

Trends in Ship Electric Propulsion

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Abstract-- Since the 1980's there has been an explosion in the number and variety of electric propulsion ships being built around the world with everything from cruise liners to amphibious assault ships adopting electric propulsion. This technology revolution has occurred, largely un-noticed outside the marine industry. This paper will briefly describe what has transpired in recent decades, why the resurgence is occurring and what the future may hold for electrically propelled ships.

Index Terms--Marine vehicles, Marine technology, Propulsion, AC motor drives, Systems engineering.

I. INTRODUCTION

Electrically powered ships are not new. Both AC and DC electric propulsion systems have been used since the beginning of the last century. This subject has been extensively discussed in the literature [1] – [6], [10] – [14]. Doyle [5], provides an excellent electric propulsion history for military ships. Borman [6], gives a good primer on electric propulsion for commercial ships. There have been three "All Electric Ship" conferences in recent years with dozens of countries represented and numerous technical papers presented.

A traditional electric ship propulsion system is compared to a mechanical drive system in figure 1. The electric propulsion system is essentially a transmission for changing the relatively

high speed low torque of the prime mover to the extremely low speed, high torque required to turn the propellers. The electric propulsion system must also provide for speed change and reversal of the propeller. In a DC system this is easily accomplished by varying the terminal voltage to the propulsion motor. Mechanical commutation limits DC propulsion drives to about 7.5 MW (10,000 HP), insufficient for many of today's seagoing vessels. The poor power density and maintenance record for brush-type DC motors also limits their usefulness in ship propulsion drives.

In an AC drive, the propeller's speed is adjusted by varying the motor's frequency. Until the advent of variable speed drives, this meant that the entire propulsion bus frequency needed to be adjusted in concert with the speed of the ship. A drawback which made AC electric drives rather unattractive when compared to mechanical drives for many decades.

II. MODERN ELECTRIC DRIVE

There are two fundamental changes in the way electric drive ships are designed which account for their resurgence in recent years. The first is the development of high power solid state switching devices and multi-megawatt variable speed drives. The second is the shift to an integrated architecture, outlined in figure 2.

