# History and Recent Advancements of Electric Propulsion and Integrated Electrical Power Systems for Commercial & Naval Vessels

Tao Yang, Tom Cox, Michele Degano, Serhiy Bozhko, Christopher Gerada
The University of Nottingham, NG7 2RD, UK
Tao.Yang@nottingham.ac.uk

***Abstract*****—** Due to developments in power electronics, electric machines, energy storage and control, electric propulsion and integrated electrical power systems have become major trends for commercial and naval vessels. This is mainly due to the fact that the use of electric propulsion and integrated power systems can improve efficiency and fuel consumption while reducing noise and vibration when compared to conventional systems. Such advantages are extremely attractive to vessel owners due to increasingly stringent emission requirements, especially in environmental control areas, from the international maritime organization. This paper aims to summarize the recent advancement of marine power systems including propulsion systems, electrical distribution systems and novel loads.

***Keywords*****—**Electric propulsion, Hybrid propulsion, Integrated power system, Electromagnetic launch

## I. INTRODUCTION

Although electric propulsion for marine vessels has been used for over 100 years, the modern age of electric propulsion for ships is considered as starting from 1988 with the retrofit of the *Queen Elizabeth II* to use a diesel-electric integrated propulsion system. Since then, the shipping industry has started to introduce electric propulsion as a solution to improve fuel efficiency and reduce emission due to the fact that the global regulations concerning NOx and SOx emission have become more and more stringent. Especially, the international maritime organization's (IMO) MARPOL Annex VI Tier III limits came into enforcement since 1st Jan 2016. Figure 1 shows the regulations of NOx emission from MARPOL Annex VI. The Tier I standards apply to all new engines as from January 2000. The revised 2008 Annex sets new Tier II standards that apply from 2011. It can be seen that the Tier III standards which came to enforcement this year in the ECAs will cut NOx emissions from new engines by about 80 per cent relative to Tier I.

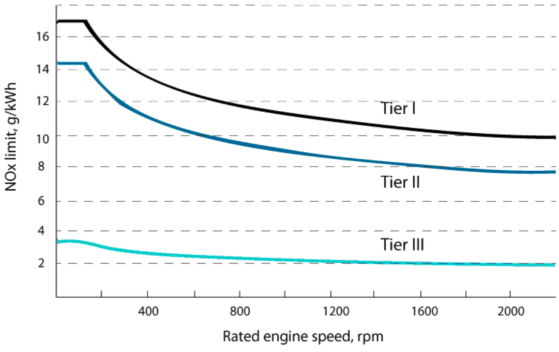

Figure 1 MARPOL Annex VI NOx Emission Limits [1]

Together with more stringent regulations on exhaust emissions, increasing fuel prices have also been forcing vessel owners and the marine industry as a whole to explore and implement more hybrid and electric power propulsion systems. The last ten years have seen fast growth of electrical propulsion vessels, including Cruise vessels, Icebreakers, DP offshore vessels and LNG carriers [2]. The LNG carriers are the last group of vessels changing from mechanical steam propulsion to electrical propulsion. The first LNG carrier with electric propulsion was constructed at Chantiers de l'Atlantique in France for the French owner Gaz de France in 2004 [3]. One of the main benefits of electric propulsion is the ability to maintain high efficiency during a wide operational speed range, while mechanical propulsion can only achieve peak efficiency within a narrow range of operating points [4, 5]. The improved efficiency will in turn reduce vessel emissions.

Recent developments in power electronics and machines also allow an integrated electric shipboard power system design. Within the integrated electric system (IPS), the electric plants provide power to all ship loads including propulsion and shipboard service loads. Navies around the world have been actively exploring IPS for use on future surface combatant ships since late 20th century [4]. The IPS offers distinct advantages including a reduced number of prime movers, shorter shaft lines, increased survivability and manoeuvrability, improved efficiency and arrangement flexibility [6, 7].

This paper aims to give readers an introduction of marine electric propulsion as well as shipboard integrated electric power systems development up to date. Three different types of electric propulsion have been reviewed, namely diesel-electric propulsion, turbo-electric propulsion and hybrid propulsion. The development of integrated power system is also discussed in this paper. Some novel electric loads are also introduced including electromagnetic launch systems, steering and stabilisation.

## II. OVERVIEW ON ELECTRIC SHIP PROPULSION

The electric ship has a long history and forms have existed for over 100 years. The first diesel-electric vessel (river tanker Vandal) was developed in 1903 and the first naval vessel with electrical propulsion (USS Jupiter) was in 1912. However as diesel engines took over as the direct propulsion prime movers of choice, electric propulsion was seldom used until in the 1980s, when the development of power electronics technologies allowed new ways of efficient variable speed control of electric motors [8]. Using electric propulsion, energy transmission from generation to propulsion systems will be achieved using electrical, rather than mechanical systems. The propulsion and thrusters can both be supplied and controlled by variable speed drives. The adoption of electric drives has been primarily due to their improved efficiency, reduced fuel consumption and environmental benefits. Recent developments in electric systems, power electronics, control strategies and electrical machines have all contributed to increase the viability of electric ship propulsion systems.

Since the 1990s electric propulsion has been revaluated with increased interest and development in the naval sector. The interest is not only related to the needs of removing the reduction (gearbox) stage, but also driven by the requirements of modern cruise ships and vessels, including:

- Increased amount of electric energy required to supply on board loads;
- High levels of manoeuvrability;
- Necessity of high dynamic manoeuvres and inversion;
- More stringent environmental regulations for navigation in protected waters;
- Reduction of noise and vibration due to operating conditions out of the nominal regime.

