



FUTURE TRENDS IN ELECTRIC PROPULSION SYSTEMS FOR COMMERCIAL VESSELS

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ABSTRACT

Since the application of the thyristor to power control in the 1970's, the advances in power electronic devices, converter topologies and digital technologies have allowed the development of electric propulsion systems, which reduce fuel consumption and environmental emissions and increase safety levels. Considering the increasing costs of fossil fuels and the strict regulations concerning environmental and safety issues, commercial vessels in the near future will include this propulsion system and the associated technologies.

New trends in power generation, emerging technologies and system integration can be applied to electric propulsion systems making them more reliable, efficient and clean. Renewable energies, such as fuel-cells based on hydrogen, can be considered as energy sources of future vessels. Moreover, new technologies based on high temperature superconductors (HTS) and innovative power converter topologies, i.e. multilevel converters, will increase the system's efficiency.

This paper reviews new power sources and emerging technologies in electronic and electrical engineering which can be applied to future electrically propelled commercial ships.

Keywords: Electric ship propulsion, power electronic devices, converter topologies, power sources.

INTRODUCTION

The analysis of future trends in ship propulsion systems must consider diverse factors such as the expected rising price of fossil fuels and more strict regulation,

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both in safety and environmental issues (Lin, 2006). The forecast of crude oil production in a near future for different authors is represented in figure 1 (The Oil Drum, 2007). Under these conditions, electric propulsion can be considered as an alternative to conventional systems due to lower pollution levels and higher efficiency. Moreover, the introduction of alternative energy sources and their associated technologies will allow a new scenario to improve the performance of electric propulsion systems (EPS).

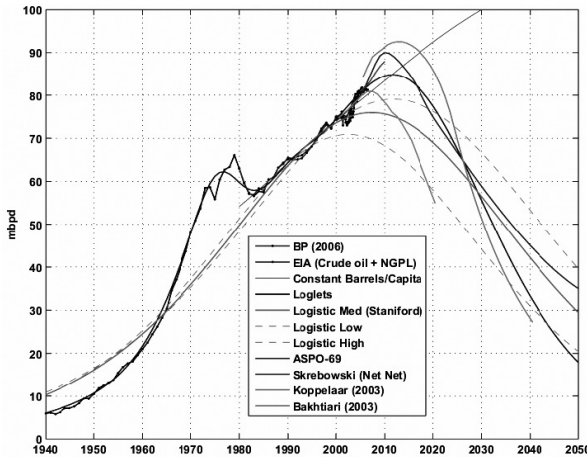


Figure 1. World oil production and various forecasts (1940-2050).

appearance of the thyristor in the 1970's allowed the design of variable speed drives based on ac/dc rectifiers and ac/ac converters in the early 1980's. Podded propulsion, where the electric motor is installed directly on the fixed pitch propeller shaft in a submerged rotateable pod, was introduced in the 1990's. This propulsion system introduced additional benefits in hydrodynamic efficiency and maneuverability. During the last decade, isolated gate bipolar transistors (IGBTs) have allowed the development of more efficient power converters controlled by means of pulse width modulation (PWM) techniques. Advances in power electronic device technologies, e.g. isolated gate controlled thyristor (IGCT), make possible the development of more efficient converter topologies and controllers for EPS, such as multilevel rectifiers and inverters. Moreover, advances in material science and technology, such as high-temperature superconductors (HTS), applied to the design of electric motors allow the power density to be increased.

The introduction of new power sources, such as hydrogen, biofuels, photovoltaics and other renewable energies, can substitute conventional energy sources for prime movers, reducing emission levels. An example of a zero emission ship model for the future is the *E/S Orcele* project (figure 2). This ship design was developed in

The general structure of current EPS consists of a set of prime movers (diesel engines or gas turbines) mechanically coupled to electrical power generators which feed the propeller motors through electronic converters. At present, EPS are mainly applied to cruise vessels, ferries, DP drilling vessels, shuttle tankers, cable layers and icebreakers.

EPS have been developed in parallel with power electronic device technology. In this sense, the



2005 by the Scandinavian shipping company *Wallenius Wilhelmsen* for an almost zero-emission car carrier capable of transporting 10,000 cars (about 50% more than today's car carriers) that uses renewable energy to meet all propulsion and onboard power requirements. The pentamaran-hulled design employs fuel cells to generate about one-half of the ship's energy, as well as wind power, solar power, and wave power. This latter is captured through 12 horizontal fins that would transform wave energy into hydrogen (for the fuel cells), electricity, or mechanical power. The fins would also act as propulsion units in combination with two podded propulsors. The developers believe a ship containing some of the *Orcelle's* features might be possible by 2010, and that a ship with all of its features could conceivably be built by 2025.



