination of modeling and simulation with hardware-in-the-loop testing. Edrington *et al.* describe the application of modeling and simulation to achieve verification and validation of the results through experimental testing using hardware-in-the-loop strategies in a rigorous and dynamic manner. The paper presents the state of the art of hardware in the loop and presents sample cases to show the impact of this technology combining software and hardware on performance and reduced R&D cost and time.

III. SUMMARY AND CONCLUSION

The papers presented in this Special Issue on Electric Ship Technologies are designed to give the readers a comprehensive overview of various ships/vessels in which electric propulsion and electric power distribution are making significant advances in the design, operational flexibility, and resiliency of the ship systems. The advances in power electronics and controls are important in making electric ships feasible and affordable. In-depth discussion and status of the various technologies and their developments are presented and future developments are outlined to achieve operational efficiency, reduced size and weight of the equipment, reduced manpower for operation, and energy efficiency.

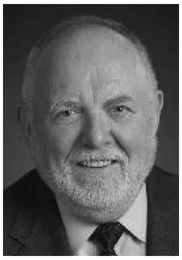
We wish to thank all the contributors for their stimulating and thoughtful presentation of the technologies and systems that makes up the electric ship both in commercial application and in naval combatants. The peer reviewers are also gratefully acknowledged for their effort and professional and insightful reviews. Vaishali Damle, the Managing Editor and Jo Sun, the Senior Publication Editor of the PROCEEDINGS OF THE IEEE have supported the development of this special issue from the proposal to the final stage, and their contributions and assistance are gratefully acknowledged. ■

ABOUT THE GUEST EDITORS

Steinar J. Dale (Life Fellow, IEEE) received the B.S. and Ph.D. degrees in electrical engineering and high voltage physics from the University of Strathclyde, Glasgow, Scotland, in 1971 and 1976, respectively.

He was Director of the Center for Advanced Power Systems, Florida State University (FSU), Tallahassee, FL, USA, from 2003 to 2014. He retired in March 2014. He was responsible for providing the technical and managerial leadership for the Center, including development of the power test facilities, research programs, program funding, and strategic directions. Prior to joining FSU, he was Manager of Strategic Technologies and Government Relations for ABB Power Technologies Division, Raleigh, NC, USA. He joined ABB in 1992, where he held several management positions in ABB's Electric Systems Technology Institute, including Manager of the Power Systems Center, Manager of the Equipment and Materials Center, and Manager of Strategic Technologies. From 1984 to 1992, he was with the Oak Ridge National Laboratory (ORNL), Oak Ridge, TN, USA. He was responsible for research and development in the area of electric utility systems for the U.S. Department of Energy (DOE), including assessments of high-temperature superconductivity applications. Earlier he worked for the Westinghouse R&D Center, Pittsburgh, PA, USA. He has authored or coauthored over 50 technical papers, including two book chapters, and was the editor of a book on the industrial application of high-temperature superconductivity (EPRI 1990). He holds six U.S. patents.

Dr. Dale serves on the editorial board of the PROCEEDINGS OF THE IEEE. In 1986–1987, he served as a Congressional Science Fellow (IEEE) on the staff of the Committee of Science Space and Technology in the U.S. House of Representatives, Washington, DC, USA.



Robert E. Hebner (Life Fellow, IEEE) received the B.S. degree in physics from Saint Mary's University, San Antonio, TX, USA, in 1967 and the M.S. and Ph.D. degrees in physics from the University of Missouri, Rolla, MO, USA, in 1969 and 1971, respectively.

