Future trends of electrical propulsion and implications to ship design

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ABSTRACT: Over the last 10 years the electrical propulsion fleet grew three times faster than the world fleet. This paper provides an overlook of the main drivers supporting this impressive growth and explores supporting drivers for future growth. The paper also explores two emerging technologies in electrical propulsion and distribution and how these influence ship design: DC distribution and energy storage.

1 DRIVERS OF ELECTRIC PROPULSION

The year of 1903 marked the beginning of electrical propulsion, when the Vandal, an 800 dwt river tanker owned by Nobel Petroleum Company, was launched in St. Petersburg to operate in the Caspian Sea and Volga River. Coincidently, the Vandal was also the first vessel to be built with diesel engines. In those days most vessels were driven by steam. From there on and until mid-90's, electrical propulsion was limited to special applications namely ice-breaking, dredging or drilling, with less than 5 units delivered per year, on average. However, from mid-90's onwards the growth rate of electric propulsion is more than duplicated.

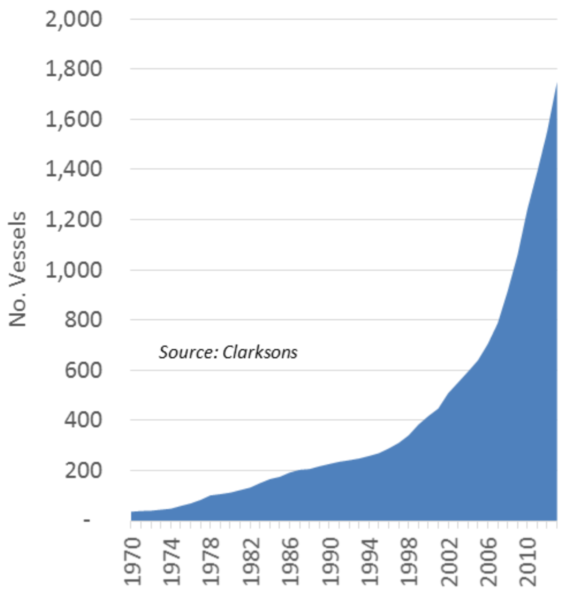

Figure 1 - Development of electric propulsion fleet

In 1995 the electric propulsion fleet was made of 269 units, with 11 units delivered that year. In 2013 the fleet accounted for 1750 units, with 199 units delivered that year alone (Figure 1 and Figure 2).

The exponential growth of the electric propulsion fleet from 1995 onwards was driven by a combination of the following three factors:

1. Technical developments
   1.1. Development of power electronics – the mass production of semi-conductors in the early 80's made possible the introduction of high power AC/AC converters which in turn led to the introduction of electrical propulsion without recurring to Controlled Pitch Propellers (CPP).
   1.2. Introduction of electrical podded propulsion – The maneuverability and ice breaking capability offered by electrical podded propulsion favored the selection of electrical propulsion on those vessels where these characteristics are highly valued, i.e. cruise vessels and icebreakers.
2. Offshore exploration - The growth of the oil offshore exploration drove the demand for vessels that benefit significantly from electrical propulsion.
3. Oil price – the increase of the oil price led shipowners to focus more and more on the fuel costs and therefore to seek energy efficient solutions.

In addition the above mentioned there are other ship type dependent factors that contributed for the penetration of electrical propulsion.

Offshore – A significant number of offshore activities require the vessels/units to keep their position with a considerable level of accuracy which led to development of Dynamic Positioning (DP). Since electric propulsion is the most suitable solution to cope with the power fluctuation and redundancy requirements from DP systems, the development of offshore segment was the biggest driver for the development of electrical propulsion, reaching more than 50% of the units in 2013.

