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Optimal Electric Ship Propulsion Solution

Introduction

Throughout the history of shipbuilding, the key challenge too often has been how to build the right ship around a given propulsion system, rather than creating a tailored propulsion system for the ship. That was true when the best propulsion "engines" available were sails, and it is also true for today's diesel, gas turbine and electric hybrid systems as well.

The ideal, of course, is to allocate cargo space, cabin space, the shape of propulsion units, and even the shape of the ship's itineraries around the needs of the marketplace rather than around the limitations imposed by the ship's propulsion system. Factors that remain in the path of that ideal include the underlying efficiency across a broad operational range with which chemical energy is turned into mechanical energy, and the ability to allocate space in the most profitable manner. In other words, if you can dramatically improve the power densities of marine propulsion motors and generators as well as their efficiencies, i.e., make these efficiencies much higher and more uniform at varying loads, many of the other issues would be resolved too — and ship design need not be compromised. In fact, with continuing improvements in power density and efficiency, electric drive propulsion systems are projected to displace mechanical drive systems across a broader spectrum of applications.

The maturation of HTS rotating machine design coupled with the upcoming US Navy-sponsored 5 MW prototype motor development and testing indicate that high temperature superconducting (HTS)-based propulsion systems represent a near-term solution to these long-standing challenges. Motors and generators employing HTS wire are very compact in size and low in weight as compared with conventional electrical machinery, and operate more efficiently at all loads. These qualities make them easier to site in the ship, allows more modular ship construction, and reduces undesirable tradeoffs that face many ship designers. Naval architects can now begin to translate these propulsion system improvements into increased profitability for ship owners and operators.

The Challenge

Even in modern ships, propulsion systems are so large and heavy that in many applications they force the rest of the ship to be constructed around them. Machine sizes and their locations also reduce the space available for cargo and passengers and interfere with efficient loading and unloading. Shafts can extend considerable lengths, further compromising efficient space utilization. Additionally, the propulsion systems, both mechanical and electrical, used in virtually all ships today operate less efficiency at lower speeds—creating excess costs on shorter routes and eliminating the use of some otherwise desirable ports.

All these issues carry associated costs. Installing propulsion systems so early in the ship's construction increases the cost of capital and reduces the builder's ability to use the most efficient shipbuilding practices. Less usable internal volume decreases the revenue generation potential for commercial vessels as well as the war-fighting capability for military ships. Inefficient loading and unloading create longer cycle times, increase port costs, and jeopardize schedules. Prolonged and low speed operation of diesel direct-drive and geared propulsion systems increases maintenance costs. Reduced efficiency at low ship speeds may make certain shipping routes unprofitable compared with other transportation alternatives.

Diesel Electric Propulsion Systems an Incomplete Solution for Ship Designers

The shift to diesel electric propulsion systems addressed some of these issues. Electric motors can be located further aft in a ship, freeing naval architects from the "tyranny of the shaft-line," giving ship designers almost unlimited flexibility in the ship arrangements. The length of the drive train is reduced, as is the requirement to maintain strict alignment requirements over long lengths from the prime mover to the propeller. For ships that incorporate podded propulsors, this length is reduced to zero. These externally mounted motors maximize a ship's hydrodynamic efficiency and its usable internal volume for revenue generation. Podded propulsors also reduce shipbuilding costs through increased modularity during construction.

Ships today tend to consume more electricity than did their predecessors. Integrated electric propulsion systems optimize ship operators' flexibility through the ability to only use the minimum amount of electricity generation equipment for a given operational scenario. The generators may therefore be operated closer to their full outputs and unneeded machines shut down, which increases the overall system efficiency and minimizes maintenance requirements.

