THE ANNALS OF "DUNAREA DE JOS" UNIVERSITY OF GALATI
FASCICLE XI – SHIPBUILDING. ISSN 1221-4620, e-ISSN 2668-3156
2021

ELECTRIC PROPULSION OF SHIPS AND ITS ADVANTAGES FOR ANCHOR LIFTING TOWING VESSELS

Aurel – Dan Maimon
University "Dunarea de Jos" of Galati,
Faculty of Naval Architecture, Galati,
Domneasca Street, No. 47, 800008, Romania,
E-mail:dan.maimon@ugal.ro

ABSTRACT

This article describes the composition of electric propulsion and highlights its advantages in case of anchor lifting towing vessels. Electric motors are increasingly present on the market, particularly in the yachting and service sectors. Electric propulsion is very interesting from the point of view of greenhouse gas emissions and navigation comfort. However, it does not, for the moment, make it possible to obtain powers equivalent to heat engines. The environmental advantages of the electric boat (absence of air and aquatic polutant discharges, absence of noise) and its technical characteristics (virtual absence of vibrations, very great maneuverability and ease of use, reduced operating cost) show this mode of operation propulsion as one of the alternative solutions to traditional techniques.

Keywords: electric propulsion, hybrid propulsion, anchor lifting towing vessels

1. HISTORY OF SHIP PROPULSION

The first propeller-driven, mechanically propelled ships were fitted with reciprocating steam engines with pistons and connecting rods. With the arrival of the large transatlantic liners, steam turbines are emerging, with the poor performance that we know them. Then diesel engines prevail, slow diesel (80 to 200rpm) or semi-fast diesel (400 to 900rpm) with reduction gear.

These engines allow the improvement of efficiency, the reduction of the volume of the machines, but also have the following drawbacks: noisy propulsion, poor flexibility involving the use of propellers with orientable blades and poor propulsion behavior at low speeds. Nevertheless, the systems currently equipping the majority of ships perform their function correctly.

However, electricity, since its discovery about a century and a half ago, quickly invaded ships, mainly for its great flexibility. The main steps were as follows:

- 1860: a submarine is equipped with electric propulsion powered by batteries.
- Beginning of the 20th century: several large submarines are electrically equipped mainly for acoustic discretion.
- 1920s: turbo-electric propulsion for 6 battleships of 40,000HP and 2 aircraft carriers of 180,000HP for the US Navy; several icebreakers and research vessels are also equipped with an electric transmission.
- 1930s: several turbo-electric liners, such as the Patria in Germany, or the Normandie in France (160,000HP), are launched.
- Second world war: the United States build more than 300 surface warships and tankers in turbo or diesel-electric.

- After the war: use of Ward-Léonard groups, then appearance of thyristor converters in the 1970s.

Advances in power electronics have allowed the application of electric propulsion to increasingly varied types of ships.

2. COMPOSITION OF ELECTRIC PROPULSION

An electric vessel comprises two assemblies: energy production and propulsion (see Fig.1).

- The power station includes several alternators driven either by Diesel engines or by gas turbines. It supplies all on-board users and in particular one or more propulsion equipment.

- Propulsion equipment includes a variable speed electric motor associated with a converter, or very rarely a fixed speed motor driving a variable pitch propeller.

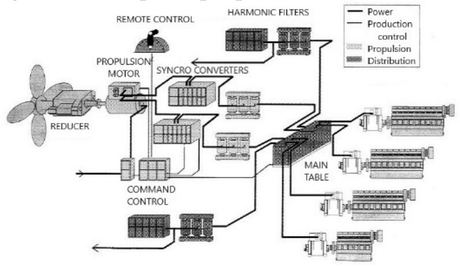

Fig.1. Scheme of energy production and propulsion for an electric vessel

Four families of power converters are used in electric propulsion:

- **The rectifier associated with a direct current motor** (see Fig.2)

This solution is hardly used nowadays. It is limited in power (around 5 MW). Taking into account the voltage and current limitations due to switching and poses maintenance problems, due to the wear of the collector and the brushes and to the clogging which can lead to a flash at the collector. The permanent magnet motors developed over the last 10 years are unfortunately limited to low powers.