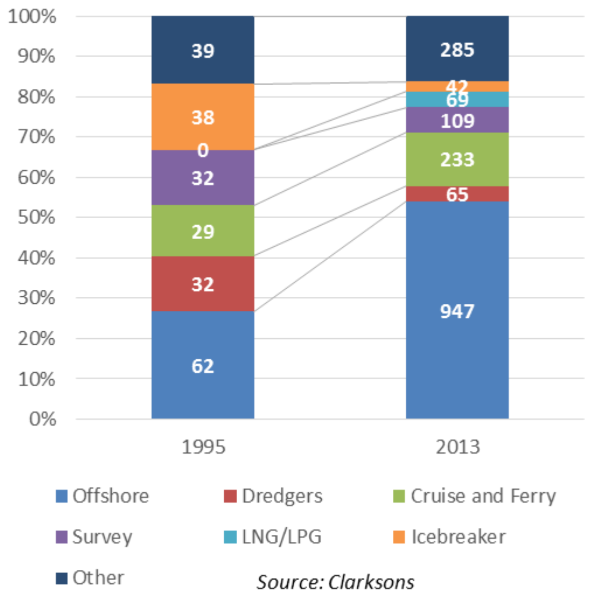

Figure 2 - Distribution of electrical propulsion fleet

Dredgers – Dredging equipment requires a considerable amount of power and consequently the auxiliary power tends to be quite high, very often higher than the propulsion power. Therefore, the merit of electric propulsion is to reduce the overall installed power on board.

Cruise – The main driver for electrical propulsion is space saving and space optimization. By shifting into electrical propulsion it is possible to reduce the space occupied by main propulsion systems and above all to place the different equipment in a way that the spaces reserved for passengers are maximized in terms of volume and quality. Nevertheless, the redundancy levels offered by electrical propulsion and its ability to meet the regulations on this segment have also contributed significantly for the adoption of this technology.

Survey vessels – These vessels are often used to tow underwater survey devices for different applications, e.g. hydrographic, seismic, etc. Therefore, the lower underwater noise offered by electrical propulsion is very attractive. In addition, the load requirements of the different operation modes can vary significantly which also favor electric propulsion.

LNG carriers – When laden, LNG carriers use their own cargo as fuel which is released by the cargo containment system in a process known as boil-off. Therefore, the propulsion system is selected so that the boil-off gas can be used as fuel. Initially, most vessels were fitted with steam turbines connected to the propulsion shaft through a gearbox. However, the introduction of dual fuel engines led to the adoption of electric propulsion (Hansen et al. 2007).

Icebreakers – Although traditional icebreakers use their own weight to break sheets of ice, it is quite often to have blocks of ice reaching the propellers. This causes a sudden drop of the propeller speed and consequently a sudden increase of torque which could easily stall the propulsion engine with mechanical drive. Electrical drives are able to vary the speed and the torque independently and therefore maintain the torque within the engine's acceptable limits (Ådnanes, 2003).

2 FUTURE TRENDS

The growth of the electrical propulsion fleet led some of the major electric power companies to develop new solutions that further improve the performance of electrical propulsion. Examples are the distribution in DC and hybrid systems with batteries.

2.1 *DC Distribution*

ABB Corporation has recently introduced DC distribution for marine applications branded as "DC Grid". The rationale behind DC distribution is to take advantage of the fact that in many applications the power demand is much lower than the total installed power. On the other hand, internal combustion engines when used as generators to produce electricity in AC are required to run at constant speed so that the frequency of the current remains constant. The implication of the fixed speed requirement is that low load operation is quite inefficient. This is illustrated on Figure 3 where the specific fuel oil consumption (SFOC) is considerably lower at low load if the engine is allowed to vary the speed to match the most efficient operation point.

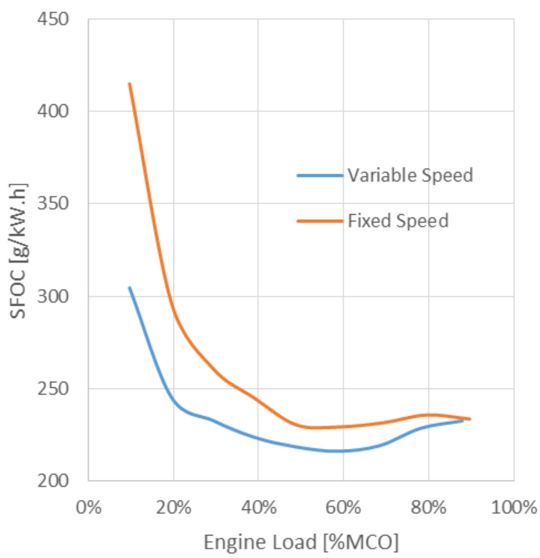

Figure 3 – SFOC of fixed vs variable speed engine

The fuel consumption of vessels with an operation profile where low load operation is common can be reduced significantly. For example, a Platform Supply Vessel (PSV) spends about 35% of the time in DP operations, 25% steaming, 15% in standby and 25% in port. With such operation profile, the fuel savings form DC distribution compared with a traditional AC system are about 13%. This is mainly achieved from the savings on DP operations, where all the generators are required to be online in order to meet the redundancy requirements, and therefore operating at low load - about 30%.