Apart from the diesel-electric system, another architecture that has gained increasing interest is the development of turbo-electric propulsion, where the motor function is implemented by a gas turbine. Turbo electric propulsion carries many advantages including:

- Better flexibility by locating the internal combustion generators away from the propulsion shafts and thus enables better positioning of the diesel engine to reduce noise
- Lower vibrations and consequently better comfort
- High efficiency

However, one of the main reasons for using electrical machines for propulsion of electric ships is the fuel saving and space reduction with respect to a conventional mechanical systems. These have been more and more employed for power generation as well as for electric propulsion, including both main and auxiliary propellers. In the following sections a brief overview of the main propulsion system configurations are presented.

## A. Diesel-electric ship propulsion

Diesel-electric propulsion can go back to over 100 years ago when the river tanker Vanda was developed in 1903 [7]. However, the modern age of diesel-electric propulsion is considered when the *Queen Elizabeth II* was transformed from a steamship to a diesel-electric motor powered ship. The *Queen Elizabeth II* was equipped with nine four-stroke diesel engines (MAN BW 9&L58/64), with a generation capability of 88MW. The engine room layout is reported in Figure 2.

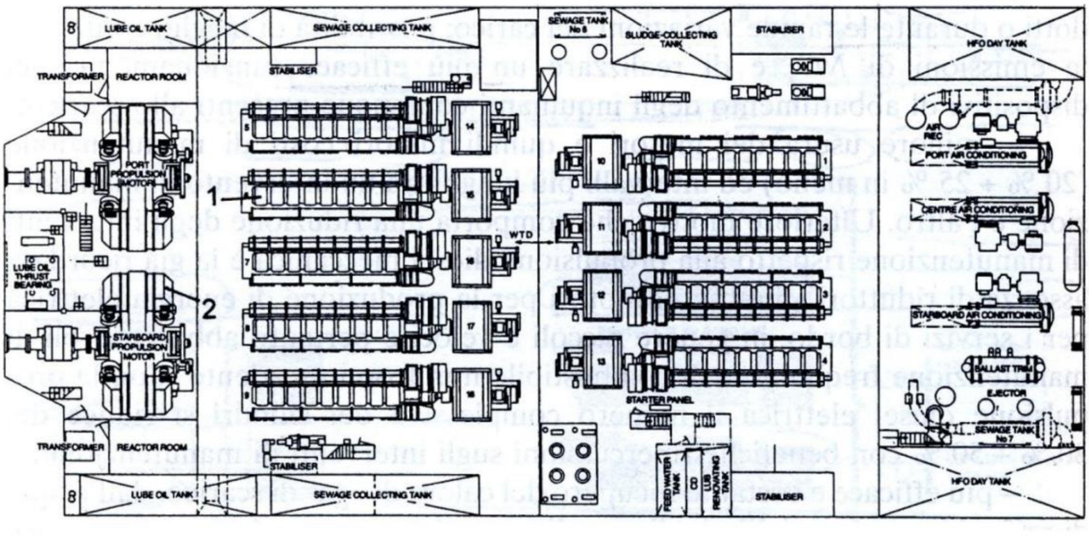

**Figure 2 Propulsion layout of the cruise ship Queen Elizabeth II: 1- Diesel Engine; 2- Electric Motor. [9]**

With this distributed configuration the power is fractioned, with the consequent advantage of operating the combustion engines at their rated condition or close to it. Furthermore that constant rotational speed gives several advantages:

- Maximum efficiency operation for the engines;
- Reduce engine usage (20-25% with respect of a single engine unit);
- Gearbox stage elimination;
- NOx emissions reduced together with a more efficient pollution abatement devices;
- Redundancy and safety, in case of one or two engine failures, the rest of the system can produce enough energy for navigation;

- Reduced volume of the electric motor, allowing ship hull designs with lower friction in water, thus improving the navigation speed.

## B. Turboelectric drive propulsion

Nowadays turboelectric propulsion is commonly adopted in fast ferryboat applications and modern cruise ships. In this case, the diesel-engines are replaced with one or more gas turbines (GT). The main advantages can be summarised as follows:

- Gas turbines offer reduced volume with respect to the conventional combustion engine for the same rated power, with a consequent increased room for cabins;
- Thanks to their relative light weight, gas turbines can be installed on the upper bridge closer to the ship smokestack, reducing the aspiration and gas waste system volume;
- Reduced emissions with respect to the diesel type.

## C. Hybrid Diesel-Turboelectric propulsion

Another interesting configuration for the vessel electric propulsion is the mixed layout, which includes both diesel-engine and gas turbine. A good example of this configuration is installed on board of the Queen Mary II, shown in Figure 3. The layout consists of two gas turbines (GE LM2500) with a rated power of 25 MW each, and four 16.8 MW medium speed conventional diesel engines (Wartsila 16V46C). The propulsion is given by four 18 MW Azipods. Depending on the navigation mode diesel engines and turbines can be used in different ways with high flexibility. For example during daylight hours when the cruise liner is navigating at a lower speed, diesel engines are used. When the ship needs to navigate rapidly, those can be assisted by the power turbines in order to increase the speed significantly. For navigation in protected waters, the ship can be propelled by only gas turbines to reduce emissions.