Figure 2. E/S Orcelle.

This paper reviews new power sources and emerging technologies in electronic and electric engineering which can be applied to future ships with EPS. After a brief history of electrically propelled vessels and a revision of the state of the art at the present, new trends in power generation, motors, propellers and power electronic converters applied to EPS are analyzed.

EPS HISTORY

Due to the lack of turn reversibility associated to marine diesel engines in the early 1900's, other kind of propulsion systems appeared. In this sense, a low power electric motor based system was proposed to simplify port maneuvers in 1903. This patent was known as Patent of *Cesidio of the Proposto* (Koehler, 1998). The first merchant vessel with diesel-electric propulsion was the *Vandal*, a ship river tanker with base in San Petersburg delivered in the autumn of 1902 (figure 3). The ship had three diesel engines with three cylinders. The engines were mechanically coupled to 87kW 500V dc generators feeding 75kW electric motors, which were applied to the

propellers. In 1905, the first diesel engine directly reversible, including two and four pistons, appeared and the researching efforts on electric propulsion systems decayed. However, the US Navy continued the researching on this topic and ordered a number of electrically propelled battleships: the *Jupiter* in 1912, one *New Mexico* class battleship in 1914, five *Tennessee* and *Colorado* class battleships in 1915 and two battle cruisers, *Lexington* and *Saratoga*, over 1916-1919.

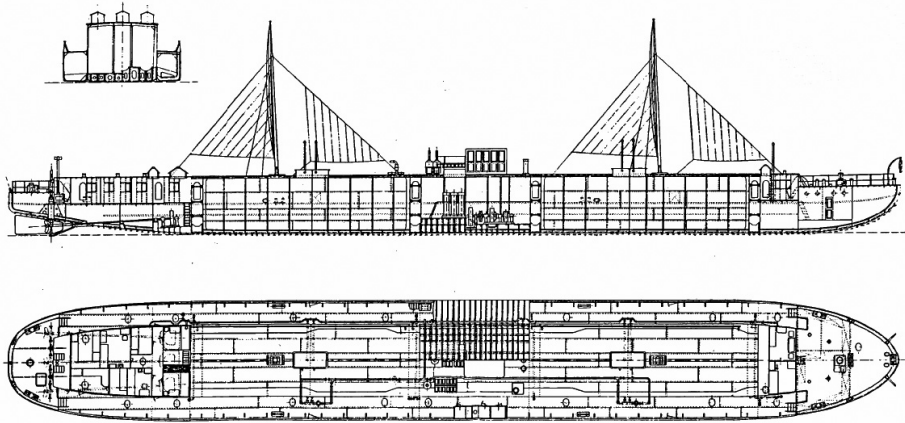


Figure 3. Vandal (San Petersburg)

In the early 1920's, due to a strong competence of transatlantic passenger liners, turbo-electric machinery was employed to increase the available propulsion power, which allowed travel times to be reduced. A French line cruiser including this propulsion system was the *S/S Normandie* (figure 4). It was launched in 1932, being the largest and fastest ship in the world, and employed electric generators coupled to steam turbines to feed four 29MW synchronous motors on each screw shaft. The propellers' speed could be changed by adjusting the electrical generator frequencies. At the rated speed, each generator fed one synchronous motor but, at lower speeds, the configuration could be changed feeding two motors per generator. However, in general, electric propulsion systems were no viable technically neither economically.

In certain cases, such as icebreakers and scientific ships, the electric propulsion presents more flexibility and maneuverability than conventional systems. The first diesel-electric propelled icebreaker was the *Ymer*, a Swedish flag ship with 9000HP and 4330 displacement tons, which was operated from 1933 until 1970 (Koehler, 1998).

The electrical propulsion systems were widely applied in US Navy ships during World War II. More than 300 vessels were built including this propulsion system. Most of these warships included 6000HP diesel-electric groups although in certain



Figure 4. Normandie (Compagnie Générale Transatlantique).

cases, such as T-2 tankers, turbo-electric systems were also applied. After World War II, the mechanical-drive technology was improved due to high efficiency diesel engines and the electric propulsion systems almost disappeared in merchant vessels until the 1980's. The *SS Canberra* line cruiser, launched in 1960, can be considered as an example of such electrically propelled vessels. Two synchronous three-phase 6000V electrical motors were applied to twin screws and fed by means of two 32.2MW steam turbine driven alternators. With 42500HP, the *SS Canberra* becomes the most powerful steam turbo-electric propelled passenger ship ever built. In the 1980's, the introduction of new power semiconductor devices allowed the development of modern electric propulsion systems.

