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Emerging Electric Ship: Modern Power Technology And Propulsion System

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Abstract

Rising demand for electric power, as well as new requirements for servicing frequently changing loads while reducing the total size and weight of the electric power system and its related components on board ships, the examination of a variety of new power systems designs and technologies, particularly for naval surface combatants, drives the examination of a range of new power systems architectures and technologies. In marine systems, electrical propulsion is not a new notion. Power electronic converters, on the other hand, have proven to be the Key Enabling Technology for the electrification of large ships. This study begins with an overview of EP drives, which resulted in the development of all-electric ships. After that, electric power generation and control systems are discussed. The standard design approach is given to help understand the problems in creating such a system. The motivations for pushing forward research in the field of shipboard power systems are then discussed.

Keywords— Electric ships (ES), design tools, electric power generation and control, electric propulsion, hardware- in-the-loop (HIL), Electrical power systems (EPS), ship design, shipboard power systems, Integrated Electrical and Electronics Power Systems (IEEPS),simulator.

1. INTRODUCTION

The objective of a ship, in general, is to maximize the payload quota while lowering the ship owner's purchase and running costs. The development of power electronics in those years allowed new electric technologies from various industrial domains (steel industry, rolling mills, railways, petroleum and chemical facilities, and so on) to be made available for marine systems. While alternating current (ac) systems continue to improve, the introduction of wide band-gap power electronics for high-power applications has accelerated the development of medium-voltage direct current (MVDC) power systems. For future ships, these are likely to deliver considerable operational and economic benefits. MVDC systems, on the other hand, provide a number of technical hurdles. Power electronics converters are replacing the thermo mechanical, mechanical, hydraulic, and pneumatic power units in the MVDC system for more electric shipboard applications to minimize system size, weight, and maintenance costs while increasing high efficiency and dependability.

The fast dynamic interaction among power converters, on the other hand, offers a challenge to keeping the MVDC system stable. One of the most significant issues of future medium-voltage direct current ship electrification is that all power provided to loads must pass via power electronics. This will increase the overall size and weight of shipboard equipment, which has yet to be assessed. In order for naval architects to execute shipboard designs and shipboard design optimizations in this new paradigm, approaches for scaling power conversion equipment from kilowatt to megawatt levels will be required. Shipboard MVDC systems are projected to allow for substantially higher rates of load power ramps while maintaining prime movers within their operational parameters. As a result, energy storage is both necessary and desirable in order to enable those processes. Another technical challenge is the development of high-efficiency and compact power conversion equipment to serve as interfaces between the MVDC distribution bus and ac sources (e.g., generators), main ac and dc loads (e.g., propulsion motors and mission loads), and the numerous (lower voltage) ac or dc service loads throughout a ship.

2. SHIP BOARD ELECTRIC POWER GENERATION AND CONTROL

The power system in an on-board an electric ship must meet requirements that are distinct from those of conventional ships (where "conventional" refers to both land-based and mechanically powered ship systems). The distinction between essential and non-essential users is one of the initial differences. Essential users are loads whose supply and proper service must be guaranteed, even in the event of a significant system failure (as defined by laws and regulations), because their functionalities are critical to the ship's safe operation. Propulsive systems, rudder motors, thruster systems, fire suppression systems, communication systems, emergency lights, and navigation systems are all examples of these. In some classes of ships, air conditioning, ventilation, bathrooms, and sanitization systems are now beginning to be regarded important services (for example, in cruise ships following safe return to port regulations, sanitization systems). In fact, they ensure the onboard living conditions, despite the fact that they are not required. The lack of an unlimited power bus onboard a ship is a second consideration (the IEPS is a weak system). In comparison to conventional power grids, the insertion or disconnection of both big loads and generators can result in electro-mechanic perturbations with bigger magnitudes and longer recovery times.