It is because of advantages like these that nearly all cruise ships and many other ship types including shuttle tankers, product carriers, ferries, icebreakers, and offshore oil exploration platforms have made the transition to integrated electric propulsion systems, in both in-hull and podded propulsion variants. In addition, 13 navies of the world have either modern electrically propelled ships, are already designing/constructing electrically propelled ships, or have announced plans to initiate such programs. Prominent among these is the U.S. Navy, which in 2000, announced that its next generation of surface combatant ships will have electric propulsion systems.

Although they are an improvement over their predecessors, modern electric drives still have not presented an ideal propulsion solution for shipbuilders across a wide range of applications. Electric propulsion motors at higher power levels can be large and heavy, which limits their flexibility in placement within the ship. In propulsion pod applications, this large size and weight provide an upper bound to the pod's applicability, apparently around 20 MW. In addition, today's electric propulsion motors have significantly reduced efficiencies at lower ship speeds, thereby failing to take best advantage of one of their primary attributes – reduced fuel consumption when compared to low speed diesel engines operated at low power levels.

The Keys: Improving Energy Transformation Efficiency and Machine Power Densities

Unlike the force of gravity or the speed of light, the efficiency of mechanical/electrical energy transformation is not a universal constant. Efficiency is a function of variables that have been well known for decades, including the geometry of the motor or generator, the presence or absence of an iron core in its rotor, the material from which the wire in the rotor coils is composed and so forth. In fact, the variable found to have the biggest impact on efficiency is the rotor coil winding material.

The maturation of electrically loss-less ceramic materials, known as high temperature superconducting (HTS) wires, has dramatically improved rotating machine efficiencies, and allowed their designs to be modified so that they can now be built at a fraction of previous sizes and weights.

Just as optical fiber transmits data much better than copper does, so too can ceramic filaments transmit electricity much better than copper. The difference is that optical systems must plug into special adaptive electronics, while motors and generators using HTS wire plug into the same grid and operate in exactly the same way as their copper-based counterparts.

Electric propulsion motors using coils made with HTS wires are just a lot lighter and smaller for a specified power output, and more efficient at all loads. This makes them easier to site in the ship, allows more modular ship construction, and reduces undesirable tradeoffs that face many ship designers. HTS motors in larger power ratings will fit easily into external pods, for example, and therefore simplify the shipbuilding process.

The only consideration for these HTS motors and generators is that they require a small, commercially available refrigeration system to cool the HTS wires. These refrigerators are similar but less complex than those used satisfactorily in thousands of medical diagnostic equipment world-wide.

These cooling compressors give new meaning to the term “hot swappable” as they are easily stocked and field-replaceable even when the generator or motor is running and they occupy the space of a single-drawer file cabinet. HTS motors and generators are typically designed with “n + 1” refrigeration system redundancy to preclude presenting an operational limitation to the ship operator. In addition, the power consumption of these refrigerators is negligible relative to the output of the generator or motor.