FROM THE THYRISTOR UNTIL THE IGBT

The thyristor is the first controlled solid-state electronic device that manages high electrical powers and was employed for industrial variable speed drives in the 1970's (ABB AS Marine, 2003). The cruiser *Queen Elizabeth II*, restructured including electrical propulsion (95.5 MW) in the mid 1980's, was a pioneer using thyristor-based power converters. Other line cruisers, such as the *Fantasy* (USA) and the *Crystal Harmony* (Japan), were modified including thyristor-based electrical propulsion systems. In the 1990's, the Finnish shipyards and ABB developed the Azipod system, an innovative design for electrically propelled vessels, which improved their performance and maneuverability. The *Seili*, a service vessel modified in 1990, was the first ship including a 1.5MW Azipod system.

The basic components of an EPS are the electric power generation subsystem, the power conversion stage and the electric motors applied to propellers. Recent and current developments of these electric propulsion components are discussed inside this section.

Electric Power Generation

The power source of EPS is a set of electrical generators mechanically coupled to combustion engines which are fueled with diesel or heavy fuel oil. Alternative power sources, especially at high power levels, are gas engines, gas turbines, steam turbines or combined cycle turbines (Mowill, 1998). Moreover, in certain cases such as LNG carriers, gas is a low-cost option (U.S. Congress, 2006).

In comparison to mechanical propulsion systems, a conventional EPS consists of a number of diesel engines operating at medium or high speeds, with lower weight and cost. This prime movers redundancy allows the system reliability and the design flexibility to be increased reducing the repairing times. Moreover, new developments on combustion engines increase their efficiency and reduce the NO_x and SO_x emissions at their rated speed. In case of an EPS consisting of several diesel engines, the optimum operational point can be maintained by starting and stopping the generator sets depending on the connected electrical loads and trying to maintain the optimum load point of the diesel engine (Mahon, 1992).

Power electronic devices

Since the appearance of the first semiconductor power electronic device, the thyristor in late 1950's, a number of new devices, whose technology is now mature, were introduced e.g. the TRIAC, gate turn-off thyristor (GTO), bipolar power transistor (BJT) or power metal-oxide-semiconductor field-effect-transistor (MOSFET) (Bose, 1992).

Controlled devices, such as thyristors, TRIACs and GTOs switch at low frequency and their activation can be controlled by means of a current pulse. Moreover, in case of GTOs, if the gate circuit is properly designed, the device can be switched off. Switching at higher frequencies, the power levels which can be managed by BJTs and MOSFETs are lower but the obtained voltage and current signal waveforms are improved.

Power converters based on thyristors and GTOs have been successfully developed and applied to drive electric motors. Due to the low efficiency of these converters, new devices were introduced, e.g. insulated gate bipolar transistors (IGBTs) in 1983, static induction transistors (SITs) in 1987, static induction thyristors (SITHs) and MOS-controlled thyristors (MCTs) in 1988. Power converters based on these semiconductors are commercially available but new advances of design techniques and electronic technology allow these devices to evolve continuously, i.e. reverse-blocking IGBTs (Klumpner, 2006).

Power Converters

Power converters have evolved trying to reduce size, weight, losses and cost while increasing efficiency, reliability and safety. The most employed converter



topologies in EPS are rectifiers, cycloconverters, synchroconverters and PWM voltage source inverters (VSI) (see figure 5).

Controlled rectifiers are employed as low-power dc-motor drives (up to 5MW) and, as a consequence, they are not applied to EPS in vessels. Cyclo- and synchroconverters are employed as synchronous motor drives. Cycloconverters are commonly applied to EPS in icebreakers due to their high torque at low speed. Other vessels, propelled by means of synchronous motors and without the previous requirement, can take advantage of size reduction, controller simplicity and fixed harmonic spectrum associated to synchroconverters. Being the low frequency converter topologies commonly based on thyristors, whose efficiency is low in comparison to high frequency converters, PWM VSIs have been proposed to drive synchronous, asynchronous, permanent magnet and induction motors.

Cycloconverters allow fixed amplitude and frequency input signals to be converted to variable amplitude and frequency output signals at low switching frequency and without an inner dc bus. It must be considered that the output frequency must be

