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The State-of-the-Art of Integrated Electric Power and Propulsion Systems and Technologies on Ships

The age of the electric ship began anew in the late 1980s and early 1990s. Iconic of this trend was the re-powering of *Queen Elizabeth 2*, 1986-7. In the intervening years, propulsion motor and propulsion motor drive systems and technologies have advanced and become more compact and higher performing. These advances have occurred in both naval warships and commercial ships. What systems and technologies are taken to sea today? What are the advances likely to be made in the future?

Background

Most ocean-going ships, including naval combatants, exist to affordably transport either cargo or a military mission capability. Here, the term affordable is assessed relative to other means of transport. That marine transport in ocean-going ships is affordable is borne out by established references, references [1] and [2], particularly Figures 2 and 9 of reference [2]. There also exists a range of speeds within which virtually all ocean-going ships have operated and still operate, Figure 1 from reference [3] and [4]. Within this range of speeds, roughly 15-30 knots, ship propulsor speed, in revolutions-per-minute (RPM), lie within a certain range, up to a couple hundred RPM. This horsepower range coupled with propulsor RPM range make ship propulsion motor applications a high-torque, slow-speed electric motor. Emerging ship designs which employ different propulsors, e.g. waterjets, may change in this regard. However, ship propulsion motors are predominantly high-torque, slow-speed motors and are likely to remain so for quite some time yet.

Electric Propulsion Motors

Electric motor technologies appropriate for the ocean-going ship application are catergorized as in Figure 2. Figure 2 is adapted from Figure 1 in the paper by Eckels and Calfo, reference [5]. State-of-the-Art ship propulsion motors are almost entirely AC synchronous - wound field - conventionally cooled motors, or AC asynchronous - wound field - passive motors (induction motors).

Ship Propulsion Trends

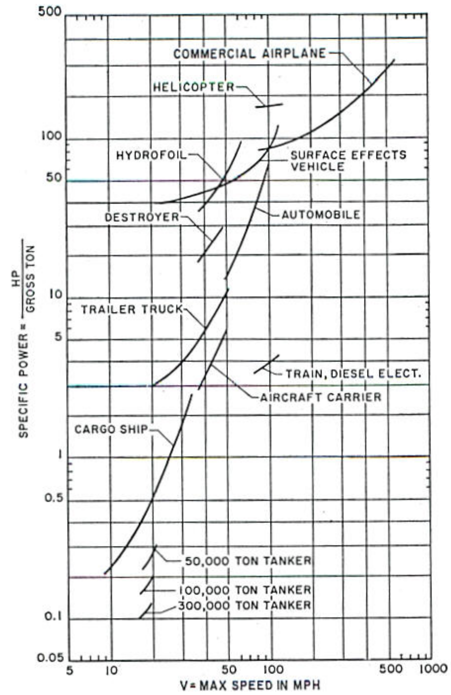


Fig. 2 Specific power versus speed for various vehicles

Harrington ed., Marine Engineering, 1971, p. 6.

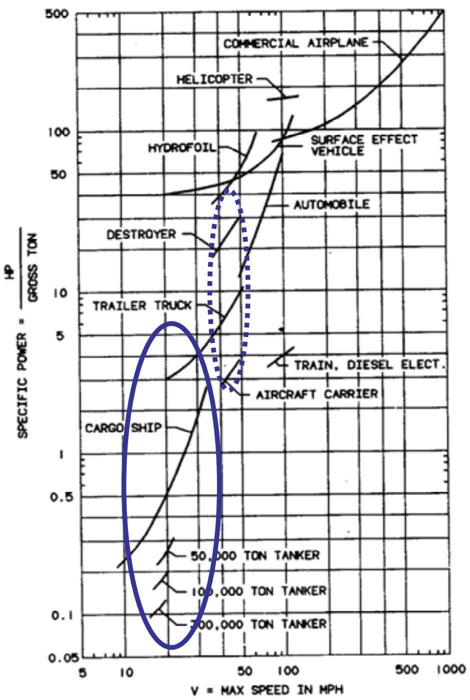


Fig. 1 Specific power versus speed for various vehicles

Harrington ed., Marine Engineering, 1992, p. 4.