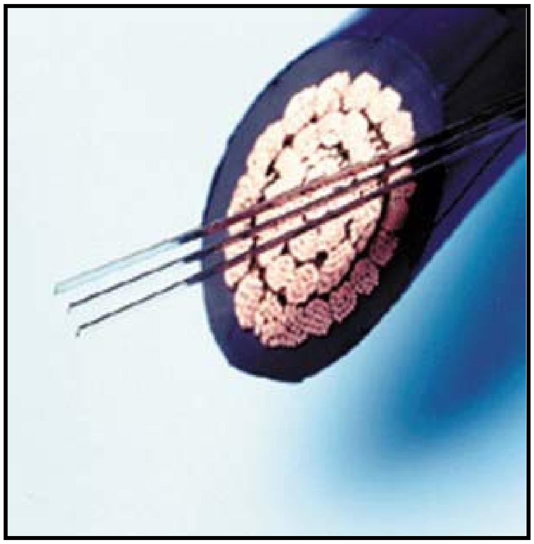
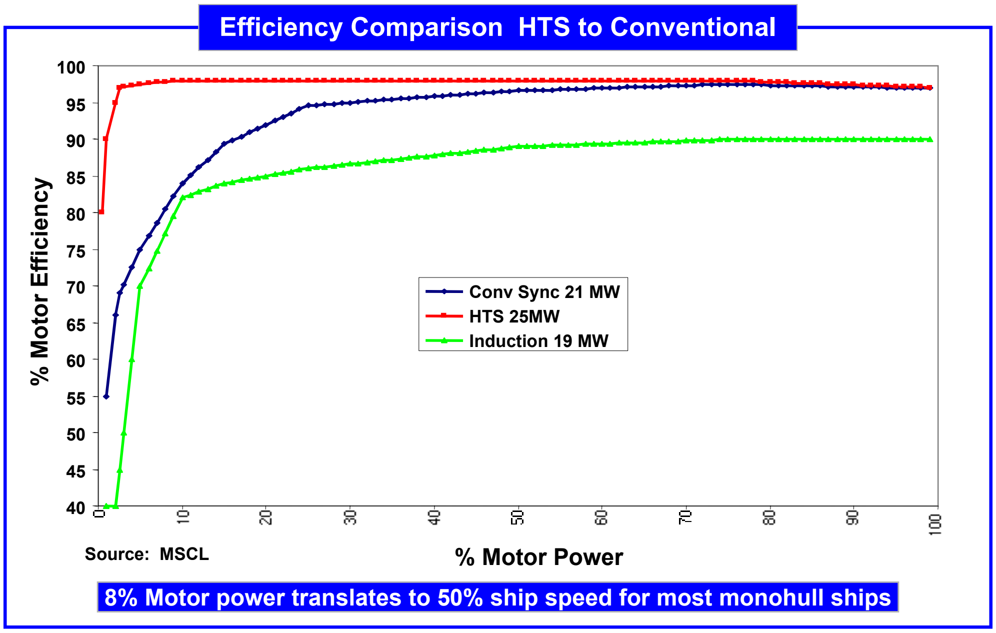


Figure 1. The small strips of HTS wire carry the same current as the much larger and heavier copper cable.

The reason HTS motors and generators are so efficient is that HTS wire can carry up to 140 times more current than the copper wire of the same size and weight, as illustrated in Figure 1. More current means greater flux density, more powerful magnetic fields and in the case of motors, more torque per unit mass of the machine.

HTS motors and generators can therefore be much lighter and smaller, not only because the wire inside them is smaller and lighter, but also because they produce more powerful magnetic fields.

HTS motors also have another advantage: their high efficiency is a constant across virtually their entire power range. Figure 2 compares the calculated efficiency of a typical HTS synchronous marine propulsion motor with equivalent conventional marine propulsion synchronous and induction motors. The calculations also include the losses from the motor cooling system. This means motors and generators can operate at close to maximum efficiently regardless of the ship's speed, creating savings that flow directly to the operators' bottom line. In one study, it was shown that in some scenarios HTS electric propulsion systems can achieve fuel and lube oil cost parity with diesel direct drive ships.