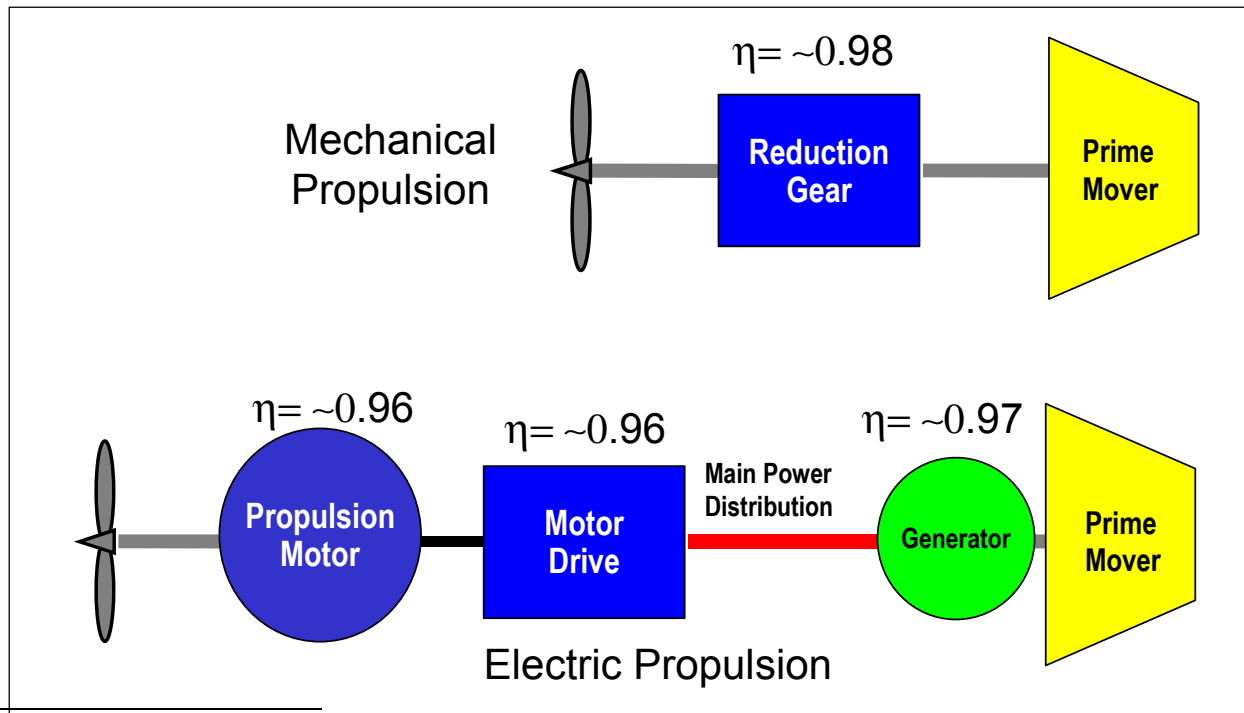


Figure 1: Electrical vs. mechanical propulsion

A. Architecture

It is important to note that the integrated architecture of figure 2 combines the propulsion system and the ship service electrical system into a single power system. The main bus runs at a constant voltage and frequency with the VSD providing the variable voltage & frequency needed by the propulsion motor. This seemingly simple change has far-reaching implications to the ship's design and capabilities.

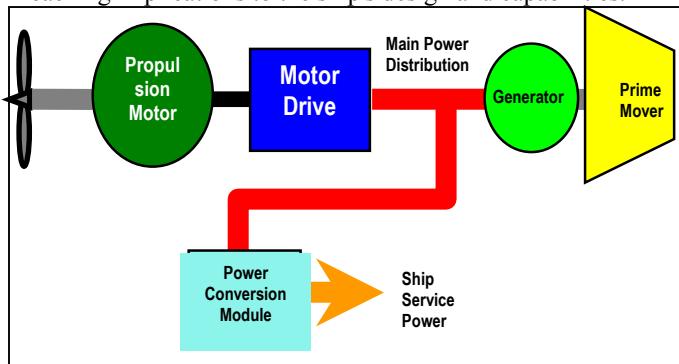


Figure 2: Integrated Electric drive ship

Conceptually, the integrated electric ship is similar to a hybrid electric automobile, albeit at a much larger scale. The reader should also note that figure 2 is a cartoon and any real ship's one-line diagram would have multiple generators, multiple or dual-wound motors and multiple conduction paths for reliability & survivability.

As everyday life has become more electrified over the past century, ships have similarly become dependent upon electricity with everything from radar to fire pumps, fuel pumps and cargo handling systems relying primarily on electric power to function. This electric "hotel load" may account for 10-20% or more of the installed power aboard. For example, a 1902 destroyer might have been built with two 5-10 kW generators whereas today's destroyers typically have three 2.5-3MW generator sets installed to serve the hotel load.

Combining the propulsion & ship service electrical systems not only makes the ship more flexible, but significant cost savings can be achieved. Fewer prime movers are needed, saving maintenance and fuel costs and all the installed power is available for either propulsion or ship service use as conditions dictate. There is virtually unlimited growth potential for the ship service loads (a common problem with warships). The fuel savings alone, upwards of 20%, makes the integrated electric approach the preferred solution for some ship types (nearly every cruise ship built in the past 10 years has included an integrated electric power plant).

An integrated electric architecture eliminates the need for shafts between the propeller & the prime movers, allowing the ship designer virtually unlimited flexibility in arranging the ship. This typically means more internal volume is available for cargo or paying customers for a given size ship, further enhancing the cost effectiveness of the integrated electric approach.

B. Components

The propulsion motor and associated VSD is truly the heart of a modern integrated electric powered ship. Most commercial ships today use either a cyclo-converter or Load Commutated Inverter (LCI) type of drive with thyristors or GTO's as the primary power devices. Cooling is achieved by air, water or a combination. As IGBT ratings increase, there is a trend to use pulse-width modulated (PWM) drives on larger & larger applications. Commercially, PWM drives are presently available to ~5MW ratings. The US Navy has developed & tested a 19 MW PWM drive for military ship propulsion [7], [8], figure 3. PWM technology is seen as a key enabler for incorporating electric propulsion onto military ships because of the ability to more precisely control the voltage waveform to the motor.

