ADVANCED ELECTRIC SHIP PROPULSION

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Abstract*. In the past 30 years, major developments can be observed in designing large oil and gas tankers, passenger cruisers and different types of military ships. In all these cases new technologies were involved - from gas turbines as prime movers, power electronics as controlled converters, advanced synchronous and induction motors. The future military boats are expected to be driven by gas turbines or fuel cells; already the windings of the rotors of generators and motors are made of HTMS materials. With the availability of the electrical energy and of the appropriate and efficient storage, new type of guns are developed and used on the new destroyers. In this paper a short survey of the most challenging developments in the electric ship propulsion worldwide is presented.*

Index Terms: *electric propulsion; superconducting motors and generators; electromagnetic launching.*

1. INTRODUCTION

Humans have used simple watercraft for tens of thousands of years. Simple dugout canoes and rafts are limited in size and they have a limited cargo capacity. Boats built of wooden planks can be much larger. The moment when people invented plank construction is not know, but recently a fleet of at least 13 Egyptian boats was discovered. Being 5000 years old, they are the oldest boats discovered so far[·].

The great ancient civilizations were flourishing at about the same time, around 3000 B.C.: the Egyptian on the Nile, the Mesopotamian on Tigru and Eufrat, the Indians on the Indus Valley and the Chinese on Huang Ho and Yangtse. All of these civilizations had in common a warm and sunny weather, a fertile land and developed as placed on major rivers, sources for drinking water, for irrigation, and for local navigation [1]. However, in all these areas the quality wood necessary to built ships was not available and other exotic materials (like bamboo in China, sheep' skin in Mesopotamia and papyrus in Egypt), had to be used, Fig.1.

Fig. 1. Papyrus plant.

Due to the dry climate, the on the 5000 years old papyrus written documents and the corresponding wood models are available; moreover, similar solutions are still in use today, Fig.2.

Fig. 2. Boat made of papyrus.

A more luxury ship was the 30m long boat found in Kufu's pyramid; it is made of cypress wood imported from Lebanon, designed to carry the Pharaoh towards the sun and latter on, to the Paradise, Fig.3.

Fig. 3. The funeral boat from Kufu's pyramid.

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An evolved solution is presented in Fig. 4 where the wind's energy complements the human energy [2].

Fig. 4. Sail boats on the Nile.

For over 5000 years this solution was the basic one, and only by 1800, these two sources of energy were replaced by the piston steam engines and later on by Diesel, steam and gas turbines.

Traveling by water, propelled by wind, was one of the oldest human activities. With the industrial revolution, the wood was replaced by iron in the boat hull building and new forms of energy and new solutions for propelling had to be developed.

2. Modern solutions in ship propulsion

In 1874 Siemens developed the first diesel-electric propulsion system in order to combine the benefits of constant-speed operation of prime mover, the Diesel engine first, steam and gas turbines later and the capacity of variable speed operation of electrical motor-propeller [3]. This solution was applied initially to the civil and, later on, to the military ships; an example is the famous Queen Mary 2, Fig.5, with four diesel engines generating a combined 67MW, as well as two gas turbines which together provide [4] a further 50 000 kW. The Liner is propelled by four 21.5 MW electric pods, two fixed and two azimuths.

Fig. 5. Queen Mary 2 Cruise Ship.

The Azipod propulsion system, Fig.6, was developed initially for cruise vessels; latter on it was used also by the navy. This kind of drives has a great advantage in harbor positioning, requiring only two lengths of a ship for a 360* rotation [5].

Fig. 6. Double azipods.

In military applications, it is preferred a so called electrical integrated system, where all the AC generators are connected in parallel and all the propulsion motors are supplied from a single AC or DC bus from which all ship's services are also supplied. Navy has seen an opportunity to improve its boat performances; by using the electric propulsion, their survivability and affordability will increase. In this way the ships present an increased power density enabling, new advanced weapon and propulsion concepts and better stealth.

For military applications, in order to provide an increased propulsive efficiency and an improved maneuverability, one can use an underwater discharge water jet instead the classical propellers; this solution contributes to reducing the noise, the surface wake and improves the boats stealth, Fig. 7.

Fig. 7. Water jet propelled Destroyer model.

Integrated electric ships have [6] a superior survivability, a longer range, higher resolution sensing, a more effective self-defense, an improved speed and endurance, improved fight through capability, reduced signatures and vulnerability, superior affordability, use of datable platforms, reduced workload, superior mission performance, higher rates of fire, deeper magazines, increased weapons range, improved support for forces ashore etc.