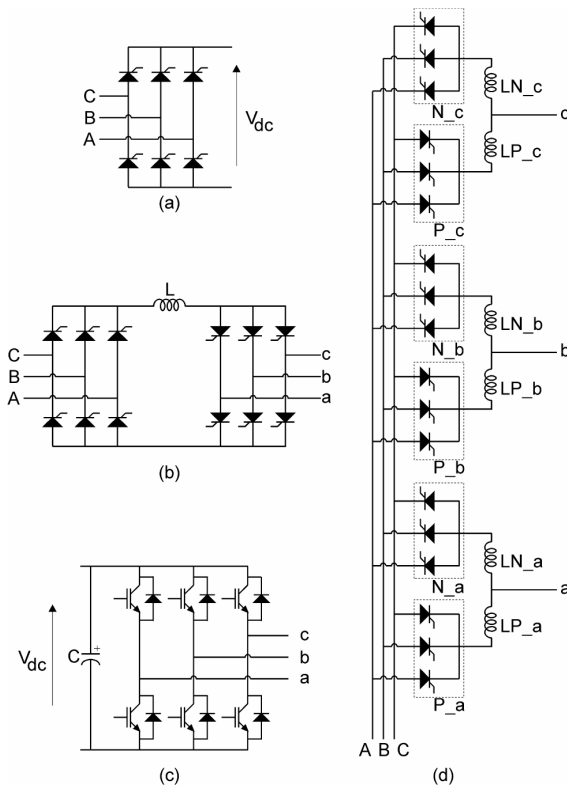


Figure 5. a) Controlled rectifier, b) Synchroconverter c) PWM VSI and d) Cycloconverter.

lower than the input frequency. Due to the variable frequency and amplitude of the output signal, they are especially appropriate in vessels which require high torque at low speed, i.e. icebreakers or dynamic positioning (DP) vessels. Typical loads of these converters are 30MW, 500 rpm ac motors.

Synchroconverters contain a controlled thyristor rectifier, an inductive dc-link and a thyristor inverter which is operated as a current source inverter. The motor speed can be controlled by adjusting the frequency of the output current while torque and power are managed by regulation of the dc bus voltage. Due to the fact that the operation of rectification and inverting stages can be changed dynamically, the propellers can be stopped

or changed their rotation sense very fast. As a consequence of the available dc bus, input and output converters can be independently controlled, which improves the quality of the input current waveform (Clegg 1999). Moreover, this topology can manage higher powers than cycloconverters (around 100MW). However, due to low frequency switching, the motor torque can beat at low speeds. At rated speed, this topology generates less noise and vibrations than cycloconverters, which makes it interesting in passenger vessels.

PWM VSIs are based on power devices with controlled turn-off, such as IGBTs and GTOs, and operate at higher frequencies than thyristor-based converters. In order to generate the gate patterns which control the converter devices, pulse width modulation (PWM) is employed (Holmes 2003). A typical PWM VSI drive is composed of a full bridge diode rectifier as input stage, a capacitive dc-link and an output inverter. The diode rectifier can be substituted by a PWM controller rectifier in order to improve the electrical characteristics of the drive front-end stage (Kazmierkowski 2002), which avoids large passive harmonic filters. The amplitude and frequency of the output voltage waveform can be controlled and, due to high frequency switching, the motor torque can be controlled accurately and smoothly. The drive performance is maintained in the whole range of available voltage amplitudes and frequencies. Typical rated values of motors connected to these drives are 20MW, 2000rpm and 6.6kVac. Gear boxes, with high efficiency, small size and low weight, can be applied between the motor and the propeller if required.

Electrical Motors in Propulsion

The electrical motors are applied in EPS, including thrusters, and other on-board loads such as winches, pumps or fans. Typically, 80-90% of the ship electrical loads are electrical motors such as dc, asynchronous (induction), synchronous and permanent magnet synchronous motors (Mitcham, 1995).

The dc motor must be fed from a dc supply, and since the power generation and distribution system use to be a three-phase system, the dc motor must be fed from a thyristor controlled rectifier which also gives speed control. Maintenance costs and power limitations associated to these motors (up to 5MW) reduce their applicability in naval designs (Sponer, 1995).

The asynchronous or induction motor can be directly connected to the electrical network and, hence, being operated at constant speed, or can be fed from a cycloconverter or a PWM VSI in order to obtain a variable speed control. In despite of a low power range (up to 5-10MW), it can be useful due to their low maintenance costs in comparison to dc motors.

The synchronous machine is employed in large propulsion drives, typically >5MW in configurations with direct connection to the propeller shaft and >8-10MW in case of a connection through a gear box. In smaller power ranges, the asynchronous



motor is a cost-competitive solution. Diverse synchronous motors are commercially available due to their design similarities to synchronous generators. The synchronous motor is controlled by means of a synchroconverter. Figure 6 shows an example of synchroconverter-based EPS.

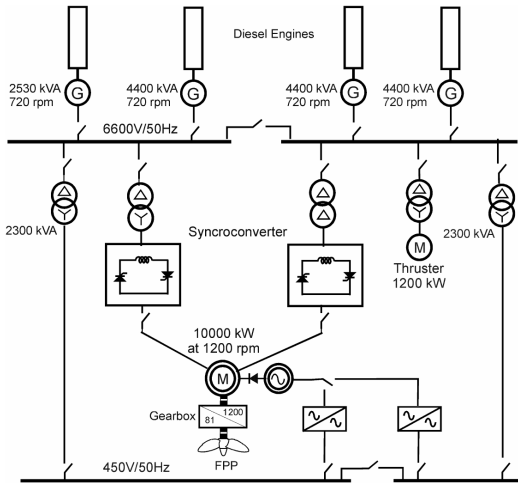


Figure 6. EPS with synchroconverter and synchronous machine.