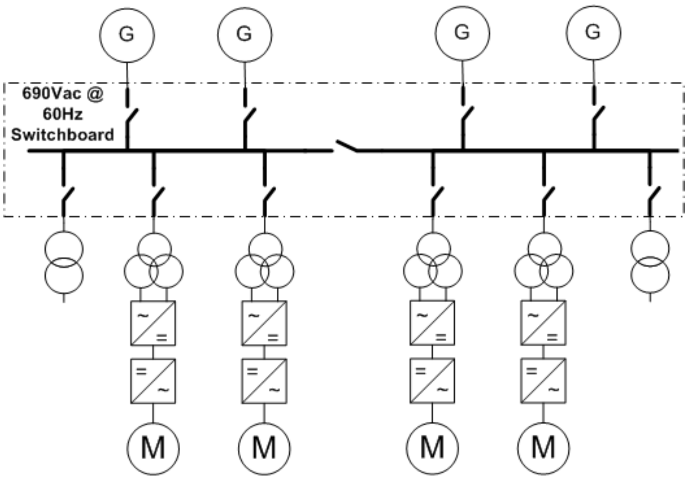

Figure 4 - Traditional AC system's single line diagram

The biggest challenge of distributing electricity in DC has always been the protection against short circuits and the ability to recover from black-outs within a short period of time. In conventional AC systems, circuit breakers are much more effective since the voltage reaches zero every half-cycle which is not the case with DC as the voltage is constant. This limitation of the traditional protection systems was overcome by ABB by developing a protection system that combines isolators with thyristor rectifiers.

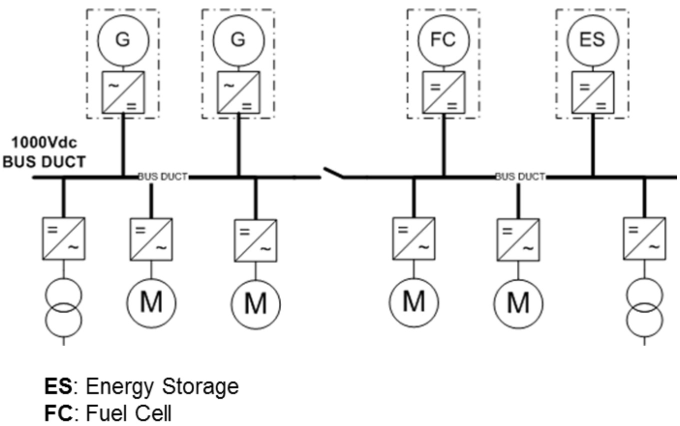

Figure 5 – ABB's DC Grid single line diagram

On DC Grid, the current is generated in AC and then rectified into DC. This avoids the need of synchronization of the different generators and therefore a "main switch board" is no longer required. The current is distributed between the generators and consumers on DC at 1000 V. Propulsion motors and big consumers are equipped with a converter, whereas small consumers are connected to the grid through an island converter. Consequently, motors and other consumers remain standard AC components (Figure 5).

The first vessel fitted with DC Grid is the PSV "Dina Star" built in 2013 by Kleven Maritime, Norway to the Norwegian based owner Myklebusthaug Management (Figure 6).

Figure 6 - PSV "Dina Star" equiped with DC electric propulsion

2.2 *Energy Storage*

Currently there are two energy storage technologies suitable for marine propulsion applications: batteries and super-capacitors.

Batteries are suitable for short and medium time applications with high power and energy demand. Typically, Li-Ion batteries have an energy density of 100 W.h/kg and power density of 750 W/kg. Super-capacitors are suitable for repetitive charge and discharge cycles, with abrupt power variations high power demand and very short time (<1 min). The typical energy density of a super-capacitor is 4 W.h/kg and the power density 7 kW/kg.

Batteries can be used as the main source of power or as a part of a hybrid solution.