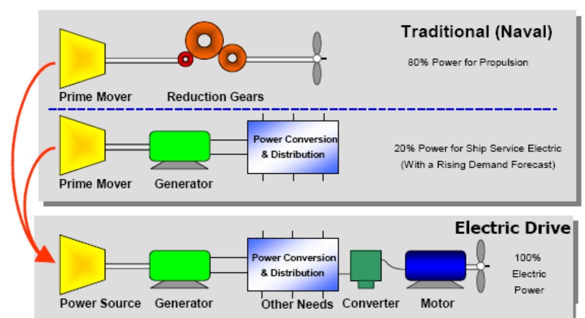

Fig. 8. Integrated power system.

The classical, mechanical driven, power architecture of the Navy ships differs from that of electric-drive architecture, Fig.8. Traditional architectures provide at least two separate power systems. Main propulsion provides about 80 percent of all power for a typical ship; The ship's service generators meet the other 20 percent of the ship's needs, in the form of electricity. In contrast, electrical integrated architecture provides all ship's power, in the form of electricity, for any need. Thus, electric-drive power systems unite the traditionally separate power sources. Operators can determine how well to use the power as this solution can save 10-19% of fuel, for example in gas turbine surface combat ships.

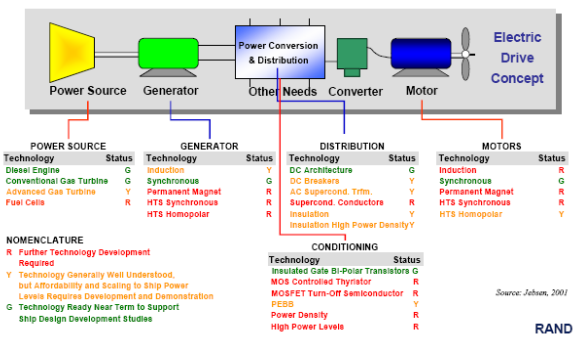

Fig. 9. The configuration of an integrated electrical system: past, present, future. [6].

The synchronous motor can be considered the most mature technology in view of its application to large ships. There is consensus among both naval and industry sources that the synchronous motor, if scaled up to the higher horsepower ratings needed to move surface combatants and submarines at high speeds (i.e., 30+ knots), would be too large and heavy, not suitable for these ships. The induction motor is generally considered the second-most mature motor type for the use on large ships, after the synchronous motor [7], [8]. Most of the sources consulted for this report argue that it can be sufficiently power-dense to be suitable for use on U.S. Navy surface combatants. The permanent magnet motor can be made quieter and significantly more power dense than the induction motor—enough to make it suitable for submarines or surface combatants. The permanent magnet motor is less mature technologically than the induction motor; consequently it may arise a development risk when considering to incorporate it into a nearer-term ship acquisition program [9], [10]. The superconducting synchronous motor has a higher power-density and it is quieter than a permanent magnet motor. The superconducting synchronous motor is less mature technologically than the permanent magnet motor. The superconducting homopolar motor, if successfully developed, could similarly provide a higher power-density and also be quieter than a permanent magnet motor; however, the homopolar motor, like the superconducting synchronous motor, is less mature technologically than the permanent magnet motor. The power electronic devices needed for such applications are cycloconverters, synchroconverters and PWM IGBT inverters [10] and all require adequate cooling systems. Air-cooled systems are less complex but also less compact. Water-cooled systems are more complex but also more compact [11], [12], [13]. A comprehensive view on modern solutions in electrical propulsion is presented in [14]-[19].

3. Future solutions in ship propulsion

In Fig. 10 is presented the structure of an integrated ship with all possible types of energy sources, connections, energy storage, motors and gears. Such a ship is expected to be commissioned by 2012, the so called the DD(X); it will be a high performance destroyer with high acceleration capacity and speed over 30 knots, an efficient electromagnetic gunnery and stealth characteristics.

Fig. 10. A future DDX Navy Destroyer.

All these performances cannot be reached by classical solutions and require new materials and more powerful engines. The generators and motors used for electrical propulsion have to allow high current densities, i.e. the conductors have to be of superconductive materials [20].

Remarkable advancements have been made in the last years [21], [22] in the development of the second generation, high temperature superconducting (HTS) 2G coated conductors, operating in liquid nitrogen with high current-carrying capacities up to 1,000 A/cm2, Fig.11.

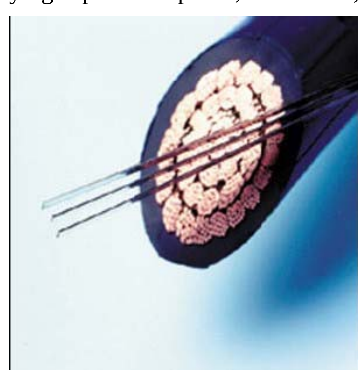

Fig. 11. The small strips of HTS wire carry the same current as the larger and heavier copper cable.