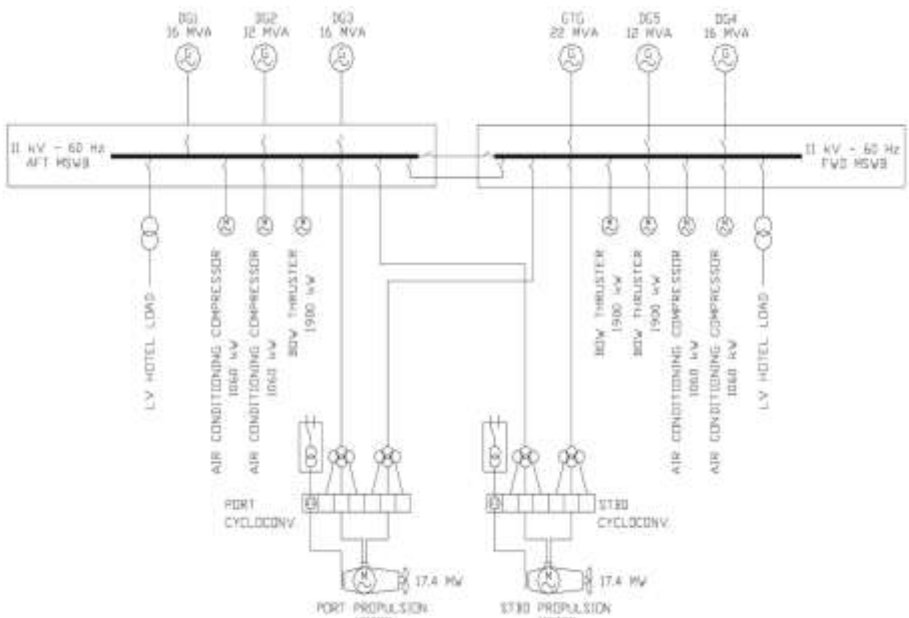

Figure 1. Common cruise AES IEPS

According to these assumptions, the IEPS design necessitates a strong systemic approach, with a focus on the functional integration of the various subsystems. Conventional power plants knowledge is not enough, because the IEPS of a large AES includes almost all the possible electrical engineering subsystems: a large power station with generators working in HV (intended as voltage above 1 kV in shipboard applications); a main HV distribution system; a secondary distribution system working in low voltage (LV); almost each kind of electrical machinery used in industrial applications (both in HV and LV, either direct-on-line or supplied by a variable-speed drive). A modern IEPS exploits also an extended use of power electronics, real-time control systems (lower automation layers), and distributed automation systems (higher automation layers), each built and installed by different suppliers, which have to be fully integrated, representing the core of the so-called power management system. In a word that on land would be defined as a “micro-grid,” the large power levels and the degree of ICT applications dedicated to power control make the AESs’ IEPS a natural-born multi-megawatt smart grid. Because each ship is unique, a new, fully tailored IEPS must be created each time. Finally, it should be noted that in an AES, the IEPS powers practically all of the loads, making it a system with high QoS requirements. In fact, a total blackout should be avoided at all costs, as it results in the ship's total loss of mobility as well as the loss of life support systems. As a result, the electrical engineer serves as both a typical plant designer and a true system integrator for both the electro-mechanic and ICT components of the IEPS.