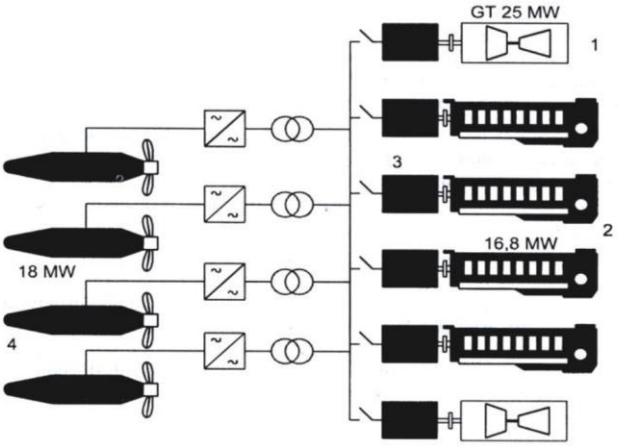

**Figure 3 Functional schematic layout of the Queen Mary II on board propulsion system. 1- Gas turbine; 2- Diesel engine; 3- Alternator/Generator; 4- Mermaid Pod [9]**

High-power and large low-speed synchronous machines are commonly used in hybrid systems for shipboard propulsion and generation. These are often part of a system arrangement where the diesel engines and motors are connected through a multi-shaft gear-box to the propeller. For those applications where the priority requirement is space reduction, high speed electrical synchronous machines, with their simple and compact design, competitive in terms of high efficiency, compact volume and low weight as well as easier maintenance, present the most promising solution. The development of high switching frequency devices and the increased reliability of high power drives have enabled the development of full speed control of propellers and thrusters, allowing a better distribution of the electromechanical converters and a reduction of mechanical structure complexity.

### D. Types of Electric Machines for Power Generation and electric propulsion

Before giving an overview on the best electrical machine topology to be employed for propulsion and generation in large vessels, since the prime movers are still mainly Internal Combustion Engines (ICE) and Gas Turbines (GT), it is worth considering the power and speed rating of those. This will allow us to better understand which types of electrical machine are the best to use. As shown in the previous layouts, the total rated power required by a ship is produced by distributed generators with a maximum power of 18-20 MW per unit. Figure 4 is representing on the power-speed plane the solutions available in the current market, reporting data extracted by lead manufacturers such as Rolls Royce, Siemens, General Electric, Wärtsilä and others. Referring to figure 4, ICE are covering the desired power range with very low rotational speed up to 1000 rpm (red squares), while GT have a much wider operating speed range from 3000 to 18-20 krpm (blue circles).

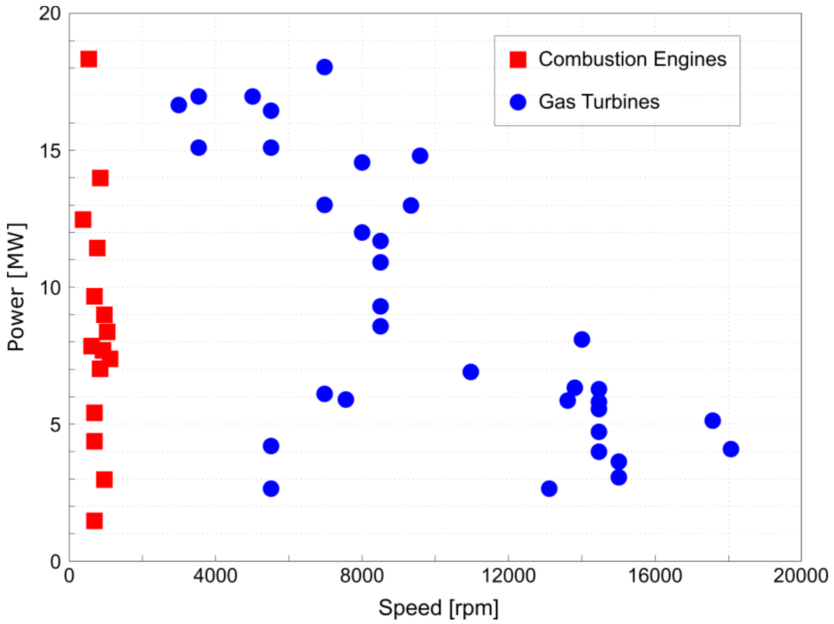

**Figure 4 Rated power of gas turbines and internal combustion engines for different rotational speed: available commercial solutions.**

The motor and generator selection to be employed in ships electric systems it strongly related to the size, requirements and application of the ship. However, in general lower speed machines with a wide power range capability are most suitable to be used for propulsion purposes. Higher speed machines instead find their best application as generators to be directly coupled to the main engines or turbines. During the past 20 years, progress in electrical machines has rapidly increased and their development has taken two main directions: the revamping of conventional synchronous machines; and the design of new advanced permanent magnet motor configurations and high temperature superconducting motors.

Considering the most conventional motor developments, it is interesting to understand which machine topologies are suitable to be coupled with the above prime movers, shown in figure 4, according to the rated speed. In figure 5 the capability areas of some machine topologies are reported in combination with the prime movers power highlighted in figure 4. The best available topologies are:

- Four-pole machines with laminated isotropic rotor, for rotational speed between 500 to 2000 rpm with a maximum power of 19 MVA;
- Four-pole isotropic solid rotors for speeds ranging from 1800 rpm up to 6000 rpm maintaining the generated power up to 16 MVA;
- When the operational speed required is higher than 6000 rpm, the solution with 4 poles surface mounted permanent magnet machine is the most common, with a limit of 4 MVA at a maximum speed of about 19000 rpm.