The HTS windings produce magnetic fields higher than those of conventional machines, thus resulting in smaller size and weight. HTS motors have higher efficiency at partially load (from 5% of full speed), which results in saving fuel and operating cost. The advantage in efficiency [23] can be over 10% at low speed, Fig.12.

HTS generators and motors have lower acustical emissions than the conventional machines; the HTS air-core machines are characterized by a lower synchronous reactance which results in operation at very small load angles. Operating at a small load angle provides greater stiffness during the transient and hunting oscillations. HTS motor field windings operate at constant temperature, unlike the conventional motors and, therefore, are not subject to thermal fatigue.

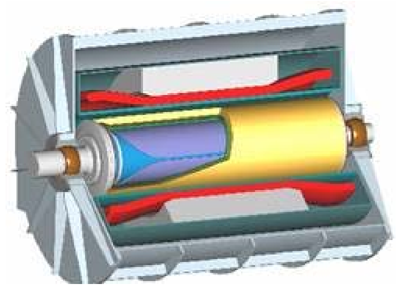

Fig. 12. HTSM generator.

HTS motors, when compared to the conventional motors, will not require the common rotor overhaul, rewinding or re-insulation. The results can be seen in Figures 13-15 where is presented the 36.5 MW superconducting motor in comparison with a 21 MW classical one.

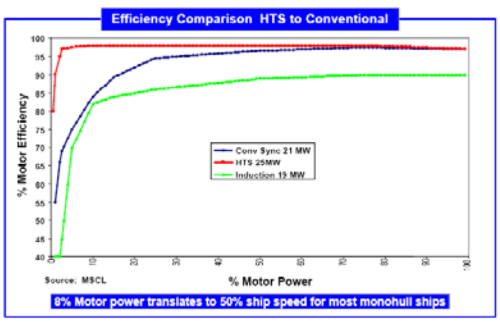

Fig. 13. The efficiency advantage of the HTS motors.

Fig. 14. Classical Motor of 21 MW 180 tones compared with a HTMS 36.5 MW 75 tones.

Fig. 15. Stator and rotor of 36.5MW HTSM motor.

This type of ships uses also auxiliary systems that are today based on steam, hydraulic, or pneumatically power. Converting these systems to electrical ones, and combining them with electric drive propulsion would produce an all-electric ship. Electric drive also offers significant benefits in terms of reducing the ship life-cycle cost, increasing the ship stealthness, payload, survivability and power.

4. The electric supply system

The typical ship power system consists of a set of electrical generators supplying a busbar of one or several sections. The total amount of power will depend on the total ship electrical load and its diversity. The type of generators, their number and power rating are chosen as a function of the specifications. For example, a Navy Class 2 vessel will be designed in such a way that any single point failure in the electrical system, including its generators, shall not result in a loss of the total electrical power system and ship maneuverability. The electrical power system would [24] incorporate at least a two-section busbar arrangement with an interconnecting circuit breaker in between, Fig.16.

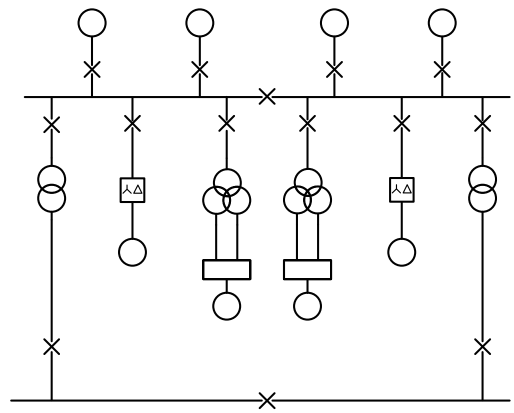

Fig. 16. The typical electrical supply system of a today ship.

For reaching a stable control of the active power, the governor has a drooping characteristic, which causes the engine speed to fall with an increase in active load. Similar to the governor, the Automatic Voltage Regulator (AVR) is equipped with a drooping voltage / reactive load characteristic in order to allow a stable, parallel operation with the other generator sets.

The rapid connection of generation to the power system is a common requirement on ships. The ability of the power system to support any additional load demand is essential if blackouts are to he avoided and vessel maneuverability is to be maintained. The power system will incorporate an automatic synchronizer for each generator that provides fast, accurate and reliable connection of the generator to the power system.

The electrical system of the future naval electrical ship must be reliable and survivable. This requires a special control and a dedicated electric power supply circuit which permits fast reconfiguration of the shipboard power system in case of failure. This leads to a power distribution system with several loops and redundant components. The closed loops require fast operating circuit breakers. In the recent years, electronic circuit breakers have been developed by using thyristors. These breakers interrupt the current within a half cycle, but their steady state conduction losses are high.