3. ELECTRIC SHIP DESIGN

The differences in ES design are related to the EP and IEPS design phases, while the rest of the ship design is comparable to mechanically propelled ships. As a result, a sequence of general design phases can be defined with the goal of generating a complete ship from the initial design requirements (Fig. 2) [2]. The IEPS design overlaps different phases, starting from concept design (where the possible layouts and solutions of the onboard IEPS are conceived) up to the functional design (where the single IEPS components to be acquired by the shipyard are defined). During these phases, the IEPS design is a partially self-contained activity. However, because such an activity has interrelationships with others, it is vital to think about the entire ship design when defining it. Due to the unique constraints of ships, each subsystem is both critical for functioning and competitive in terms of space and weight (dedicating more space to a subsystem implies reducing the available space for another one). As a result, a balance must be struck between costs, space occupied, and achievable performance while also ensuring compliance with standards. As a result, each subsystem's design process is intertwined with the others, making it difficult to accurately design the IEPS without taking into account the overall ship design. Moreover, in complex systems the overall optimal design solution is rarely the composition of the optimal solutions of the sub-design processes, making it necessary to develop a design methodology that is able to balance the IEPS design with the other subsystems. Several design methodologies can be found in the literature [3]–[9], but the most relevant three are the design spiral, the collaborative concurrent design, and the design space exploration. The first is the simplest, since it entails conducting all design activities in order, starting with the most general detail level (achieved during concept design) and progressing to more detailed design levels. Doing this, information resulting from previous design cycles can be used to revise the current iteration, developing more detail at each round and improving the design [3].

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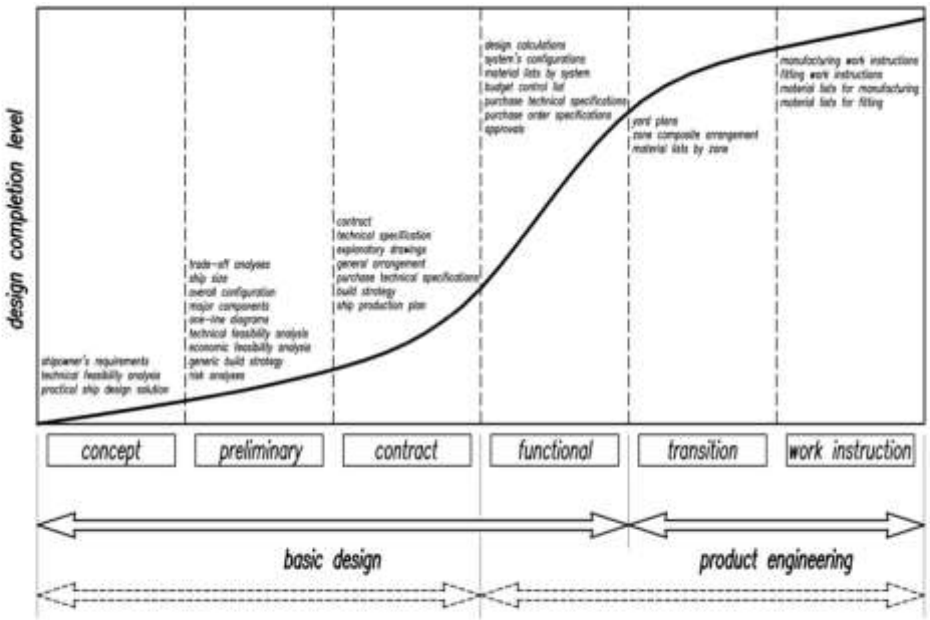

Figure 2 Ship design process [9].

An explanation of how IEPS design is achieved can be found in [10], while here, some considerations about the relevant steps are made referring to the traditional IEPS design spiral process shown in Fig. 3. The estimation of the so-called "electric loads balance," which is a list of all the electric loads to be put onboard, is the first step in the design process. To account for both the ship's operating and environmental conditions, their power is weighted using appropriate load factors. The result is a matrix that shows the projected amount of electric load delivered by generators for each potential ship's operational and climatic parameters, including propulsion. The rating and number of generators to be put onboard are then determined using the electric load balance, as well as other influencing factors (such as classification society restrictions). Typically, these two parameters are chosen in order to maximize efficiency in all of the ship's operational situations while being compliant with the standards. Obviously, installation expenses and occupied onboard space must be considered as well, and they must be kept to a minimum. The total electric power generation capability installed onboard drives the main bus voltage selection, while frequency is usually defined by the ship’s area of operation. The voltage is kept as low as feasible to keep the cost and volume of the electric machinery (which is dependent on the insulation level) as low as feasible, while the fault current levels are kept within the limits of commercially accessible safety mechanisms.