He joined the University of Texas at Austin (UT), Austin, TX, in 1999. He is the Director of the Center for Electromechanics. The Center focuses on the production, conversion, and storage of power and energy. Prior to joining UT, he was the acting Director of the National Institute of Standards and Technology (NIST), an agency of the U.S. Department of Commerce. He also served as Deputy Director of NIST, the Chief Financial Officer of NIST, and the Director of NIST's Electronics and Electrical Engineering Laboratory. He also worked in the Office of Management and Budget, where he helped prepare the technology portions of the Administration's 1990 budget; at Sandia National Laboratories, where he worked in accelerator design; and at the Advanced Research Projects Agency of the U.S. Department of Defense, where he developed programs to stimulate technical advances in semiconductor manufacturing. He has served on a number of government review teams to assess the management of technical programs in other organizations. He was the principal investigator and the government's key witness in a celebrated court case involving an alleged novel approach to the efficient generation of electricity. He has had extensive experience in technical collaborations being former Chair of the Board of the Center for Transportation and the Environment and Chair of the Electric Ship Research and Development Consortium. Throughout his career, he authored or coauthored over 140 technical papers and reports. He has served on numerous technical committees that develop voluntary standards for the electric utility industry. His personal research focuses on smart grid technologies, microgrids, renewable energy, and energy storage. He has been an active contributor to the Pecan Street Project that is helping to gather the information needed to design a smart grid architecture that is attractive to both consumers and industry.

Dr. Hebner is a past member of the Board of Directors of the IEEE and past VP for Technical Activities of the IEEE. He is a past president of the IEEE Dielectrics and Electrical Insulation Society.

Giorgio Sulligoi (Senior Member, IEEE) received the M.S. degree (with honors) in electrical engineering from the University of Trieste, Trieste, Italy, in 2001 and the Ph.D. degree in electrical engineering from the University of Padua, Padova, Italy, in 2005.

He is the Deputy Rector for Community Affairs and Business Relations of the University of Trieste. He is the founder and Director of the grid connected & marine Electric Power Generation and Control (EPGC) Laboratory at the Department of Engineering and Architecture, University of Trieste. He joined the University of Trieste as an Assistant Professor of Electric Power Generation and Control in 2007, tenured in 2010 and appointed Assistant Professor of Shipboard Electrical Power Systems in 2012. In 2013, he has received the national qualification for the level of Associate Professor in Electrical Energy Engineering. Prior to joining the University of Trieste, he worked as Deputy Manager R&D in a small private industrial company (M.A.I. Control Systems, Milan, Italy) and has developed, tested, and commissioned innovative releases of digital voltage control systems for power stations participating in primary and secondary voltage regulation, both in Italy and abroad. He spent a semester (2003–2004) at the Department of Engineering, University College of Cork, Ireland, as a visiting Ph.D. student. He carried out an internship (2000–2001) at the Fincantieri design center of Trieste (Merchant Ships—Electrical and Automation office). He is the author of more than 70 scientific papers in the fields of shipboard power systems, all-electric ships, generators modeling, and voltage control, where he also has earned some scientific awards. He has been the Scientific Manager of the MVDC Large Ship research program (funding institution: the Regional Government of Trieste, lead partner: Fincantieri; research partners: University of Trieste, the Polytechnic of Milan) and of the Naval Smart Grid research program (funding institution and lead partner: the Italian Navy; research partners: University of Trieste, the Polytechnic of Milan, University of Rome "Sapienza"), both in the field of next-generation integrated power systems for all-electric ships. He has been a member (2012) of the Board of Directors of ACEGAS-APS S.p.A., distribution system operator in Trieste/Padua (traded on Milan Stock Exchange), Italy, and a member (2007–2011) of the Board of Directors of Sincrotrone Trieste S.c.p.A., a joint stock company of national interest managing the Synchrotron Light Source "Elettra" and the Free Electron Laser "FERMI@Elettra" laboratories in Trieste, Italy. Currently, he is a member of the Board of Directors of the Maritime Technology Cluster of the Friuli Venezia Giulia region (MARE-TC FVG), in Italy, where he serves also as President of the Technical-Scientific Committee.

Dr. Sulligoi is one of the technical program chairmen of the International Conference on Electrical Systems for Aircraft, Railway and Ship Propulsion (ESARS). He is a member of many technical/scientific committees and working groups in the field of marine electrical applications. He is a Registered Professional Engineer in Italy. He is a member of the IEEE Industry Applications Society (IAS), the IEEE Power and Engineering Society (PES), the American Society of Naval Engineers (ASNE), and the Italian Society of Naval Engineers and Marine Architects (ATENA). He is a reviewer for a number of international conferences and journals. He is the President of the Italian Association of Electrical Engineers (AEIT), the Trieste Section.