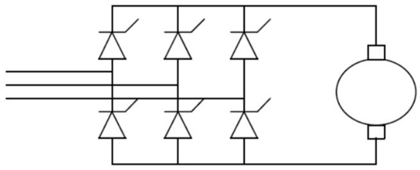

Fig.2. Rectifier associated with a direct current motor

- **The cycloconverter associated with a synchronous motor** (see Fig.3)

In marine applications, to date, only synchronous machines have been used, while asynchronous machines have already been used in industrial applications, such as rolling mills.

Synchronous motors are preferred over asynchronous motors for their ability to provide large air gaps without being penalized by abnormally high magnetizing currents. This solution is particularly suitable for icebreakers, which require high torque at low speed; it is thus possible to free a propeller stuck in the ice or to cut a block of ice without wedging the propeller.

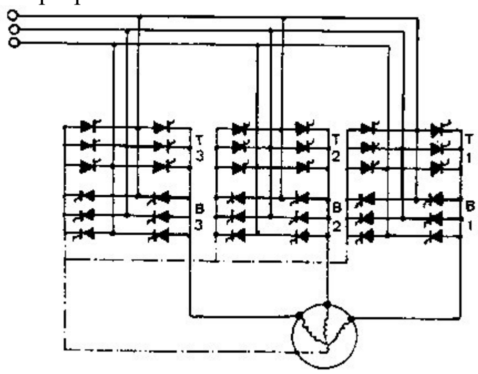

Fig.3. Graetz head-to-tail industrial cycloconverter with 3 bridges

- **The synchronous converter associated with a synchronous motor** (see Fig.4).

This association is unequivocally the best for all that is propulsive drive of ships other than icebreakers, because of its intrinsic qualities of simplicity and reliability. Indeed, it includes 3 times fewer thyristors, controlled independently than the cycloconverter, resulting in less space and weight, better efficiency, increased reliability and better availability.

Its other advantages over the cycloconverter are:

- more favorable sizing in kVA for propulsion converters and transformers,

- a better power factor on the network side, resulting in an apparent power and therefore a smaller size and weight of the alternators,

- lower harmonic pollution of the network. Unlike the cycloconverter which generates harmonics at variable frequency as a function of the machine speed, the synchroconverter generates harmonics at frequency proportional to the fixed frequency of the network, therefore perfectly identified and easily filtered; thus, where converters, rotating are necessary with a cycloconverter to supply a network ("clean" for sensitive users (navigation, lighting, TV. video, Hi-fi systems, etc.), simple static filters are sufficient for a synchroconverter,

- better operational reliability. On a synchroconverter, the control and protection of the network bridge and the machine bridge are separate and independent; under these conditions, a fault in one of the bridges can be easily controlled by the other bridge, and the short-circuit current values thus remain very low,

- low noise and vibrations. The noise and vibration level of an electric transmission is very low, and the results are good and similar for both types of drive.

The only ones advantages of the cycloconverter are:

- slightly better torque pulsations on the engine side, but they are anyway negligible compared to those produced by a diesel engine or by the propeller itself

- a slightly smaller sizing of the motor, the difference, in kVA, is due to the power factor on the motor side which is better for the cycloconverter than for the synchroconverter; the dimensioning being in theory inversely proportional to the power factor, the lower the power factor, the bigger the motor,

- dynamic performance in terms of torque and speed. The cycloconverter has a better dynamic response than the synchroconverter. However, for a ship (other than an icebreaker) with diesel-electric propulsion, the possibilities of the synchroconverter itself greatly exceed what a ship can accept (propeller, thrust bearing, power plant. ...). Under these conditions, the control must provide adequate limitations (slopes, speed and torque, etc.) so as not to damage other equipment, and this as well in cycloconverter as in synchroconverter.

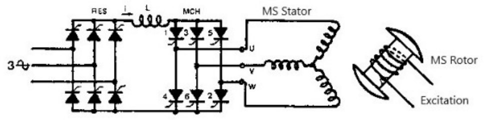

Fig.4. Synchronous converter associated with a synchronous motor

- **The forced switching inverter associated with an asynchronous motor** (see Fig.5).