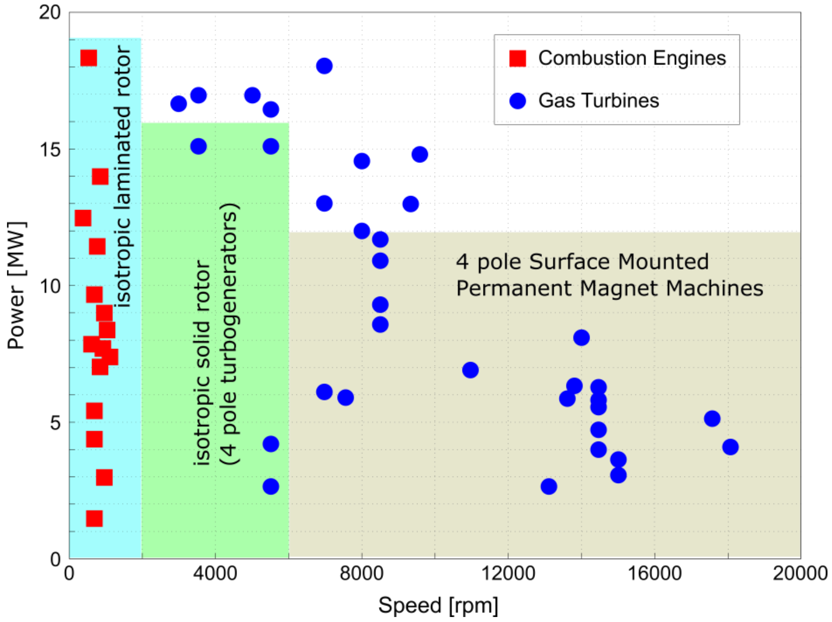

**Figure 5 Rated power to the shaft for gas turbines GT and internal combustion engines MCI as a function of the rotational speed.**

## E. Fault Tolerance

Additional requirements of modern electric motor drives and on board plants, out of the functional requirements, are increased reliability and fault tolerance. One of the most promising strategies to guarantee continuity of motoring and generating operations to be used in electric ships is the adoption of multi-phase technology. Fault tolerance is a basic requirement for modern electric motors and generators that have to be installed in electric ships. This can be achieved with a number of integrated approaches such as suitable system design architectures or post-fault control strategies. A simple way to apply redundancy is to use more identical motors or generators mechanically coupled to the propeller by means of a gearbox stage. Another widely recognised method to improve the fault tolerance features of an electric propulsion system is the use of multiphase windings.

## III. INTEGRATED ELECTRIC POWER SYSTEM

There are two fundamental electric power and propulsion architectures in use for vessels today: segregated and integrated [7]. In the segregated architecture, the propulsion and electrical system are essentially separated. The main engines are connected to the propeller directly or with a gearbox. For the integrated architecture, the main engines are driven by electrical generators, which provide power to on-board loads as well as propulsion. The integrated configuration has attracted more and more attention due to its advantage of improved fuel efficiency and arrangement flexibility. Based on the electrical power distribution type, the integrated power system can be categorized as radial architecture and zonal architecture. These two categories can be either AC or DC based on the electrical power types, as shown in Figure 6.

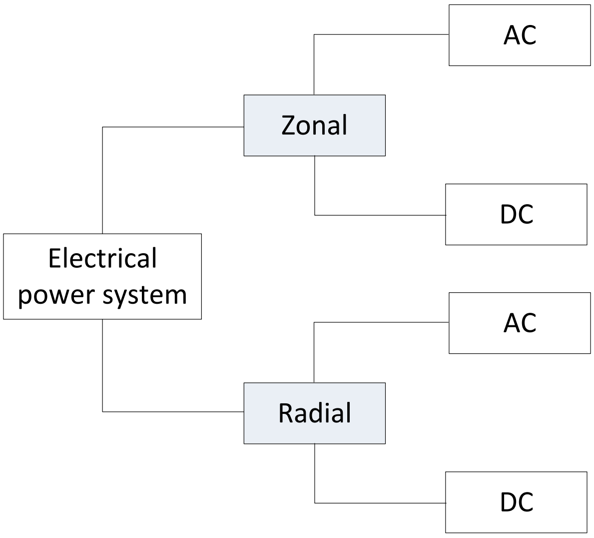

Figure 6 Electrical system categories

### A. AC systems

For the AC architectures, the generators on-board are normally synchronous machines that are running at constant speed and produce power at a constant frequency (50Hz or 60 Hz according to EU or US frequency standard). The generators are normally driven by diesel engines. Figure 7 shows an example of an integrated electrical power system of a cruise ship [9].