Permanent magnet synchronous motors have been included for large power applications, such as navy vessels. The benefits associated to these machines are their high efficiency and compact design. This makes them appropriate in podded propulsion systems where the dimensions must be minimized to improve the hydrodynamic characteristics and direct water cooling can be applied. A frequency converter is applied to control the motor speed and torque. Moreover, the design and installation of

podded propellers are simplified by means of these electrical motors. There are three basic approaches in podded propulsion (figure 7): fixed pod, azimuth pod (Nicod, 1998) and *Contra Rotating Propellers* (CRP) (Pakaste, 1998).

TRENDS IN EPS

Electric Power Generation

Considering decreasing fossil fuel reserves (Van Geuns, 2005), alternative energy sources, such as hydrogen, photovoltaic, wind, wave, biomass or methane hydrate, will become necessary in a near future. This section describes the application of these energy sources in future EPS (U.S. Congress, 2000).

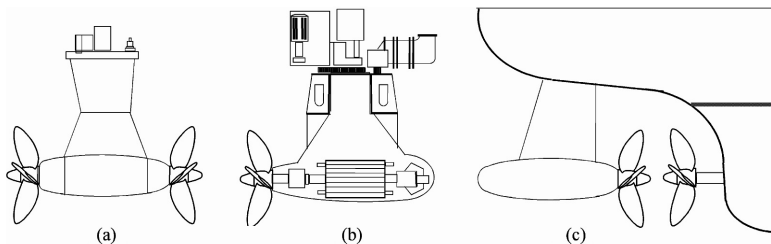


Figure 7. a) Pod, b) Azimuth pod and c) CRP.

Fuel cells are based on an electrochemical reaction which allows the hydrogen to be converted into electricity directly, continuously and efficiently. The reaction continues if hydrogen and oxygen are available and only water and heat are generated as residues. The efficiency of this technology is a 15% greater than conventional-combustion based generation plants, which reduces the required fuel consumption. As a consequence, the interest on this technology applied to powering shipboard equipment and EPS is rising in Europe, Japan and the United States (Lever, 1998, The Society of Naval Architects and Marine Engineers, 2001). In this sense, and due to the international environmental regulations, the appearance of a fuel cell based commercial ship is expected in some years. Moreover, the absence of noise and vibrations make this technology appropriate to be applied to future passenger vessels. The life cycle of fuel cells, which is highly dependent of the temperature, must be considered as a drawback.

A fuel cell-powered passenger ship is being currently designed by *Proton Power Systems* and will be operative during the summer of 2008 (Proton Power Systems, 2007). The ship, is being developed as a part of a *Zero Emission Ship* project which is funded by the European Commission. The vessel will carry up to 100 passengers through the Alster river in Hamburg, Germany.

Renewable hydrocarbon fuels, such as biodiesel and methane hydrate, allow the structure of diesel-electric propulsion systems to be maintained and, hence, can be considered as alternative energy sources to fossil fuels. The biodiesel is produced from vegetable oils or animal grease and, being employed in terrestrial vehicles, it is expected to have a great impact in marine power systems. The methane is produced by the microbiological decay of organic compounds and, being encapsulated inside a water ice-like cage, it is named methane hydrate. These fuels, in comparison to fossil fuels, reduce particle, carbon monoxide and nitrate and sulfate oxides emissions (National Biodiesel Board, 2007).

Photovoltaic (PV) panels allow the solar radiation to be transformed to electric energy. Main technologies commercially available are monocrystalline silicon cells (12-15% efficiency), polycrystalline silicon cells (10-12% efficiency), amorphous silicon cells (4-9 % efficiency) and thin film PV modules (11% efficiency). New technologies are being developed in order to increase the transformation efficiency, i.e. multijunction concentration technologies reaches up to 36% efficiency (National Renewable Energy Laboratory, 2007). Due to the fact that a number of solar cells are required to build a solar panel, control algorithms and electronic power converters are needed in order to ensure the maximum power transfer under all possible radiation conditions. As drawbacks of this technology applied to EPS it must be considered that the solar panels must be directly faced to the sun in order to extract the maximum available power, the maintenance due to marine environment and the required ship surface to attach the panels.