This solution is only used on a few ships in the world, in particular on ships equipped with many low power thrusters. In fact, it has limitations both at the maximum power level and at the engine speed level, making the use of a reduction gear essential. In addition, the forced-switching converter being more complex, its maintenance requires the presence of a highly qualified electrician.

Regardless of the type of converter used (except for the forced-switching inverter), in most cases the propulsion motor is coupled directly to the shaft line; however, when the size and weight must be limited, the solution to be adopted is a high speed motor (1000 to 1500rpm) associated with a reduction gear.

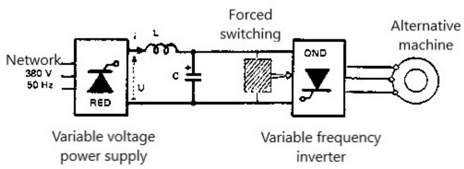

Fig.5. Forced switching inverter associated with an asynchronous motor

3. ADVANTAGES OF ELECTRIC PROPULSION

3.1. Optimization of ship architecture

Diesel engines are separate from the shaft line, which makes it possible to install the equipment in the best possible locations and to obtain substantial space savings. Thus, the choice of electric propulsion for a series of 10 chemical transporters made it possible to add 2 additional tanks out of 40 tanks for some of these vessels or to shorten the vessels by 8 m on the others.

Figure 6 shows the difference in size between a slow diesel solution and the diesel-electric solution chosen.

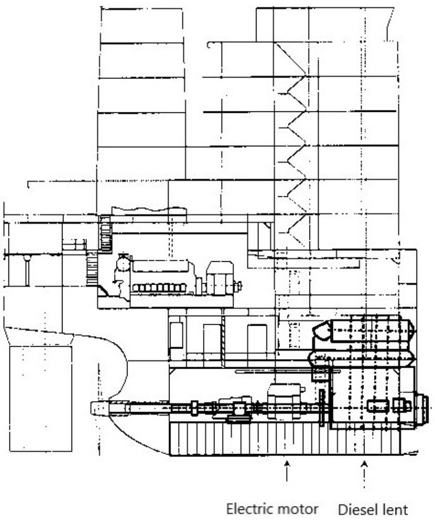

Fig.6. Size difference between slow diesel and diesel-electric solutions

On ships requiring dynamic positioning, such as shuttle tankers, the central power/propulsion system dissociation allows power to be better distributed to several points on the ship. On ro-ro ferries, the optimum arrangement of equipment increases the ease of loading ships. On cruise ships, saving space can increase the number of cabins. This flexibility of installation can also make it possible to optimize the rear shapes of the ship, as well as the propeller, and thus to compensate for the losses in propulsion efficiency.

This is what was carried out very successfully on the chemical tankers mentioned above: compared to a classic 2-stroke diesel solution, the reduced size of the electric motor + reducer assembly made it possible to locate them to the extreme stern of the ship, matching the shape of the hull as well as possible.

3.2. Decrease in installed power and cost

In many ships, propulsion equipment is installed on the one hand, and a power plant supplying the on-board network on the other hand. In electric propulsion, the same diesel-alternators can be used alternately for one or the other function. This is particularly interesting for tankers, where the propulsion power and the power required for the loading / unloading pumps are used alternately. In addition, being decoupled from the shaft line, the diesels can be sized for higher speeds (600-900 rpm instead of 450-514 rpm), therefore being more economical.

3.3. Lower maintenance costs on diesels

In diesel-mechanical propulsion, the speed and load of the main diesel depend on those of the shaft line to which it is directly linked.

In electric propulsion, the diesels run at a constant speed corresponding to the fixed frequency of the network.

On the other hand, by constantly monitoring the number of generator sets coupled to the network, through an electrical energy production management system, it is possible to operate the diesels at their optimum load (50 to 90%) whatever the operating conditions of the vessel would be (clear route, maneuvering, loading, etc.). These conditions of fixed speed and optimized load allow a significant reduction in engine wear and therefore maintenance costs, since the electrical propulsion equipment requires practically no maintenance. In addition, a Diesel running at constant speed and rated load is more efficient and produces less nitrogen oxides, the emissions of which tend to be limited by national and international laws.