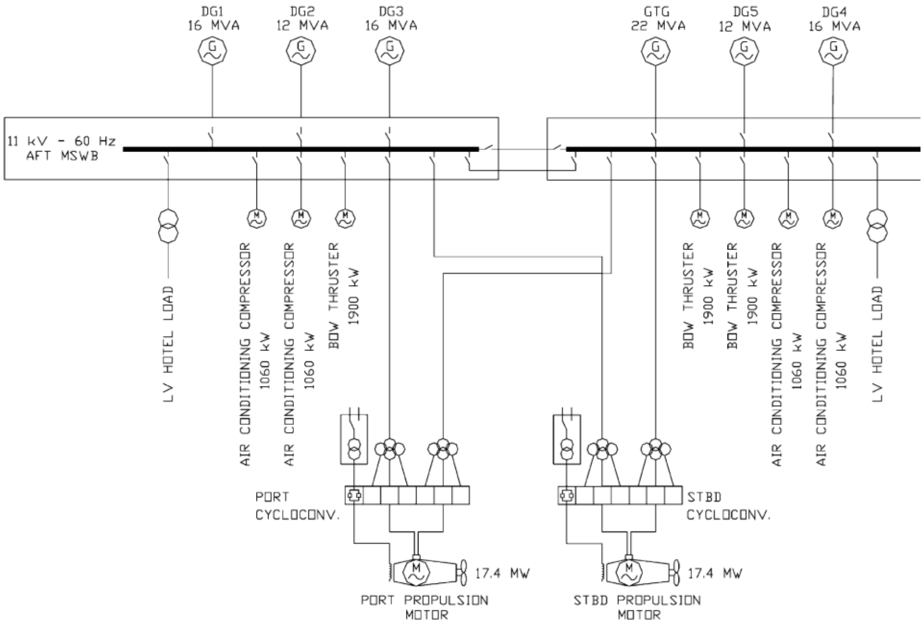

**Figure 7 Common cruise all-electric ship integrated electric power systems [9]**

As can be seen from Figure 7, the integrated electric power system (IEPS) in the cruise ship supplies almost every subsystem including propulsion, air conditioning, BOW thrusters and hotel loads etc.

## B. DC system

With the development of power electronics, especially solid-state DC breakers, the DC network is becoming more attractive for IEPS applications. Indeed, on-board DC Grid is a new electric power distribution concept that opens new opportunities for efficiency improvements and space savings. In addition, conventionally used AC generators and motors can be conveniently integrated with the DC network through power electronic converters. The main advantages of a DC network include

- Simplified connection and disconnection of different power sources and energy storage systems
- Elimination of reactive power
- Elimination of the challenge of phase angle synchronization of multiple sources and loads which is essential for an AC network
- Improved efficiency

The efficiency improvement is mainly accomplished by the fact that the system is no longer locked at a specific frequency (usually 60Hz on ships), even though any 60Hz power source also would be connectable to the Grid. The new freedom of controlling each power consumer totally independently opens up numerous ways of optimizing energy consumption.

There are several ways of configuring the On-board DC Grid including a multi-drive approach (Figure 8) and a fully distributed system (Figure 9). In the multi-drive approach all converter modules are located in the same line up within the same space layout as today’s main AC switchboard. For the distributed system each converter component is located as near as possible to the respective power source or load.

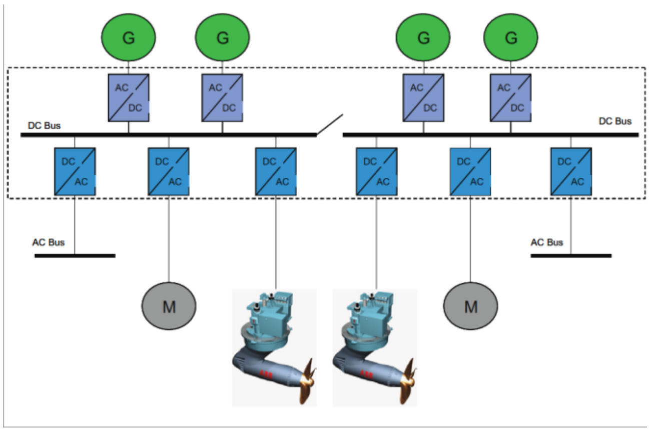

**Figure 8 On-board DC grid with multi-drive approach [10]**

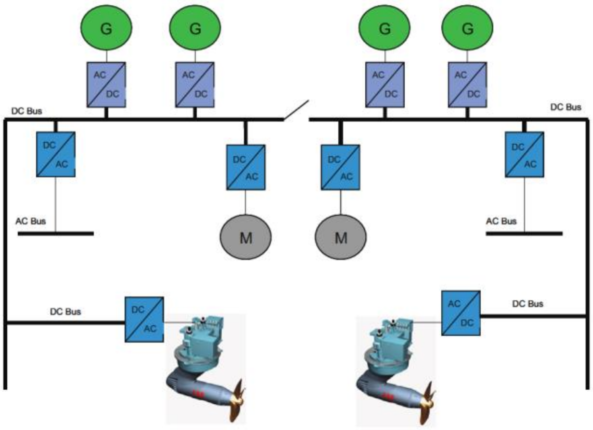

**Figure 9 On-board DC grid with distributed approach [10]**

The main traditional challenges with DC distribution in general have been to achieve full selectivity and equipment protection during the fault conditions. Compared with AC, DC current has no natural zero-crossing point and so it is difficult to break the current if there is a fault in the system. AC currents are by nature far simpler to break because of their natural zero crossing every half cycle. DC circuit breakers do exist but are more complex, larger and more expensive than comparable AC circuit breakers.

Due to the high power requirements for electric ships, increasing the DC voltage is inevitable to reduce the cable size. The adoption of voltages higher than 1kV is very common for electric ships, which leads to the MVDC distribution system proposal. Recently, the IEEE has published a recommended practice for 1kV to 35kV MVDC power systems for ships [11]. The main characters of this diagram include:

- Main generators supply the MVDC bus through an AC/DC converter.
- Offshore power interface is available with a transformer and a AC/DC converter
- The energy storage is interfaced with the MVDC bus with a DC/DC converter
- Ship propulsion motors are driving from the MVDC bus through a variable speed drive DC/AC inverter
- Pulse loads including rail guns, electromagnetic launch systems, free electron lasers etc. draw power from the MVDC bus through a DC/DC converter, with their own energy storage systems where needed to manage peak power demands
- Ship service loads are supplied by the MVDC bus through DC/DC converters