Nowadays there are available different ships with photovoltaic based EPS. The *Solar Sailor Ferry Boat* (figure 8) is a small hybrid diesel-solar-electric ship (69-foot 100-person) with eight maneuverable “solar wing sails” which can be used for both sail-assist propulsion and electricity generation. The ferry was built in 1999–2000 as a demonstration project and can operate on wind power, solar power, stored battery power, diesel power, or any combination. The ship was developed and built by Solar Sailor Holdings Ltd. with assistance from the Australian government, and operates in Sydney harbor.

As in the case of PV systems, wave and wind based energy sources can not be directly applied to EPS and must be combined with other generation systems due to their low efficiency and power level. The *Andromeda Leader* is a car carrier ship which includes a 4-meters-diameter and 4.5-meters-high vertical-axes wind turbine which allows 30kW to be extracted from a 25m/s wind for auxiliary machinery (Nippon Yusen Kaisha, 2004)

Power electronic devices

Three main areas focus new developments in power electronic devices: new manufacturing technologies, the improvement of already known devices and integration issues. Silicon carbide power (SiC) device technology is growing quickly (Elasser, 2003) and different research works show first results applying it to power devices. Switching frequencies of SiC devices can be 100 higher than conventional Si, with conduction resistances 100 times lower (Hefner, 2001) and higher voltage capability, and, as consequence, faster and more efficient power devices can be commercially available in a near future (Zhang, 2006, McNutt, 2007). Advances on present day power devices allow converter topologies to be re-designed improving their performance. In this sense, reverse blocking insulated gate bipolar transistors (IGBTs) have been proposed in order to obtain bidirectional switches, as required by matrix converters (Takei, 2004).

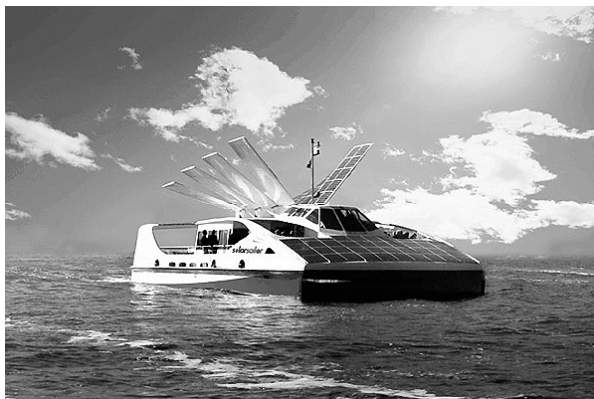


Figure 8. Solar Sailor Ferry Boat.

Bidirectional switches based on conventional IGBTs require additional series connected diodes in order to obtain reverse blocking capability but these diodes introduce extra power losses which reduce the matrix converter efficiency (Itoh, 2005). New MOS-controlled thyristors (MCT) architectures have also been proposed in (Spullber, 2000) to decrease

the forward voltage drop of IGBTs in high-voltage applications. Great efforts have also been carried out on integration issues in power electronic devices. Mass-produced power electronics building blocks (PEBBs) will be available in near future and will include the electronic power converter, input and output passive filters, current and voltage sensors and the programmable controller (Ericson, 2006) with communications interface, which will simplify the design of new EPS (Logan, 2007) and allow the management of electric loads in order to reduce the vessel operational costs (Domaschk, 2007). Other issues under researching are the minimization of thermal losses and the improvement of passive elements, i.e. inductors and capacitors.

Power converters

A number of new power converter topologies have been proposed in diverse researching papers but, probably, the most interesting ones considering future EPS are multilevel, matrix and multiphase converters (figure 9).

Multilevel converters were proposed in the early 1980's (Nabae, 1981, Bhagwat, 1983) and their importance has been growing up to date due to the continuous technology developments and new modulation techniques (Holmes, 2003). The operation principle of these converters is the generation of different dc-bus voltages in order to improve the quality of the ac voltage waveform. Three main classes have been

proposed in literature: diode-clamped, flying-capacitor and cascaded series converters. In case of n-level diode-clamped and flying-capacitor multilevel converters the dc bus is unique and consists of n-1 capacitors which are connected to 2(n-1) switches composed of IGBT with FWD diode. As a consequence, the ac voltage waveform can be synthesized from n available dc voltages, including zero voltage level, which reduces the harmonic distortion of the ac output signal (Pan, 2005). Cascaded series converter topologies consist of single-phase H-bridges with separated dc buses which, depending of