Efficiency Comparison HTS to Conventional

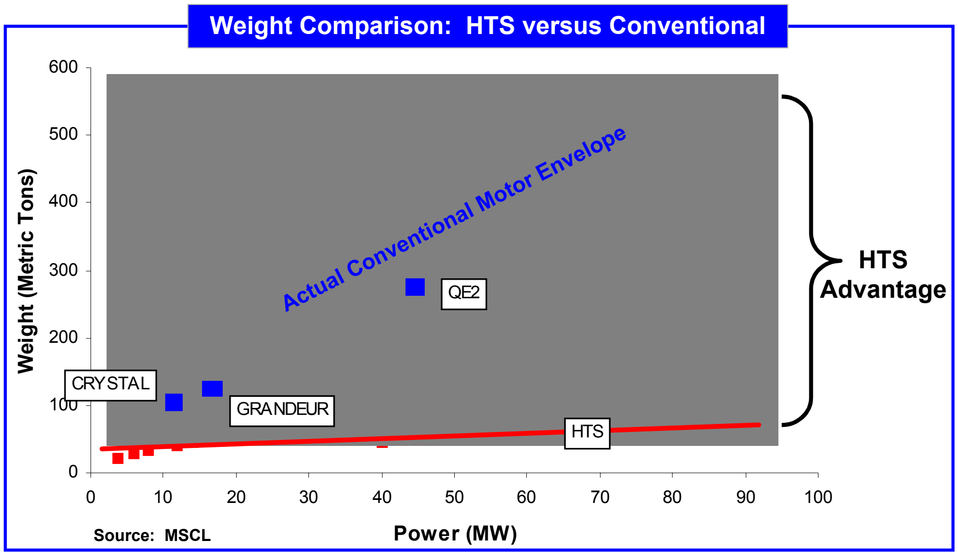
Source: MSCL

8% Motor power translates to 50% ship speed for most monohull ships

Figure 2. The efficiency advantage of HTS versus conventional motors is significant at full load and even greater at partial loads.

Size/Weight/Power Comparisons of HTS and Conventional Synchronous Motors

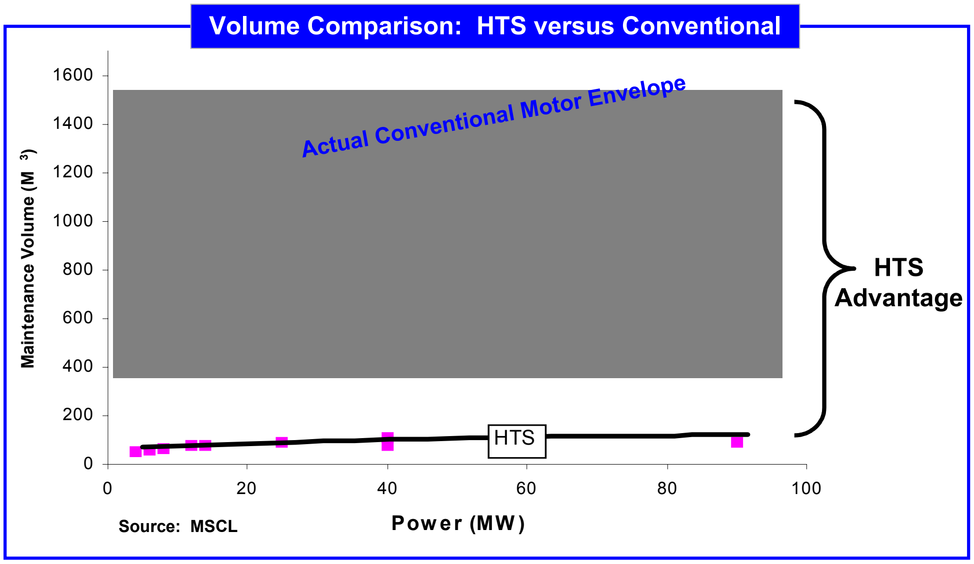
The implications of these advantages for shipbuilders are far-reaching — especially since they apply to both the generator and the motor. Let's compare, for example, the weight and size of a variety of HTS and conventional synchronous motors ranging in power ranges from 5 to 90 MW, and at slow speeds as required for marine propulsion. All are 4.2 KV machines. Figure 3 shows a weight versus power comparison for the two technologies. Figure 4 shows a size versus power comparison. The size comparisons also include maintenance volume, allowing one meter all around the HTS motor (except the bottom) and two meters all around the much larger conventional motor (again, except the bottom).



Source: MSCL

Figure 3. Comparing HTS and conventional motors: weight versus power

The weight savings advantage achieved by HTS motors is particularly valuable in pod applications. It has been estimated that for every 500 tons less light ship weight, about 40 more containers can be carried. Thus, a container ship using HTS podded propulsors will be able to carry about 2.5% to 4% more containers.