Figure 1

Research and development has been conducted on permanent magnet motors, principally the radial and axial variety, AC synchronous - wound field - superconducting motors, DC homopolar - superconducting motors, and some little on transverse flux permanent magnet motors. While appealing on the grounds of more compactly and efficiently supplying the required torque at the relatively slow speeds of ship propulsors, these advanced motor technologies will require large investments before being available. These advanced motor technologies, to be widely applied to ocean-going ships, must, though, become cost competitive, on any basis, with the presently employed technologies. On strictly a motor-to-motor comparison, the advanced motor technologies may be 50 - 75% less massive and occupy 20 - 70% less volume than the state-of-the-art motors. However, when ALL ***system*** changes necessary to incorporate the advanced motor technologies are accounted for, the total power systems based upon advanced motor technologies may be 10 - 20% less massive and occupy up to 10% less volume than the total power systems based upon state-of-the-art motors. These are worthwhile improvements at the system level.--Are they worth the investment?

Rather than focusing strictly on the propulsion motor technologies available, perhaps more attention should be paid to application of new technologies to the propulsion motor drives.

Taxonomy of Electric Motors

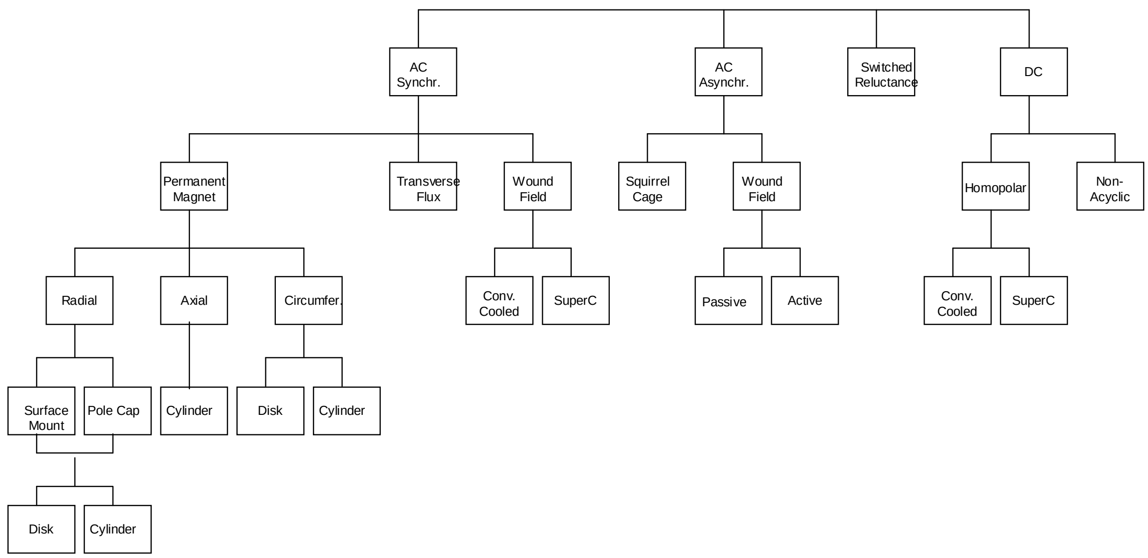


Figure 2

Electric Propulsion Motor Drives

The high power variable speed motor drive is the 'enabling technology' for the modern integrated electric propulsion ship. It is this piece of solid-state power conversion equipment that permits the variable speed AC motor to be powered from the same set of prime movers as the mission, ship service and hotel electric loads. This reduction in prime movers, with its concomitant space, weight, maintenance and fuel savings, serves as the source of the affordability benefits which have lead to the increasing popularity of electric propulsion systems for ships.