3.4. Reduction of the level of vibrations transmitted to the structure of the vessel

On mechanical propulsion systems, it is observed that the slow main diesel engines of high power with variable speed generate vibrations, the spectrum of which is wide and variable, and includes low frequencies that are difficult to attenuate. The use of electric propulsion has the following advantages:

- the amplitude of the vibrations is reduced, the number of units in service being always minimal,
- the motors of the groups running at fixed speed, the frequency spectrum of the vibrations is narrow and perfectly defined; it is therefore easy to size efficient damping systems,
- due to the position far back of the electric propulsion motors, the shaft lines have a reduced length, which also contributes to reducing the amplitude of the vibrations,
- the freedom to choose the speed of the propeller makes it possible to choose the most suitable propeller for the vessel in question and having the best possible efficiency.

Reducing noise and vibrations is a decisive factor on military vessels, research vessels and cruise ships.

3.5. Increased maneuvering flexibility

Electric propulsion allows precise and progressive control of the speed of rotation of the propellers, while avoiding the use of a propeller with orientable blades, a device more expensive, more fragile and complex, therefore less reliable, and of lower efficiency than a fixed-pitch propeller. Unlike the diesel engine, which only develops useful torque from around 40% of its nominal speed, the electric motor is capable of delivering its maximum torque over its entire speed range; this allows unparalleled maneuvering precision, used in particular for cable-type ships, oceanographic research vessels, ferries, ships requiring dynamic positioning such as shuttle tankers.

3.6. High availability and safety of equipment

Electric propulsion requires very little maintenance.

Transformers and propulsion converters are static equipment, and propulsion motors have no wearing parts. Diesel generators, always used optimally, have a high reliability rate. On the other hand, the various redundancies allow continuity of service in the event of a failure: redundancy at the level of the energy production plant (in the event of a failure or maintenance operation on one of the groups, the others can provide an almost normal operation of the vessel during repair of the latter, without immobilization of the vessel) and redundancy in the propulsion equipment (the use of double winding electric motors provides complete independence of the transformers and converters of each 1/2 motor, which can still provide half of the nominal torque of the complete motor.

4. THE ADVANTAGES OF ELECTRIC PROPULSION FOR ANCHOR LIFTING TOWING VESSELS

Electric propulsion has been used on platforms and offshore support vessels since the early 1990s. Technological progress makes it now possible to optimize the propulsion system according to the targeted objectives: fuel savings and reduction of the environmental impact, simplification of design and construction, saving of space on board and improvement of working conditions for the crew. In the case of electric propulsion, the main driver of progress has been the reduction in fuel consumption and operating costs with, in turn, substantial savings. Until recently, offshore support vessels were an important outlet for this technology. The attention is now shifted to anchor-lifting towing vessels and other vessels that can make the most of electric propulsion.

For offshore support vessels, the advantages of electric propulsion over direct mechanical propulsion are well established. In fact, fuel savings are between 15 and 25% in typical operating modes and can reach 40 to 50% in dynamic positioning modes.

Even though most power plants and propulsion systems use the same basic concepts, the market offers different configurations. To optimize savings, shipowners, shipyards and designers must analyze all possible solutions and assess a number of criteria in choosing products, systems and services.

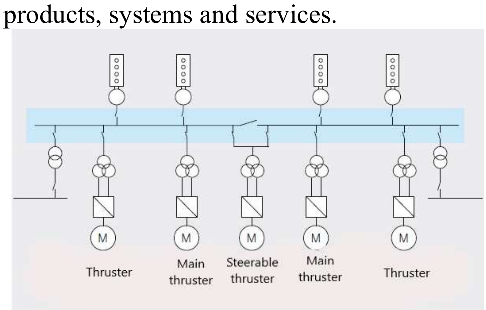

Fig.7. Electric propulsion for offshore support vessels

4.1. Saving fuel

The use of electric propulsion means replacing the shaft between the main motor and the propeller with a system made up of generators, switchboards, transformers, converters and motors. With an efficiency of around 90%, this system exhibits additional losses which must, in one way or another, be taken into account. If the level of electrical losses of the different configurations varies slighlty, yet they remain minimal compared to the hydrodynamic losses of the propellers and the combustion efficiency in the main engines. All in all, the total losses of electric propulsion remain lower than those of conventional mechanical propulsion.