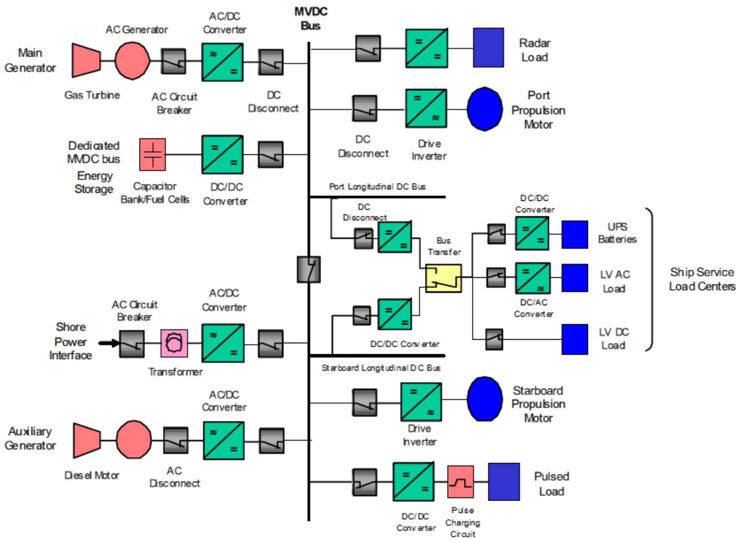

Figure 10 IEPS of electric ship with radial MVDC architecture [11]

Besides conventional radial MVDC architecture, another distribution topology has emerged [11]. This architecture maximizes operational capabilities even under extreme conditions.

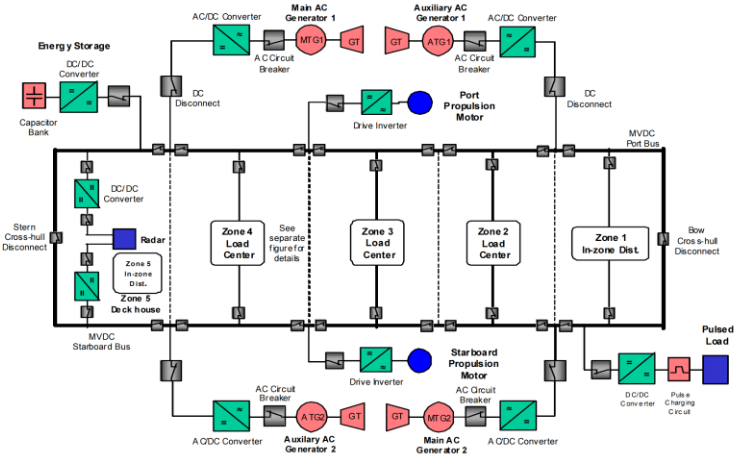

Figure 11 IEPS of electric ship with Zonal MVDC architecture [11]

Ship service loads are distributed in four zones from bow to stern along the ship and are fed by both MVDC ports and starboard buses. The two MVDC buses are connected by the Bow and stern cross-hull links. This arrangement provides the capability of configuring a ring-bus, from which the power generation and load subsystems operate. One main and one auxiliary gas turbine generator set is connected to the MVDC bus. This ensures at least two different and independent sources of supply for each load. Although this is one of the most researched topics in the shipboard power systems technological research area, a shipboard MVDC distribution system is yet to be installed on-board a ship [12]

## IV. NOVEL ELECTRIC LOADS ON-BOARD

As the primary shipboard systems move towards full electrification, many secondary systems and functions are increasingly being electrified. The availability of a significant electrical power distribution system supports the development of full electric alternatives for a number of distributed systems without needing an exclusive electrical network. Of particular interest has been electrical actuation of the ships steering and stabilization surfaces, the rudder and stabilizing fins.

An integrated power system also supports new applications of electrical system, particularly “energy weapons”, namely railgun, laser and microwave systems where a high pulsed power load can be supplied from a relatively modest continuous power supply via a suitable energy storage system.

Another potential application is electromagnetic launch. Electromagnetic catapults for manned fighter launch from carriers are currently nearing deployment. Compact electromagnetic launch systems also have the potential to allow the launch of Unmanned Aerial Vehicles with significant combat capability from small naval platforms. Figure 12 shows an example of the potential novel load requirements on an electric ship from both replacement of conventionally actuated systems with their electrical counterparts, and from the addition of some novel electrical systems.