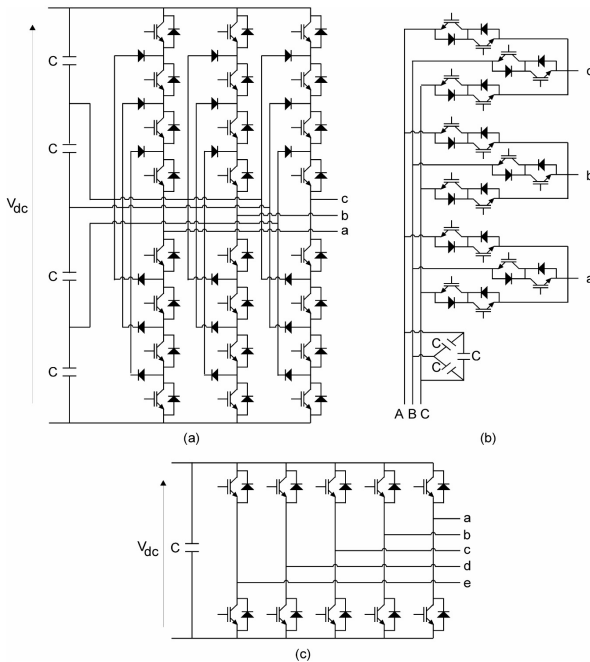


Figure 9. a) Multilevel, b) Matrix and c) Multiphase converters.



their switching status, change the overall ac voltage at each time instant (Loh, 2005). Three main control techniques are applied to generate the gate patterns controlling these topologies: low frequency PWM (Du, 2006), high frequency PWM (Holmes 2003) and hybrid (Manjrekar, 2000). In first case, each switch composed of IGBT and FWD diode switches one time at the fundamental ac frequency. As a consequence, a higher number of levels is required to minimize the output harmonic distortion. In case of high frequency PWM operation, different techniques are available but probably, if cascaded PWM converters are considering, the most interesting approach is the carrier shifting technique, which minimizes the output harmonic distortion in case of equal dc voltages. A hybrid multilevel converter considers that one converter, composed of IGCTs, switches at low frequency and a second high frequency PWM converter cleans the harmonic spectrum of the first one. Commercial multilevel converters based on IGCTs are already available for EPS, such as ACS series from *ABB*, reaching 25MW. Being a recent technology, a fast evolution of commercially available drives can be expected during the next decade.

Matrix converters were proposed in the early 1990's as an alternative to buck-to-buck high frequency PWM topologies without dc-link, which reduces drive maintenance costs and increases reliability. Matrix converters consist of an array of $m \times n$ bidirectional switches, where m and n are the number of input and output phases respectively, which allows the interconnection status of input and output phases to be changed (Kazmierkowski, 2002). It must be considered that two input lines can not be connected to the same output phase and the output line circuits can not be disconnected. Under these assumptions 27 different switching states can be applied to a 3×3 matrix converter, which increases the complexity of pulse width modulators (in case of a 3-phase 3-wires inverter, only 8 switching states are available). Moreover, different practical issues, such as the passive input filter for compensation of reactive power or a clamp circuit to avoid over-voltages during the converter operation, must be considered during the converter design (Wheeler, 2002). The amplitude and frequency, for low frequency components, of matrix converter output voltages can be changed by applying properly a modulation technique. The first modulation technique was attributed to Venturini in the early 1980's but the maximum output voltage was limited to 50% of the input voltage and the displacement factor must be equal to 1. Being impractical, it was modified to reach 87% and variable displacement factors in (Alesina, 1989). Due to its complex implementation in real-time, scalar modulation methods were proposed obtaining equivalent results at high switching frequencies. SVPWM methods, as in case of PWM inverters, were proposed in order to simplify the modulation technique conceptually. Moreover, these methods can result into a better performance in case of unbalanced input voltages, as it is shown in (Jussila, 2007). Commercially 75kW motor drives based on matrix converters are available nowadays (Yaskawa, 2007) but it can be expected a fast growth of this technology due to developments in power modules, i.e. a new 360kVA module from *SEMELAB* is available, and new reduced size input filters.

Multiphase converters have been proposed, firstly in 1969 (Ward, 1969), to drive multiphase induction motors. As will be shown in the following section, these motors have greater reliability than conventional 3-phase motors (Singh, 2002) and, as a consequence, can be successfully applied to EPS. Multilevel converters share a common dc-bus and include so many legs, composed of two or more (multilevel) switches, as phases of the controlled motor. It must be considered that 3-phase inverters can be treated as a particular case of multiphase topologies and the modulation techniques applied to 3-phase inverters, such as sinusoidal or space-vector PWM, have been extended to multiphase converters (Iqbal, Ojo, 2005).

Electrical Motors in Propulsion

Conventional electrical motor technologies have reached their maturity and only permanent magnet motors could be improved in a near future. The expected advances in electrical motors are related to the introduction of superconductors and multiphase technologies.