The fuel savings provided by electric propulsion are the result of two factors. Firstly, the variable speed control of the propellers minimizes their no-load losses compared to conventional steerable blade propellers rotating at constant speed. Secondly, automatic starting and stopping of diesel engines keeps their load as close as possible to their optimum operating point, within operating limits.

Offshore support vessels, including anchor lifting towing vessels, traditionally use propellers with adjustable blades and constant speed. Compared to the variable speed control, this type of propulsion is very inefficient due to the high no-load losses of the propellers rotating at constant speed (see Fig. 8).

This aspect alone explains the majority of the savings induced by the electric propulsion of offshore support vessels. In addition, in dynamic positioning, the propulsive power is used very little on a daily basis, even in the most difficult regions such as, for example, the North Sea.

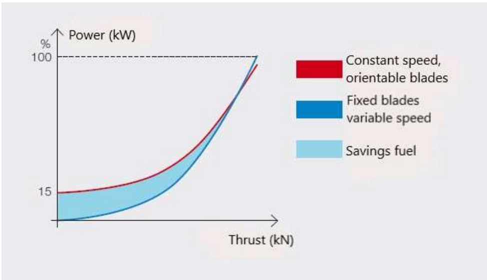

Fig.8. Power-thrust curves of a propeller with adjustable blades rotating at constant speed and a propeller with fixed blades controlled in variable speed

Another major advantage of electric propulsion is the optimization of diesel engine load by using several small engines rather than a few large machines. Depending on the load level, automatic engine starting and stopping increases the output power, reducing fuel consumption.

In the case of an anchor-lifting tug vessel with over 200 tonnes of fixed-point pull, electric propulsion saves nearly 1,900 tonnes of fuel.

The latter requires more installed propellant power than a typical offshore support vessel. Therefore, propulsion systems and their installation cost more. In conventional anchor lifting towing vessels, the design is optimized to contain construction costs and ensure fixed point traction. While in the past, the operating costs were less of a factor in the design and choice of propulsion concepts, things are changing today in the light of the unpredictability of fuel prices and environmental pressure. Now, operating costs and, in particular, the energy bill dictate the design of many ships.

4.2. Hybrid propulsion

Hybrid propulsion, combining mechanical and electrical systems, is an alternative to "all-electric" (see Fig.9).

In this case, three operating modes are possible:

- Exclusive electric propulsion for low speed maneuvers, navigation and dynamic positioning;
- Exclusive mechanical propulsion for towing and high speed navigation;
- Hybrid propulsion using electrical equipment to boost mechanical propulsion to maximize fixed point traction.

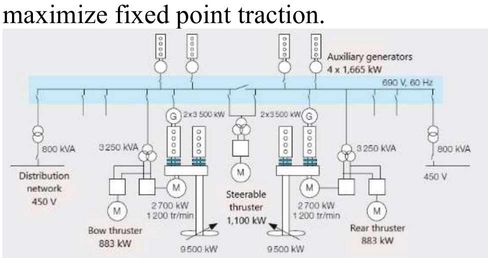

Fig.9. Hybrid electric and mechanical propulsion of an anchor lifting tug vessel with 200 tonnes of fixed point traction

In terms of installation costs, hybrid solutions are more economical than all-electric solutions, while in terms of fuel consumption they are quite comparable. It is for this reason that several ships were build with hybrid solution

Recent anchor-lifting tugs are equipped with hybrid solutions, especially those with high pulling capacity.

However, the increased mechanical complexity of these hybrid systems should not be overlooked, forcing the crew to be more "on deck" and to manually optimize operating modes according to sea conditions. In an all-electric vessel, it is much easier to automatically optimize the configuration of the power plant and the propulsion system for permanent operation as efficient as possible, with minimal human intervention, if any.

4.3. Focus on energy sobriety

The design of propulsion systems for anchor-lifting towing vessels has traditionally focused on towing capacity and construction costs, at the cost of high fuel consumption and significant pollutant emissions, in particular CO_2, compared to electric propulsion. By adopting the latter, offshore support vessels and, today, anchor-lifting towing vessels have significantly reduced their fuel consumption, emissions and operating costs.