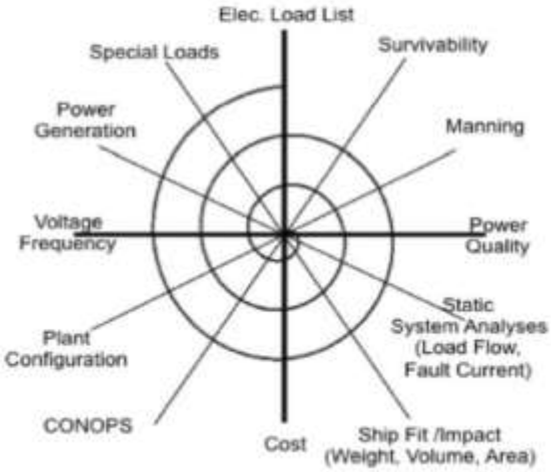

Figure. 3. IEPS design spiral process [10].

The selection of the plant configuration is the following step, which is the design of the power system to be installed onboard. Such a design has to take into account requirements from rules and regulations, applicable laws, and owner's needs. Due to this, the IEPS architecture generally is chosen between some configurations already validated in the past, depending on the scope of the vessel to be built. This is done in order to decrease the design effort. In this regard, it has to be remarked that complex distribution systems are applied only when the eventuality of a blackout (due to internal or external causes) is to be avoided as much as possible (such as in naval vessels or dynamic positioned ships). Otherwise, simple radial configurations are preferably used. Luckily, nowadays some major power component suppliers are starting to invest in industrial research related to MVDC application, with the aim of opening new business opportunities [12].

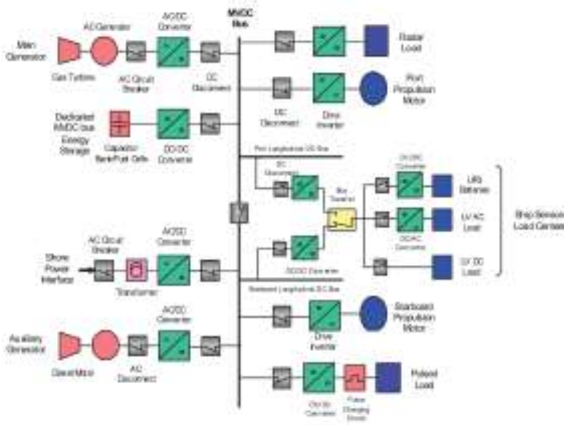

Figure. 4. MVDC radial distribution [11]

Aside from the traditional radial distribution, which is the industry standard, and ring distribution, which is rarely used onboard ships (dynamically positioned vessels have a ring power distribution to achieve high re-configurability, but are typically operated with open buses), another distribution topology that has recently emerged is zonal distribution. Zonal electrical distribution systems (ZEDSs) are conceived to maximize the QoS, ensuring at least two different and independent power supply inputs for each load.

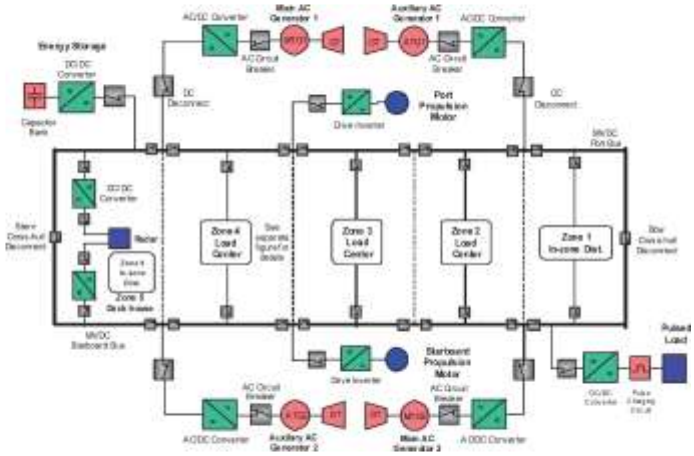

Figure. 5. MVDC Zonal distribution [11]