Researching advances on electrically loss-less materials, known as superconducting wires (Gubser, 2003), has improved the efficiencies and power densities of rotating machines while reducing their sizes and weights. There are two basic superconductor types: Low temperature superconductor (LTS), around 10K, and high temperature superconductor (HTS), above 100K. Due to the operation temperature both technologies require a refrigeration system, being smaller and simpler in case of HTS wires. It must be considered that the power consumption of these refrigerators is negligible related to the generator or motor power (Bretz, 2004).

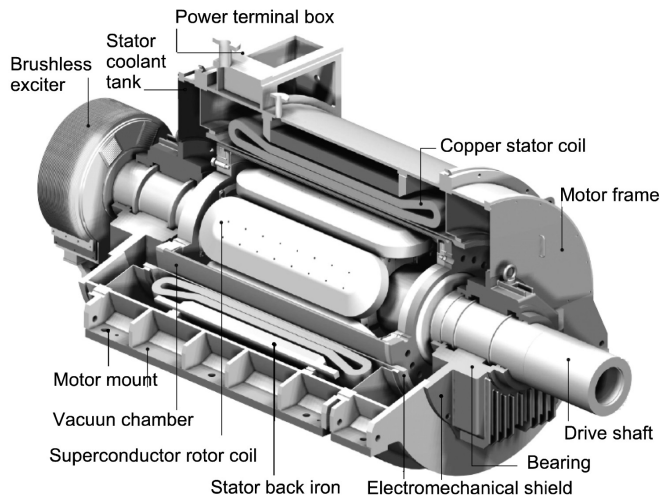


Figure 10. 5MW HTS motor prototype (source: American Superconductor)



Depending on the selected superconductor material and the motor configuration, different researching prototypes of these electrical machines have been proposed (Pallarès, 2002) but first commercially available approaches are based on HTS synchronous motors (American Superconductor, 2007). These motors are more power-dense, quieter, lighter and smaller than the equivalent conventionally designed machine. American Superconductors, Inc. has developed two HTS synchronous motors at 5MW (figure 10) and 36.5MW for the US Navy (Snitchler, 2005). Siemens have also developed electrical machine prototypes based on HTS for ship propulsion systems (Siemens, 2005).

Multiphase induction motors are known since 1969 (Ward 1969) and, due to their characteristics, during the last years, the researching efforts on this topic have been increased (Levi 2006). In comparison to ac three-phase induction motors, multiphase machines decrease the per-phase required power, reduce the torque ripple and noise, have a higher reliability and reduce the rotor harmonic currents (Terrier 2004). These characteristics make these multiphase machines appropriate in high-power and high-current applications, such as EPS.

The general structure of a possible future EPS is shown in figure 11. The electrical power is generated by means of conventional and renewable energy sources such as diesel, fuel cells or PV. HTS motors and generators can be included during the design stage in order to improve the electrical power consumption efficiency and power density. Moreover, the overall efficiency and reliability is ensured by applying power electronic converters which allows a global electrical power flux management. In this sense, a flywheel-based active compensator can be considered to mitigate the dc-bus power disturbances.

CONCLUSIONS

This paper shows the historical evolution, the state of art and analyzes future trends in electric propulsion sys-

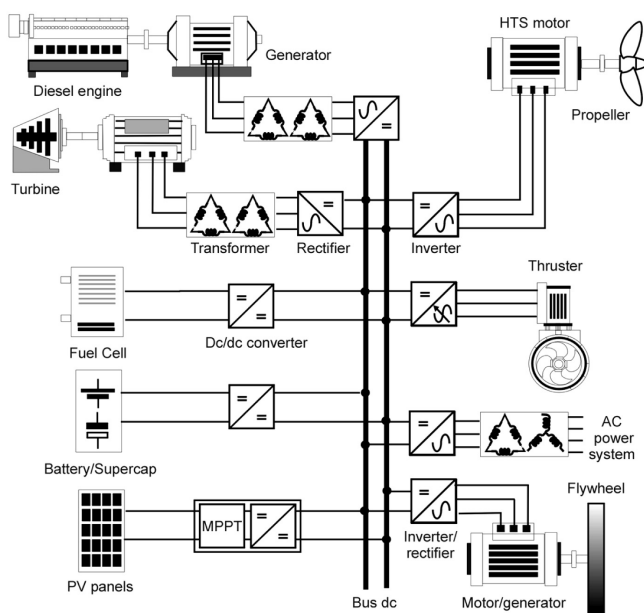


Figure 11. EPS including new trends



tems in commercial vessels. Diverse issues related to EPS, such as electric power generation, electronic devices, power converters and electrical motors, have been discussed considering the present day available technology and their future developments.

Advances in power electronic devices and converters, new renewable energy sources and applications of material science to the design of electrical motors will allow conventional EPS to be improved: higher efficiency, reliability and security, easier EPS design and automation process, lower emission levels and better power management.



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