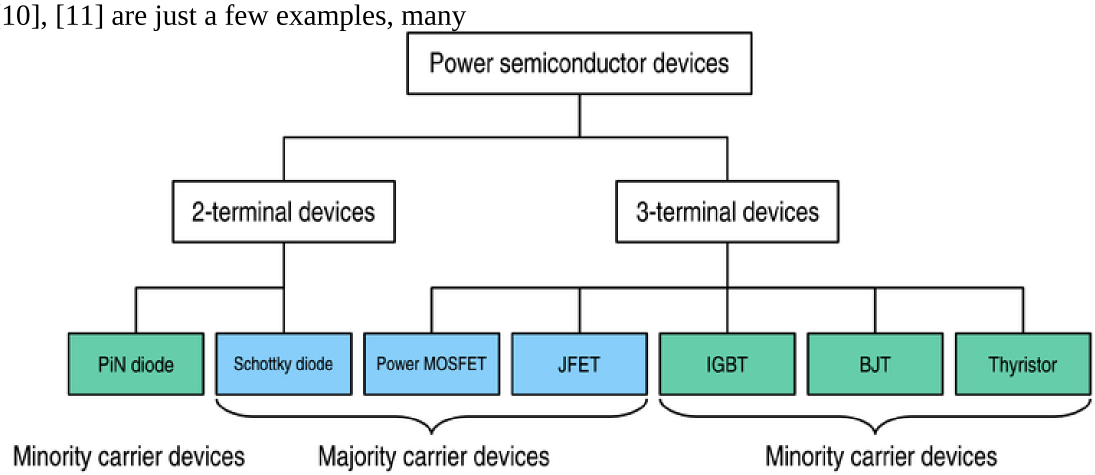
Motor drive development has followed the power semiconductor evolution over the past 50 years. In the 1960's SCR-based rectifiers were used to drive mechanically-commutated DC motors. Later AC-AC cyclo-converters and Load-Commutated Inverters (LCI) or synchro-drives were developed to provide variable voltage & frequency to power AC synchronous motors. In recent years, the development of high voltage, high current Insulated Gate Bipolar Transistors (IGBT's) with much higher switching speeds has facilitated a transition to pulse-width modulated (PWM) voltage sourced inverter drives. Today's state-of-the-art drives are usually either two- or three-level PWM voltage source inverters. The most common front end rectifier is the 12-pulse variety that requires a phase shifting transformer on a three-phase distribution bus.

There are two new technologies that will impact converter design in the coming years. The first has already been fielded in industry and is now making its way into the commercial marine sector. This is the adoption of press-pack IGBT devices using deionized water cooling. Press-pack devices allow for cooling both sides of the semiconductor device, thereby allowing greatly increased power density. They also improve reliability by eliminating bond wires between the semiconductor chips themselves and the packaging.

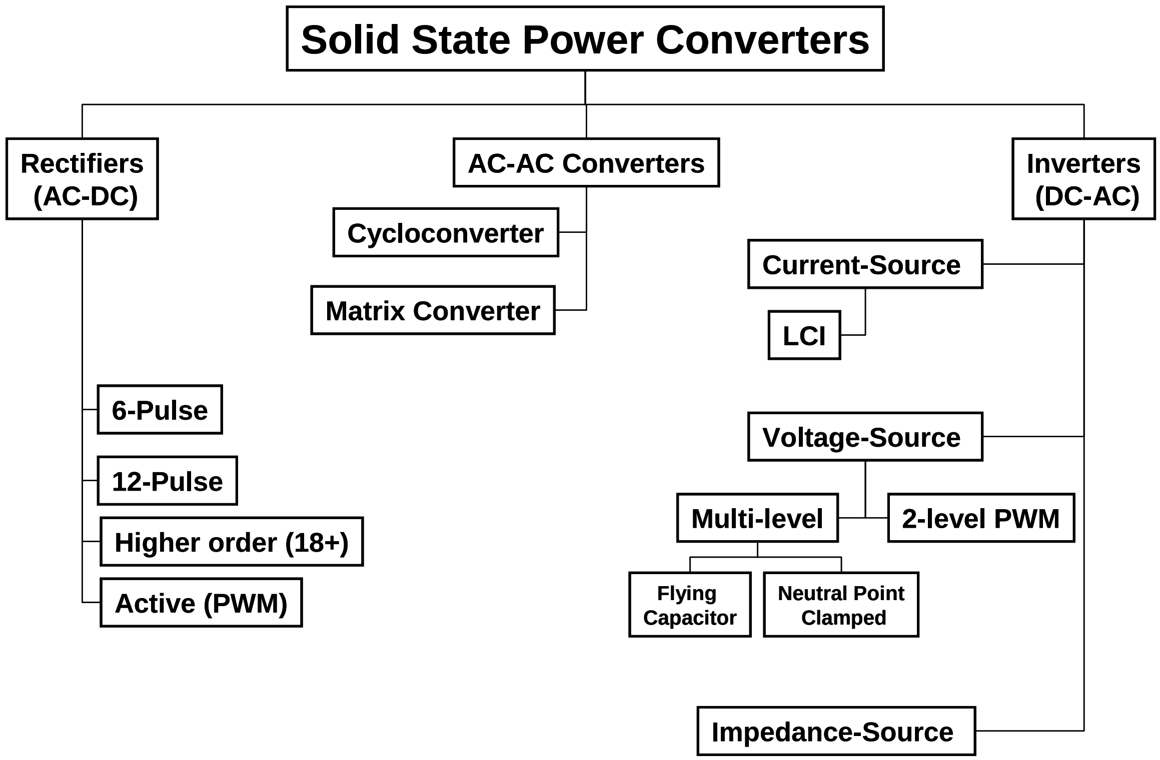
The second technology that will change the landscape of the high power converters is Silicon Carbide (SiC) switching devices. Today, SiC diodes are available commercially with voltage ratings acceptable for use in high-power propulsion drives, albeit at very low current ratings. There are a number of researchers who have successfully tested SiC-based IGBT's, MOSFET's and JFET's in the laboratory. However, commercialization of these devices and scale-up into current ratings needed for ship applications appears to be some years in the future. The benefits of SiC devices have been well published: [8], [9], [10], [11] are just a few examples, many more could be cited. The question at hand is, when will SiC switching devices be available and affordable commercially?