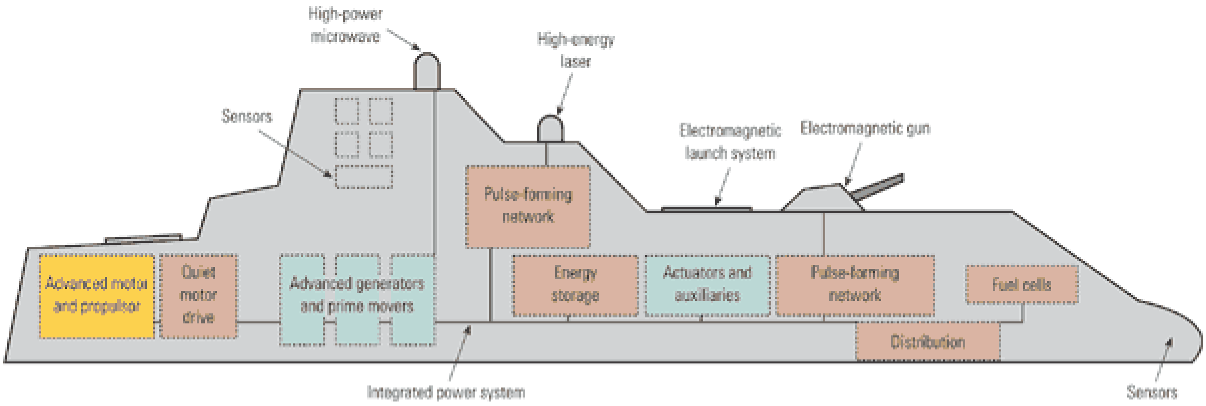

**Figure 12: Example electric ship novel load requirements [13]**

## A. Steering and Stabilisation

The established method of steering control and stabilisation fin actuation relies on hydraulic motors for rotary actuation and hydraulic pistons for linear actuation. With the move to more-electrified vessels, a strong case can be built for the electrification of these shipboard systems. While hydraulic systems such as in Figure 13 have a long history in shipboard use, they typically suffer from [14]:

- High maintenance requirements including replacement of oil, seals and filters and checking for and repairing leaks.
- Low overall system efficiency with high no load losses from maintaining hydraulic pressure in case of demand.
- Significant weight and size, limiting placement and adding constraints to the structural design.
- High complexity due to a high component count with increased risks of failure, increased maintenance and spares requirements.
- Slow response of hydraulic systems to demand.
- Limited fault tolerance, with no actuator redundancy.

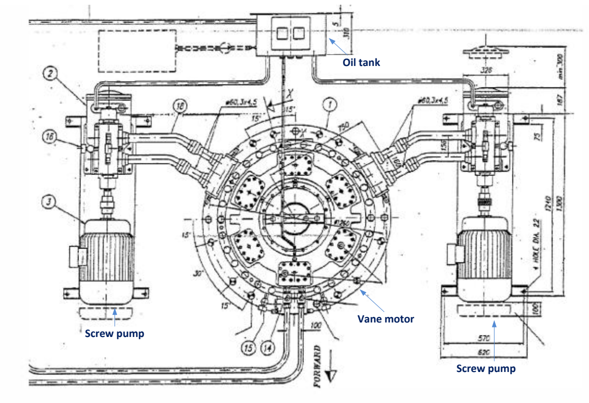

**Figure 13 Hydraulic steering (HS 180X2S-plant on board Ship "Etna",2002) [14]**

Typical requirements for steering and stabilisation from the device seen in Figure 13 are shown in TABLE I:

**TABLE I: Italian Auxiliary ship "Etna" [14]**

| | |
|---|---|
| Rated mechanical power (two pumps) | 26kW |
| Rated electric power (two pumps) | 59kW (440V, 60Hz) |
| Rated efficiency | 44.3% |
| Rated speed (two pumps) | 0.77rpm |
| Rated operating torque | 322kNm |
| Maximum operating torque | 462kNm |
| Mechanical design torque | 604kNm |
| Overall weight | 4300kg |
| Volume (Excluding pipes) | 3m$^3$ |
| Plant footprint (excluding auxiliaries) | 9m$^3$ |

And typical requirements for stabilisation are shown in TABLE II:

TABLE II:: Stabilisation requirements from UK type 23 Destroyer [15]

| Description | Measured Load (kN) | Load with 20% Margin (kN) | Fin Rate (deg/s) | Time Held at Load/Rate (seconds) |
|---|---|---|---|---|
| Maximum load measured during sea trial (equalised) | 118 | 142 | 0 | 120 |
| Maximum load at maximum rate (41deg/s) | 54 | 65 | 41 | - |
| Maximum stall load of incumbent hydraulic actuator | 159 | - | | 10 |
| Maximum load seen in-service | 258 | | | |

In [15] the requirements for stabilisation fin load were defined for a UK type 23 Destroyer from sea trial measurement. The work then focussed on replacing the existing hydraulic actuators with electro-mechanical actuators (EMAs), using a rotating electrical machine to drive a ball screw. The solution using EMAs for fin stabilisation underwent sea trials, and from this reported significant benefits from the switch to EMAs including higher reliability, lower maintenance requirements and full life costs, reduced weight and space and reduced power consumption.

Bruzzese has further explored the adoption of electric actuators, with work focussed on both steering and stabilisation. The work focuses on the full adoption of electric machines for linear actuation to directly drive the actuation surfaces without using mechanical gearing or rotary to linear translation. This simplifies the mechanical system, eliminating the need for a complex, expensive and high maintenance ball screw system [16].

In the work, use of permanent magnet Linear Synchronous Motors (PMLSMs) is proposed to directly drive both rudder and stabilization surfaces. The body of work shows that PMLSMs can meet the challenging requirements for both steering and stabilisation with improved performance, higher efficiency and a high degree of fault tolerance when compared to existing hydraulic systems [17].

### B. Electromagnetic Launch

Electromagnetic launch technology has reached a new level of maturity, with Electromagnetic launch systems being installed on the latest generation of US Navy carriers, CVN78. Electromagnetic launch systems have been used to replace the steam catapults previously used for carrier launch. Some of the motives for replacement include [18]:

- Steam catapults are heavy and large, including significant subsystems such as accumulator tanks.
- They operate without feedback control and can impart large transient loads to the airframe.
- Heavier faster aircraft will soon result in a launch energy requirement that cannot easily be met by the steam catapult.
- Steam is not as readily available on the newest generation of largely electric drive ships, particularly those without nuclear reactors.