Ship propulsion motors are very low speed (100-175 RPM), high torque ($10^6 - 10^7$ N-m) machines, typically rated in the 10-25 MW range. Their diameter is controlled by naval architecture constraints rather than motor design considerations. Commercial propulsion motors are predominately wound field synchronous or induction type, totally enclosed, water-to-air cooled. For military ships, this commercial technology isn't seen as possessing the requisite power density so an assortment of more power dense motors are being studied. These include permanent magnet, superconducting synchronous and superconducting homopolar machines. All of which are in various stages of development to achieve full scale torque levels. PM machines are commercially available up to 7.5 MW ratings.

Main bus voltages range from 4-13kV with transformers providing low voltage for most "hotel loads." Industrial medium voltage switchgear & cables are used aboard commercial ships. Military ships can use the same components when allowances are made for surviving the severe shock incurred from nearby underwater explosions. Not to be understated, the US Navy's shock requirement [9] can be a significant driver of technology and cost. However, just last year USS Cole reminded us of the need for such military requirements.

Generators are typically wound field synchronous units with brushless excitation. System control is normally handled by a system of networked controllers and is critical to the safe & stable operation of the onboard power system. It is important to limit the large propulsion drives power consumption to what can be achieved by the on-line generators at any given time. System dynamics and control are similar to a small, isolated terrestrial power grid.

III. TODAY AND BEYOND

Today, integrated electric ships are becoming common throughout the commercial marine industry. In recent years cruise ships, shuttle tankers, product carriers, ferrys, icebreakers and offshore oil exploration platforms have all been built with integrated electric power systems.

The latest trend in the commercial world is the "podded propulsor" where the propulsion motor is mounted in an azimuthing pod below the stern of a ship as shown in figure 4. Presently, five companies manufacture pods in sizes ranging