Electric Power Distribution Systems

Today, distribution systems are 3-phase, 60 Hz, radially oriented for the most part. System voltage may range from 450V to 11,000V, depending on the system power requirement. However, there is interest in moving to medium voltage DC distribution (~3-5kV) in both the commercial and military marine sectors. There are size & cost advantages attainable with the DC distribution system that are attractive to both the commercial and military marine sectors. The issue of fault isolation still needs to be overcome but these systems should become reality within the next decade.



Taxonomy of Power Semiconductor Devices - Figure 3



Taxonomy of Propulsion Motor Drives - Figure 4

Conclusions

Dramatic improvements have occurred since the large AC synchronous - wound field - conventionally cooled motors went to sea on *Queen Elizabeth 2*, podded propulsion motors not even having been discussed. Electric propulsion motors have become smaller, better and more affordable. Electric propulsion motor drives have followed a similar trend. Subsequent improvements, in both naval and commercial ships, are almost certainly going to be implemented using the systems and technologies which offer the best Life-Cycle Cost benefits; thus ocean-going ships, including naval combatants, will continue to most affordably transport either cargo or a military mission capability.

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Authors

Dr. John V. Amy Jr. received a B.S. in E.E. from the U.S. Naval Academy, then served in USS Boone (FFG 28). He earned a Ph.D. in naval electric power systems at M.I.T. An Engineering Duty Officer, he was Assistant Project Officer for Aircraft Carrier Overhaul at Newport News VA. At Naval Sea Systems Command, he was Assistant Program Manager for Systems Engineering/Ship Integration within the Advanced Surface Machinery Programs, and later Deputy Program Manager for the Integrated Power Systems Program, followed by Deputy Assistant Program Manager for Requirements and Test & Evaluation for the Navy's Future Aircraft Carrier Program. Following this, Dr. Amy was Associate Professor of Naval Construction and Engineering at M.I.T. Retiring from the U.S. Navy in 2003, Dr. Amy is now Vice President of Power Systems at BMT Syntek Technologies, Inc.

Dr. Timothy J. McCoy has over 25 years experience in naval ship design, program management and naval science & technology development. His US Navy career as an Engineering Duty Officer included work on design and construction of the AOE-6, DDG-51, DDG-1000 and LPD-17 classes. His active duty tours included development of new technology with the Standard Monitoring and Control System (SMCS) and Integrated Power System (IPS) programs, both of which have been implemented in the US fleet. Dr. McCoy completed his active duty career on the faculty of M.I.T. where he taught the Naval Construction and Engineering Program as an Associate Professor. Presently, Dr. McCoy is Director of Research & Development for Converteam North America and President of Converteam Naval Systems Inc. In this position, he executes a multi-million dollar R&D program of both customer-funded and internally-funded projects for the US military, Oil & gas, metals and renewable energy markets. Dr. McCoy holds a B.S. in Mechanical Engineering from the University of Illinois, a Master's in Electrical Engineering, Naval Engineer's Degree and Ph.D. from M.I.T. A licensed professional engineer, he has published over 35 technical papers and holds an adjunct faculty appointment with the Carnegie Mellon University Electrical Engineering Department.