The recently developed micro-electromechanical switches (MEMS) operate within microseconds and have lower conduction losses. The voltage drop on a closed MEMS switch is less than a hundred mV. The MEMS switch is designed for cold switching operation and therefore it can not interrupt a flowing current. This suggests the combination of an electronic device with a MEMS switch. The concept of MEMS based interruption for a shipboard power system is that the opening of the MEMS switch transfers the current to the electronic device, which interrupts the current on the next current zero. The use of combined electronic-MEMS switches might allow the use of advanced operating strategies to rapidly disconnect the faulted components and rerouting the currents of faulted segments to un-faulted segments. This will significantly increase the system reliability and survivability [25], [26].

Micro-Electro-Mechanical Systems tend to be used as building blocks for power breakers. The dimension of a MEMS switch using microchip technology is measured in microns, designed initially for cellular phones. This property permits the fabrication of switching chains for the naval application with a fast interruption of the fault current. The all electric ship will use medium rated voltage, which requires the series and parallel connection of larger number of devices. The expected size reduction is a significant advantage in a naval environment.

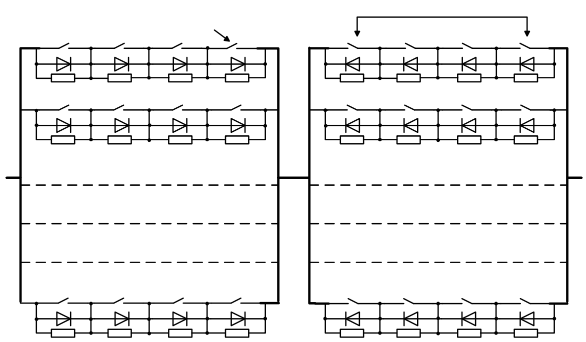

Fig. 17. An example of a MEMS switch.

The basic building block of the circuit breaker is a MEMS switch shunted by a diode and a large (1 MΩ) resistance. Several units connected in series forms a switching string and several switching strings are connected parallel to form the switching assembly. The diodes determine the conduction direction in a switching assembly, when the MEMS switches are open. Two switching assemblies are connected in series to form the circuit breaker. The conduction directions in the series connected switching assemblies are opposite.

5. Launchers and electromagnetic guns

The new high tech ships require new high-power weapons such the electromagnetic guns. The present destroyer's naval gun technologies are limited in range, with firing distances of 12 to 15 miles. The electromagnetic guns have to provide support to ground troops operating as far away as 250 nautical miles. The gun would accelerate the projectile to 800 m/s^2 and send it with seven times the speed of sound in the stratosphere for four minutes [27], [28]. After re-entry in the atmosphere, the control system would acquire information from the Global Positioning System and the projectile would strike the target at Mach 5.

In order to achieve such performances, an electric current of about 6 MA is required. Due to its high power requirements, the rail gun's energy supply would have to be drawn from the ship's generators over time and stored.

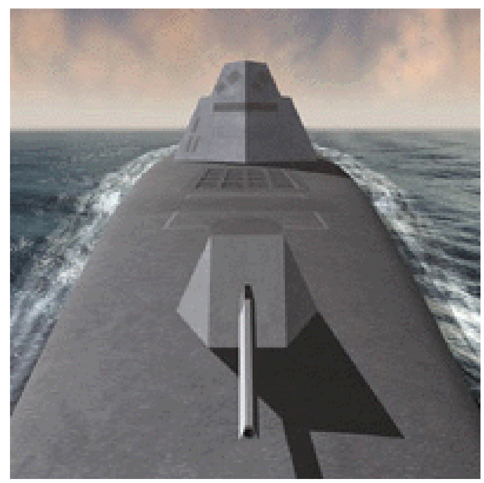

Fig. 18. The electromagnetic gun of a DXX destroyer.

Several storage devices, including capacitors, inductive devices and batteries, have been tested and a maximum of 60 MJ in inductive storage was reached at Texas University; as for comparison, to launch a projectile it is needed a kinetic energy of 64 MJ. If the weapon fires at 50 percent efficiency, then the amount of energy will have to be doubled at the input of the gun. For example, muzzle energy of 64 MJ requires an input of more than 120 MJ.

EMALS is a new electromagnetic aircraft launch system developed for the next-generation of aircraft carriers, and it will replace the current steam catapults. This solution will replace the steam-based system with an electrical one, resulting in lower operating costs, fewer people needed to operate, a higher catapult performance and an expanded range of manned and unmanned aircraft that the carrier can launch.

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