2.2.1 *Batteries as main power source*

In some applications batteries can be used as a main source of power for a short period (up to a couple of hours). These are typical inland or coastal passenger vessels that operate short legs and can charge the batteries whilst alongside using shore power. The economic rational of this type of battery application is the lower cost of shore electricity when compared with the cost of generating on board. Although the equipment cost is considerably higher than of a traditional propulsion system, especially because batteries have a limited life, today's solutions allow for a payback period of less than 5 years.

The German-Danish ferry operator Scandlines has recently retrofitted the double-ended ferry M/V Deutschland (Figure 7) with an array of batteries from Corvus Energy. The system has a total energy capacity 2.7 MW.h which is enough for the 45 min route between Puttgarden and Rødby. The batteries are charged at each end over a period of 30 min.

Figure 7 - M/V Deutschland recently retroffited with batteries as main power source

2.2.2 *Hybrid systems*

Batteries can also be combined with a conventional electric propulsion system which is normally referred as hybrid propulsion. As before, the main advantage of a hybrid system is the reduction of the fuel consumption. In addition, batteries also offer increased levels of redundancy which might significantly improve the reliability and availability of the asset.

The fuel savings of a hybrid system are achieved through: **peak shaving** and **spinning reserve**.

Peak-shaving

The concept of peak-shaving is related to the ability of storing the energy that is produced in excess due to load variations and to use it later when the demand is higher than supply. In an electric propulsion system it is possible to stop a propulsion motor within milliseconds whilst the prime movers take considerably more time to reduce power to zero. Normally, the correspondent excess of current is converted into heat through a breaking resistor.

The benefit of peak-shaving depends on the operational profile and type of vessel. DP operations are a typical example of an operation with considerable load fluctuation where the load of a generator can easily vary between 20%-80% for a specific weather condition. Consequently, DP operations would benefit from peak-shaving using energy storage.

However, there are many other operations where the frequency and extent of load variations is less obvious and therefore underestimated. For example, the additional fuel consumption driven by load oscillation induced by heavy weather – both due to added wave resistance, rudder use added resistance and fluctuation of propeller immersion – has the potential to be mitigated through peak-shaving.

Another application of the peak-shaving concept is to reduce the low load operation of the diesel (or gas) engines. Internal combustion engines have a high specific fuel consumption at low load. It is possible to avoid low load operation by storing the excess energy in batteries for later use. For example, a passenger ferry with electric propulsion requires less than 10% of installed power when in port. Typically, these vessels have 4 generators for both propulsion and hotel load, meaning that when in port one generator would run at about 30% load or less. By increasing the load of on generator form to about 70% load, and store the excess energy for later use, it is possible to reduce fuel consumption in about 20%.

Spinning reserve

Many operations require some level of redundancy, either to increase safety or in order to maximize the operation efficiency. For example, passenger vessels are required to have always 50% of the total propulsion power available. However, this might correspond to much more power than the required for a specific leg.

For example, M/V Viking Grace operates a ferry service between Turku in Finland and Stockholm in Sweden. The passage through the Stockholm archipelago requires much less power than the total installed due to speed limitations. Still, safety regulations requires at least two generators running even though one would be enough for a significant extent of the passage (Figure 8).

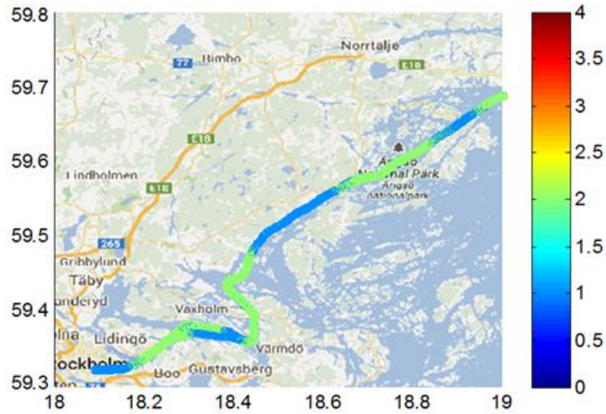

Figure 8 - Number of generators running in normal operation

By using batteries it is possible to shut down one generator and improve significantly the fuel consumption (Figure 9).