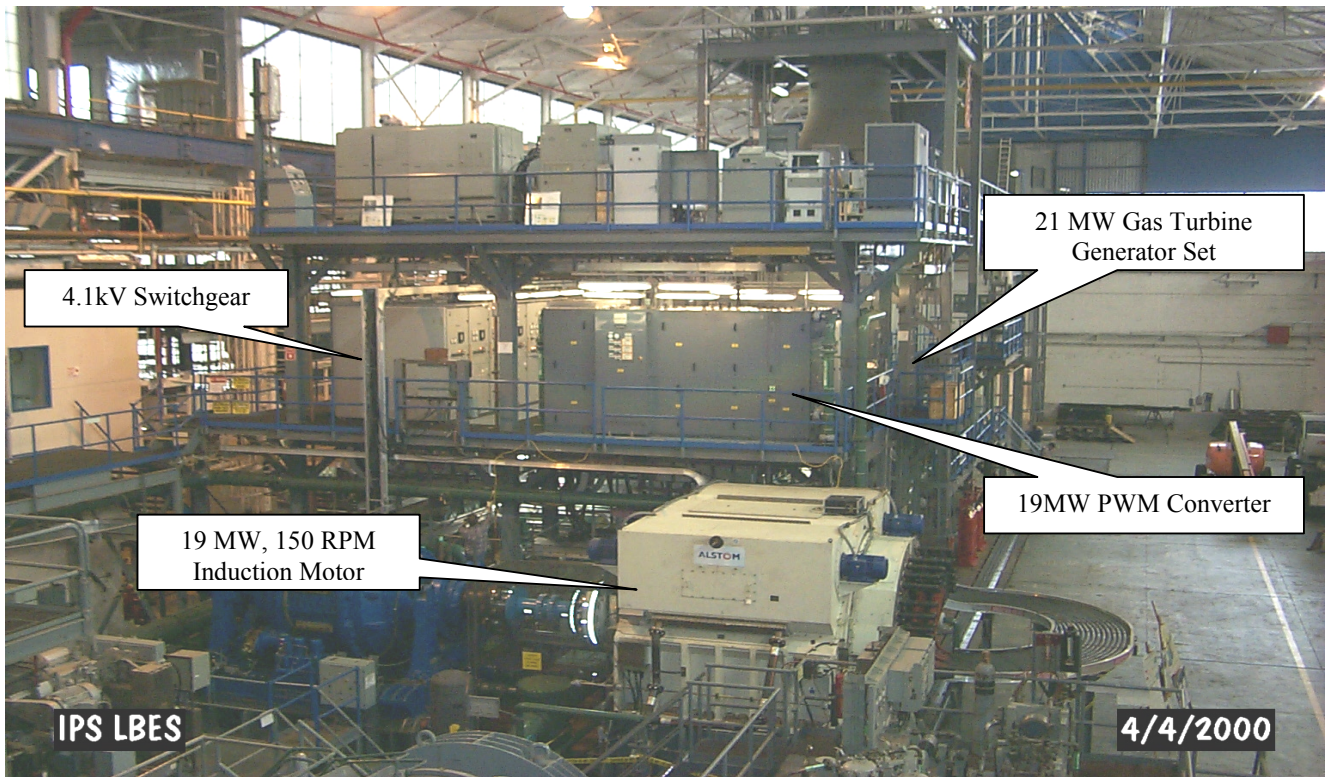


Figure 3: US Navy Integrated Power System Test Facility

from a few hundred kilowatts to ~25 MW. There are numerous advantages to podded propulsors. They improve the ship's efficiency and maneuverability dramatically, they eliminate propulsion shafts completely and locate the large propulsion motors outside the skin of the ship, further reducing the volume devoted to machinery within the ship.



Figure 4: Podded Propulsor

Various Navies are beginning to follow these commercial trends with integrated electric amphibious and auxiliary ships and are developing components for use in combatant ships. Part of the interest for military ships is the potential of having tens of megawatts of power available for other uses besides propulsion. There are an assortment of high powered sensors and weapons presently in development including electric rail

guns, directed energy weapons (lasers), electromagnetic aircraft catapults, electric armor and high power radar and sonar systems. While most of these advanced weapons are still in the laboratory, research is ongoing and the long (>40 years) life of a naval ship make it imperative that the infrastructure (i.e. the electric power plant) be put into place today for systems that may be fielded in the coming decades.

Toward that end, Navies in the US, UK, France, Netherlands and other countries have programs developing components and systems for all electric warships that are adapting the commercial technology where possible and developing unique technologies where commercial hardware falls short.

There are an assortment of ongoing areas of research and development for both components and systems engineering issues associated with integrated electric ships. Stability, Electromagnetic compatibility and control of common mode currents are all serious issues aboard ships where the nonlinear propulsion motor drives are the largest load on the power system. High frequency PWM voltage waveforms are being impressed on ever larger machines where the design impacts may be significant. The potential for large "pulse" loads such as the weapons listed above may require further work to ensure power system stability through the pulse transient. The hostile marine environment makes high reliability a mandatory feature of all power equipment and the military application adds the requirement to a survive hostile attack. Both can be achieved through robust design and system redundancy although more cost effective means are being sought. Advances in both large machines and drives are being investigated by a number of researchers.

Electric ship propulsion is an active and growing field, driven by the rapid growth in the power electronics industry. It has seen two decades of explosive growth in the commercial arena and is expected to take over the military marketplace in the coming years. There are still numerous possibilities for future research and technological development in the years ahead.

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V. BIOGRAPHY

Timothy J. McCoy (M '93) was born in Urbana, IL where he attended the University of Illinois, graduating in 1983 with a BS in mechanical engineering. He joined the US Navy in 1984 as an Engineering Duty Officer and has held a variety of assignments including sea duty aboard a destroyer and ashore as technical director for the Navy's electric propulsion development program. He attended MIT from 1990 – 1995, earning a MS in electrical engineering, a Naval Engineer's degree and a Ph.D. in Naval Engineering. He is a member of IEEE, ASME, USNI, SNAME and has authored numerous technical papers.