Source: MSCL

Figure 4. Comparing HTS and conventional motors: size versus power

Complementing their light weight and compact size, HTS motors can be optimized around specific dimensional requirements. These requirements may include minimizing a propulsion motor's diameter to maximize the hydrodynamic performance of a propulsion pod or to create increased cargo capacities in ships/ lower decks, or maximizing the machine's efficiency. The machines' reduced size creates volume and deck savings that are advantageous in virtually all types of ships, both military and commercial.

Likewise, HTS generators will be much smaller and lighter than their conventional counterparts. In fact, HTS generators enjoy an additional advantage: they operate with greater efficiency than their conventional counterparts even when the refrigeration requirements are considered.

With such small motors and generators, ship machinery space allocations become much less restrictive — making room for more revenue producing volume and allowing for highly innovative designs. Consider for example a 25 MW HTS generator. Coupled with a marine gas turbine engine at about 17 tons, the overall unit could weigh less than 50 tons. This might be light enough in some ships to mount the system in the deckhouse, offering much more revenue space below, better turbine efficiency, and better maintenance access which may, in some instances, offset the drawbacks of environmentally friendly but relative inefficient gas turbines. Such small and light HTS electric motors might, for example, enable more efficient electric drive pump-jet systems and hydrodynamically optimized pod drives that offer better efficiency and higher power than is achievable with conventional motors.

HTS Propulsion Systems Operate Equally Efficiently at any Speed

As noted earlier, HTS propulsion systems have the additional advantage of being able to operate just as efficiently down to low speeds, which is especially important for cruise ships, coastal merchant ships and warships that spend much of their time operating at partial loads. Overall, the fuel savings from efficiency gains of HTS machines depend on the operating scenario but preliminary calculations suggest that fuel savings from \$100,000 to \$500,000 per ship per year can be expected for many ship types.

Other HTS Advantages

There are other advantages of HTS machinery as well. Because there is little or no iron in the magnetic path of the motor or generator, there is very little distortion in the power supply and little noise feedback from the motor. This should simplify power-conditioning system requirements and make for extraordinarily quiet machinery (both electrically and acoustically). The lower weight of the generator rotor also reduces noise.

In other respects, HTS machines behave like conventional electric machines. Their magnetic field can be dumped quickly in case of a system casualty, just like in a conventional synchronous motor or generator. They can be operated with existing synchroconverters, cycloconverters or PWM converters, although some simplification of these systems may be possible in order to take advantage of the lower distortion.

The machines' low weight and small size allow them to be shipped and installed intact, rather than having to be built and tested at the factory, disassembled for shipment to the shipbuilder, and then reassembled and tested at the building yard prior to installation.

Preliminary pricing evaluations indicate that HTS motors and generators should be commercially available at prices equivalent to conventional machines but be easier and less expensive to install — and could be installed later in the ship's construction.

The bottom line: An HTS ship propulsion system places the shipbuilder under far fewer restrictions than conventional power technology when designing the ship best suited for its intended purpose.

The View Forward

So what's next for HTS and how soon will it be widely deployed? HTS wire has been extensively tested in Navy and commercial laboratories, and its durability has been proven. HTS motors rated up to 5000 horsepower at 1800 rpm have been built and tested successfully to a continuous rating of 5,900 horsepower.

A 230-rpm 5 MW ship propulsion prototype motor, funded by the U.S. Navy's Office of Naval Research, is now being built at American Superconductor Corporation, and will be rigorously evaluated by the U.S. Navy in the last half of 2003. A 100 MVA HTS commercial generator, funded in part by the U.S. Department of Energy, is under development at General Electric.

From this high-level view, it appears that HTS-based propulsion systems are the next generational improvement in marine propulsion systems. Naval architects can now begin to translate these propulsion system improvements into increased profitability for ship owners and operators.