While the same gains are possible with a hybrid propulsion for a lower construction cost, this requires the crew to be actively involved in optimizing the configuration according to the conditions.

The fuel savings provided by electric propulsion are due to the greater flexibility of operation of the vessel, even though the system itself introduces further losses into the energy chain. Of course, efforts can be made to limit these additional losses; But to get the most out of electric propulsion, it is first and foremost necessary to design a system that is simple, reliable and flexible.

5. CONCLUDING REMARKS

The major decision criteria for the adoption of electric propulsion vary from one type of ship to another: acoustic discretion for submarines, research vessels, military buildings, low level of noise and vibrations for cruising ships, perfect torque control at all speeds for an icebreaker, precision and flexibility of maneuvering for dynamically positioned ships, ferries or fishing vessels, space saving on tankers, allowing to increase the cargo or decrease the length of vessels.

To these criteria are added the advantages common to all types of vessel, such as: reduced maintenance, increased operating safety, reduced pollution, etc. Whatever the case, it is clear that the study of a project electric propulsion should, in no case, be limited to an investment cost calculation, but on the contrary be the subject of a global approach.

An electric motor produces no polluting emissions. The noise level is also very appreciable, it is much lower than a heat engine. Traffic on lakes or rivers, marine protected areas, creeks etc. becoming more and more difficult for heat engines, because of new regulations, the use of an electric motor is a very good way to reconcile pleasure and respect for nature and other boaters. However, one must pay attention to the type of battery used and their management at the end of their life.

The mode of electricity production is also to be taken into account.

Today there are different solutions for recharging the batteries:

- from renewable energies (wind turbine, solar panels, hydrogenerators ...)
- from the shore power grid
- from an alternator coupled to a heat engine
- from a generator
- from a fuel cell
- etc.

Each of these solutions presents energy yields with more or less high fuel consumption, it is necessary to ask the question of the total energy yield of the system and therefore of the real environmental interest in resorting this kind of solutions.

REFERENCES

[1]. **Ajioka, Y.** "*Electric Propulsion Systems for Ships*" Hitachi Rev. 62, 231–232, 2013.

[2]. **Apsley, J.M.** "*Propulsion Drive Models for Full Electric Marine Propulsion Systems*", IEEE Transactions on Industry Applications, vol. 45, no. 2, March/April 2009.

[3]. Electric Ship Research and Development Consortium: http:H/nerc.aticorp.org/electric-ship_r&d.html

[4]. **Hai-chun, N. et al.** "*Study on the Ship Electric Propulsion System and Its Development*", Advances in Engineering Research, volume 122, 7th International Conference on Applied Science, Engineering and Technology (ICASET), 2017.

[5]. **Hyeonmin J. et al.** "*Large-Scale Electric Propulsion Systems in Ships Using an Active Front-End Rectifier*", Journal of Marine Science and Engineering, 2019.

[6]. **McCoy, T.J.** "*Trends in Ship Electric Propulsion*" In Proceedings of the IEEE Power Engineering Society Summer Meeting, pp. 343–346, Chicago, IL, USA, 21–25 July 2002.

[7]. **Nengqi, X. et al.** "*Type selection and design of hybrid propulsion system of ship*", IOP Conf. Series: Materials Science and Engineering 157, 2016.

[8]. NTNU Energy Efficient All Electric Ship: http:/Hwww.ivt.ntnu.no/imt/electricship/papers/All_electric_ship_present.pdf

[9]. **Parker, D.S. & Hodge, C.G.** "*The Electric Warship*", Trans IMarE, vol. 108, part 2, pp 109-125, 1996.

[10]. **Steinar, J.D.** "*Ship Power System Testing and Simulation*", in Proc. The Electric Ship Technology Symposium (ESTS), pp 202-205, 2005.

[11]. **Wang, Y.** "*On the ship power propulsion system development status and trends*", Science and Technology Information, (35): 102, 2010.

[12]. **Zhang, W. & Chen, H.** "*Ship propulsion technology for the 21st century*", Transportation Science and Technology, (2): 48-50, 2003.

Paper received on November 14^{th}, 2021