In contrast, electromagnetic launch systems are compact and adaptable. They can be designed to use modular stator structures that allow for a high degree of redundancy and easy replacement and repair [19]. They can be used to launch a huge variety of payloads from F35’s to small UAV’s without putting excess stress on the airframe through control of the motor power supply. Although electromagnetic launch systems have relatively high pulsed power requirements of ~100MW for an F-35, this will be supplied by an integrated energy storage system, which can in turn be charged over time from the ships electrical system. For example, the 100MW launch demand with a sortie rate of a single launch per hour could be met with a 28kW continuous supply.

While electromagnetic launch is having an impact on carrier systems, it also has significant potential at a smaller scale. Systems such as the EMKIT UAV launch system [20] have the potential to expand naval capability significantly, by allowing the launch of drones from much smaller naval platforms.

As an example, the EMKIT system has the capacity to launch a range of surveillance and combat capable drones from a 10-15m launch track, using integrated power and control systems without significant demands on the wider power system of the ship. With this capability a launch system could be mounted onto much smaller naval vessels, allowing the deployment of UAV’s with significant combat or surveillance capability from Destroyer sized platforms, or from drone motherships such as BAE Naval Systems’ UXV Combatant concept ship.

## V. CONCLUSION

The marine industry is increasingly moving towards electrification of both main and auxiliary systems, which is enabled by developments in power electronics, electric machine and energy storage systems. The main drivers behind this movement are the more stringent environmental requirements from the IMO as well as the increasing price of fuel. Electric propulsion and integrated electric power systems are the two major directions going forwards. With electric propulsion, the prime mover is able to achieve high efficiency in a wide operation range and thus reduce fuel consumption and exhaust gas emissions. The flexibility of IEPS is of great benefit to a variety of ships and makes it an important technology for marine application. It can be foreseen that these two technologies will play an increasing role in the future for both commercial and military applications.

## VI. REFERENCES

[1] *www.airclim.org/imo-marpol-convention*.

[2] H. Pestana, "Future trends of electrical propulsion and implications to ship design," *Proc. Martech,* 2014.

[3] R. L. Jan Fredrik Hansen, "Electric propulsion for LNG Carriers," *LNG Journal,* 2004.

[4] S. Y. Kim, S. Choe, S. Ko, and S. K. Sul, "A Naval Integrated Power System with a Battery Energy Storage System: Fuel efficiency, reliability, and quality of power," *IEEE Electrification Magazine,* vol. 3, pp. 22-33, 2015.

[5] T. J. McCoy, "Trends in ship electric propulsion," in *Power Engineering Society Summer Meeting, 2002 IEEE*, 2002, pp. 343-346 vol.1.

[6] T. J. McCoy and J. V. Amy, "The state-of-the-art of integrated electric power and propulsion systems and technologies on ships," in *2009 IEEE Electric Ship Technologies Symposium*, 2009, pp. 340-344.

[7] T. J. McCoy, "Integrated Power Systems&#x2014;An Outline of Requirements and Functionalities for Ships," *Proceedings of the IEEE,* vol. 103, pp. 2276-2284, 2015.

[8] J. F. Hansen and F. Wendt, "History and State of the Art in Commercial Electric Ship Propulsion, Integrated Power Systems, and Future Trends," *Proceedings of the IEEE,* vol. 103, pp. 2229-2242, 2015.

[9] M. Cupelli, F. Ponci, G. Sulligoi, A. Vicenzutti, C. S. Edrington, T. El-Mezyani*, et al.*, "Power Flow Control and Network Stability in an All-Electric Ship," *Proceedings of the IEEE,* vol. 103, pp. 2355-2380, 2015.

[10] J. O. L. Jan Fredrik Hansen, Klaus Vanska, "Onboard DC Grid for enhanced DP operation in ships," presented at the DYNAMIC POSITIONING CONFERENCE, 2011.

[11] "IEEE Recommended Practice for 1 kV to 35 kV Medium-Voltage DC Power Systems on Ships," *IEEE Std 1709-2010,* pp. 1-54, 2010.

[12] G. Sulligoi, A. Vicenzutti, and R. Menis, "All Electric Ship Design: from Electrical Propulsion to Integrated Electrical and Electronic Power Systems," *IEEE Transactions on Transportation Electrification,* vol. PP, pp. 1-1, 2016.

[13] A. N. Scott Littlefield, "Roadmap for the all-electric warship," *Power Magazine,* 2015.

[14] C. B. T. Mazzuca, "Project ISO: Innovative Solutions for Italian Navy's Onboard Full-Electric Actuators," presented at the ESARS, 2012.

[15] N. O. B. Stafford, "Technology Development for Steering and Stabilizers," presented at the UKAAC Control, 2006.

[16] C. Bruzzese, "A high absolute thrust permanent magnet linear actuator for direct drive of ship's steering gears: concept and FEM analysis," presented at the ICEM, 2012.

[17] C. B. D. Zito, A. Raimo, E. Santini, A. Tessarolo, "A Hybrid Experimental Drive Concept of Permanent Magnet Linear Direct Actuator Servoed to a Ship's Hydraulic Rudder," presented at the SMART, 2015.

[18] D. J. S. M. R. Doyle, T. Conway, and R. R. Klimowski, "Electromagnetic aircraft launch system—EMALS," *IEEE transactions on Magnetics,* vol. 32, pp. 528-533, 1995.

[19] M. J. N. D. C. Meeker, "Indirect vector control of a redundant linear induction motor for aircraft launch," 2009.

[20] E. L. A Foster, M Thompson, "EMKIT - Development of an advanced linear induction motor powered UAV launch demonstrator," London, 2006.