Figure 9 - Number of generators running with batteries as spinning reserve

By using batteries as spinning reserve the power is made available almost instantaneously. On the other hand internal combustion engines require a significant amount of time to accelerate to maximum power (Figure 10). Therefore, batteries can also be used to ensure that the propulsion power is made available when required, without compromising the stability of the prime movers.

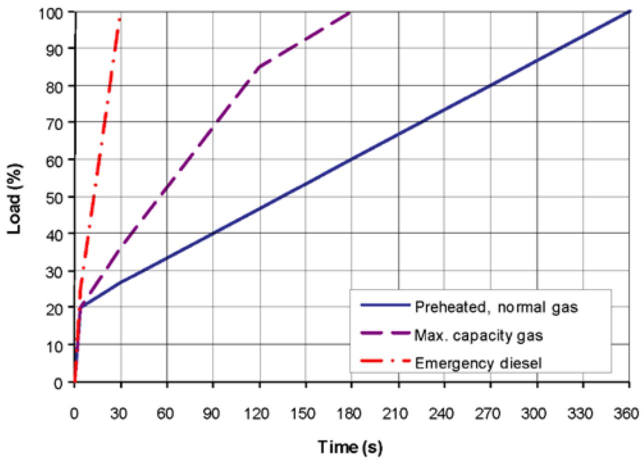

Figure 10 - Maximum load increase rate for engines operating at nominal speed

3 IMPLICATIONS TO SHIP DESIGN

The penetration of electric propulsion over the last 20 years within the different segments and into new segments suggests that the selection of the propulsion type is less and less obvious. Ship designers are often faced with the task of evaluate or validate different propulsion options. In the past this was a much simpler task then today, mainly because there are much more technical options but above all because the importance of fuel consumption has never been so high.

As usual in ship design the *mission* plays the key role and is the starting point for the design process. Any comparison between different propulsion types must take into consideration the total cost of ownership, e.g. cost of capital vs cost of operation. However, different propulsion types might result in different ships with different ability to comply with the ship's mission.

In order to choose the propulsion type designers should take the following into consideration:

3.1 *Cost of space (volume)*

In certain segments the volume dedicated for machinery comes at a very high cost. On a cruise vessel, for example, the revenue is proportional to the number of passengers and therefore the less the volume used by machinery the highest the volume dedicated for passengers, both in terms of beds and in terms of recreational areas. This is not only related to the absolute volume occupied by machinery but also related to the 'quality' of the volume, i.e. spaces above the water line come at a very high price. Consequently, cruise vessels adopted electric propulsion initially in order to optimize the machinery spaces by using a bigger number of smaller engines.

There are other types of vessels with considerable sensitivity to the volume used by machinery. PSV are another example. In this respect it is also important to distinguish between the different types of electric propulsion: AC and DC. DC distribution is potentially more flexible in terms of positioning the different equipment and in some cases has a lower volume footprint, e.g. propulsion transformers are eliminated on ABB's DC Grid solution.

3.2 *Propulsion power vs installed power*

Certain types of vessels require considerable amounts of electrical power. The following segments are examples of this characteristic. However, not all of these segments have a high penetration of electric propulsion. Probably a combination of higher initial cost with resistance to change.

- *Bunker tankers* – often the cargo pumps have the same power has the required for propulsion. On the other hand the business model of these vessels is based on the maximization of the cargo delivered and therefore pays off to have high capacity pumps and in some cases to operate more than one pump at time.
- *Deep sea fishing vessels* – the amount of power required to operate fishing gear, process, deep freeze, and maintain the cargo at frozen temperature is normally higher than the power required for propulsion.
- *Cruise* – cruise vessels always require a significant amount of electric power for hotel load. This is also the case of ferries and river cruises.

- *Dredgers* – the equipment installed onboard dredgers requires large amounts of power.
- *Drilling units* – combination of high hotel load and high power demand to run heavy machinery.

3.3 *Load profile*

The load profile of the vessel is key to select the propulsion type. Typically, electric propulsion offers higher flexibility towards running a different loads. Vessels with conventional mechanical propulsion are normally more efficient when running at constant power. However, whenever the power demand changes considerably and with relative frequency, electric propulsion tends to be more efficient. However, it is difficult to justify the replacement of a slow two stroke engine with medium speed four stroke generators simply based on the load profile. Despite the flexibility of electrical propulsion, the SFOC of two stroke engines is considerably lower than four stroke engines.