4. ELECTRIC PROPULSION SYSTEM

Installing one or more electrical drives for each rotor creates Electric Propulsion (EP) systems. EP motors, which are fueled through power electronic converters, replace traditional slow-running diesel propulsion motors (or geared gas turbines). Moving some considerations from the cruise liner case (Fig. 4), which have marked a demarcation line in the sizing of such converters, the order of magnitude is about 15–20 MW per single propeller. Normally, all electric cruise liners are equipped with two propellers (so a total of 30–40 MW), with some exceptions (remarkable is the record-case of Queen Mary II, equipped with four propellers and a total installed propulsion power of about 86 MW). Electrical propulsion offers a number of well-established benefits to both the marine architect and the ship owner:

- Electric motors have better dynamics (start, stop, and speed fluctuation) than conventional diesel motors (or gas turbines);
- Possibility of fitting shorter shaft lines or even exterior spinning pods (thus eliminating the rudder and boosting maneuverability) to accommodate electrical motors with more flexibility.
- Reduced fuel consumption due to the modulation of thermal engines running (the number of generators on duty is adjusted in order to keep them working at their minimum specific fuel oil consumption);
- Higher comfort due to vibration reduction (thermal engines run at constant speed, therefore vibrations filtering is much efficient);
- High level of automation of the engine rooms and related reduced technical crew manning.

The largest propulsion drives commonly use synchronous motors. Historical, reliability, and efficiency reasons are related to such a choice. The fact that the largest power electronics converters available for maritime EP have been load commutated inverters for many years is one of these factors. Multiphase motors can also be used in high-power applications, such as cruise liners (with related increase in converter numbers). Because the propeller's speed bandwidth needs are so small in comparison to even electromechanical transients, a traditional V/Hz speed control is usually used.

Figure. 6. Typical cruise ship: Fincantieri Royal Princess

A different solution, still employing thyristor bridges, is the use of cyclo-converters, making it possible to generate high torque values at almost zero speed. In the last 10 years, more conventional pulse width modulation voltage-source converters have become mature for propulsion system applications, so that the employment of both conventional and advanced motor types has begun (e.g., induction motors and permanent magnet synchronous motors). Diode front ends or active front ends (AFEs) can be used on the network side in this case. Some high-performance applications (mainly naval vessels, such as FREMM frigates) already employ AFEs, thus being able to exploit the bidirectional power flow from and to propulsion systems (allowing regenerative braking operation), and improving the IEPS power quality (both by reducing the current harmonics injected during operation and by acting as active filters if needed). After the experiences of the last one/two decades with large power high-voltage (HV) electric drives, induction motors are beginning to be employed for maritime propulsion, particularly when high torque density and shock resistance are required. In this case, both acquisition and maintenance costs are expected to reduce (in particular due to the absence of excitation systems and related auxiliaries and control systems).

5. CONCLUSION

The results of the massive change in ship design brought by the birth of the ESs were first shown in this publication. This revolution was sparked by the necessity to integrate a large system, such as the IEPS, onboard. This study has showed that, based on these well-known foundations, today's rivalry in the marine industry sector is pushing for a change in the traditional shipboard power system paradigms. First of all, the increasing use of power electronics con- version is leading toward a new revolution in design, due to the shift from the IEPS to the IEEPS concept. Second, advances in technological research are allowing current shipboard power systems to reach ever-higher performance and functionalities by utilizing new electrical technologies onboard ships. Some of these are so important as to be even considered as KETs, as they allow to achieve significant improvements in respect to the conventional practice, thus enabling to obtain supremacy (military or commercial) over competitors. As a result, researchers must prioritise transferring technologies, design approaches, and tools between these two traditionally well-separated study domains, as doing so will considerably accelerate the rate of progress of both technical domains.

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