Examples of vessels that benefit from the increased flexibility offered by electric propulsion are:

- *DP operated* – as discussed before DP operations imply a wide power variation.
- *Ferries* - that operate at different speeds
- *Escort and anchor handling tugs* – the load varies considerably when towing.

It is worthwhile to remind us that the power demand varies with speed, draft, trim, weather, use of lifting devices (rudder and stabilizers), fouling, hull and propeller cleaning. Therefore, it is paramount to evaluate the operational profile of the vessels with the biggest possible accuracy.

Another important aspect of the load profile is the time at sea. Some vessels spend most of the time at sea, like bulk carriers, crude tanker or ultra large container carriers. Whereas other types of vessels spend a considerable amount of time loading and discharging, like a container feeder, a bunker tanker or a car ferry. Vessels that spend most of their time at sea are more sensitive to fuel efficiency whereas those that spend most time in cargo operations tend to be more sensitive to cargo operations' efficiency and reliability. The choice of the propulsion type needs also to take this aspect into considerations.

3.4 *Maneuverability*

Those vessels that require high levels of maneuverability tend to be equipped with azimuth thrusters which tend to be electrical above certain power levels.

With electric propulsion it is possible to precisely control the propeller speed and applied torque, and therefore Controllable Pitch Propellers (CPP) are not required, which in turn improves the propeller efficiency. In addition, hybrid electric systems (with batteries) allow for instant power availability which in turn improves the maneuverability and control of the vessel. Therefore, electrical propulsion is worthwhile to be considered on vessels that require high levels of maneuverability.

3.5 *Redundancy*

Some operations require high redundancy levels which is an inherent characteristic of electric propulsion. Most systems allow for full operation with a failure on one or more generators. The introduction of energy storage opens up new possibilities to design propulsion systems.

3.6 *Fuel type*

Electric propulsion is an enabler of gas as marine fuel. Dual fuel engines can be connected to the propeller shaft through a gearbox. However, when operating in gas mode, dual fuel engines are quite sensitive to load variations and will automatically shift to diesel to avoid shut down should the load changes too fast. Therefore, electric propulsion should be considered should the load profile requires sudden and frequent variations.

LNG carriers are an example of electric propulsion driven by the fuel type. The need to burn gas as fuel led to the introduction of dual fuel engines. Typically these vessels are equipped with four generators. In this case electric propulsion is much more efficient than if the four engines would have been connected to the shaft line trough gearboxes.

3.7 *Other*

Other requirements that might led to the choice of electric propulsion are:

- *Ice breaking*– ice breaking vessels have their propellers hit by blocks of ice which often cause a sudden reduction of propeller speed and consequently an increase of torque. Electric propulsion can control the speed and torque individually and therefore avoid the engines to stall, which would be the case should a mechanical driven propeller is suddenly stopped by a block of ice.
- *Logs* – river tugs that operate in waters with high density of debris would benefit from electric propulsion due to the same reason is icebreaking vessels.
- *Underwater noise* – operations that require low level underwater noise will benefit from electrical propulsion. Not only because the underwater noise is reduced but above all because it is possible to reduce

control the noise signature by adding noise filters.

- *Battery driven* – some operations can benefit from fully battery driven propulsion, either due to lower shore power cost but also due to zero emissions.

4 CONCLUSIONS

Electric propulsion has experienced an impressive growth over the last decade. The growth of offshore exploration was one of the drivers for such development but the advances on power electronics and increased sensitivity of fuel costs have also contributed significantly to the widening of electrical propulsion systems into new segments.

In addition to the above, new technologies are now emerging from the drawing board that promise further benefits from electrical propulsion. These are DC distribution and energy storage.

Distribution in DC allows for the operation of internal combustion engines as generators at variable speed. The fuel efficiency can be dramatically improved specially on vessels with a wide and frequent load variation.

The use of batteries can further improve the fuel efficiency both as main source of energy or when combined with other sources of electricity in a hybrid arrangement.

The life of ship designers has not been made easier. The choice of propulsion type is less obvious than ever. This paper also presents a review of factors that need to be taken into consideration by designers when benchmarking electric propulsion with mechanical propulsion for different types of applications.

5 REFERENCES

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