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ELECTRO-TECHNOLOGIES FOR ENERGY EFFICIENCY IMPROVEMENT AND LOW CARBON EMISSION IN MARITIME TRANSPORT

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Abstract. The global share of greenhouse gas (GHG) emissions from ships is on the rise which will become a significant portion leading to climate changes and other environmental issues unless reduction measures are taken. Therefore, the International Maritime Origination (IMO) and other regulatory bodies have set limits for emissions and defined emission controlled areas. As a result, alternative fuel such as Hydrogen and liquefied natural gas (LNG) that are low in greenhouse gas emission and competitive in cost are gradually being entered into the shipping industry. However, these alternative fuel technologies are still in the developing stage and the necessary infrastructure is not fully developed yet. Therefore, it is reasonable to assume that majority of the ships continue to burn fossil fuel for the foreseeable future.

A promising and viable solution for reducing the emissions is to reduce the fuel consumption through efficiency improvement. In this context, electro-technologies are shown to be capable of playing a vital role in improving fuel efficiency and thereby reducing emissions. The aim of this paper is to present a review on recent advancements of electro-technologies that help improve fuel efficiency of ships. A hybrid electric ship propulsion system is discussed as an example to show the potential of electro-technologies in improving the fuel efficiency.

Key words: electric ship propulsion, emissions, fuel efficiency improvement, high voltage shipboard power systems, hybrid ship propulsion, renewable energy sources

1 INTRODUCTION

Shipping is considered as the backbone of the global economy and it accounts for more than 90% of the goods transported locally as well as internationally [1]. With the steady growth of the shipping industry, more and more fossil fuel is burnt every year and as a result, the fuel price shows a long term increase. This, in turn, increases the operating cost of shipping. On the other hand, obnoxious emissions from the burning of fossil fuel causes long term damage to the environment [2]. According to the recent GHG study conducted by the IMO, the global share of GHG emission of the shipping industry accounts for 2.8% carbon dioxide (CO_2) equivalent of the global GHG emission [3]. Even though this is a relatively small number, the long term damage that it can cause to the environment and resultant climate change will be significant, especially if appropriate countermeasures are not taken to control the emissions. Therefore, certain countries and regions have imposed strict regulations on carbon emission and defined emission control areas (ECAs) around the coast [4, 5]. Ships that come to the ports in these areas or sailing in these regions should take measures to meet emission criteria.

As the international regulatory body for maritime transportation, IMO has taken strong initiatives to set emission reduction and efficiency improvement requirement targets that encourage the entire shipping industry to act on emission reduction. Amongst these initiatives, the energy efficiency design index (EEDI) requirement stipulates that newly built ships should meet agreed efficiency targets and 20%, 25% and 30% efficiency improvements targets in 2020, 2025 and 2030 respectively. This requirement plays a vital role in achieving 50% carbon reduction by 2050 [1-6]. In order to achieve these efficiency targets, a substantial change is required in every aspect of shipping. In this context, electro-technologies play a leading role as the bulk of ship power requirements can be efficiently supplied in the form of electrical energy. Therefore, the trend in the contemporary maritime transport sector is moving away from the predominantly mechanical based systems to a greater utilization of electrical and electronic systems. Electric ship propulsion is a good example that demonstrates this trend where traditional mechanically coupled propulsion mechanisms are increasingly being overlooked in favor of fully-electric or hybrid-electric drive systems [5]. The major advantages of fully-electric or hybrid-electric propulsion technologies are the improved efficiency, resultant reduction of GHG emissions, control flexibility and superior performance compared to traditional propulsion systems. In addition to propulsion, there are number of other areas where electro-technologies can contribute to the efficiency improvement in shipboard power systems. Section 2 of this paper presents a few electro-technologies that are currently used in ships to reduce fuel consumption. In addition, a few other promising technologies that are currently in the development stage are also discussed in section 2. A typical hybrid-electric ship propulsion system is taken as an example in Section 3 to illustrate the potential of modern electro-technologies in improving fuel efficiency and thereby reducing GHG emissions in maritime transport.

2 PREVAILING ELECTRO-TECHNOLOGIES AND EMERGING TRENDS IN SHIPS

2.1 Alternative energy technologies

The use of alternative energy technologies to supply the shipboard power demand is gaining attention as a way of reducing GHG emissions in ships. Three such technologies that are feasible for ships are photovoltaic power systems, fuel cell power systems and thermoelectric energy recovery.

2.1.1 Photovoltaic (PV) power systems

In a clear day, one square meter area of the earth receives approximately 1kW of power from the direct sunlight [7]. This power can be converted into electrical form with the use of PV cells. This is a mature renewable energy technology widely used in land based power systems, accounting for more than 200GW worldwide [8]. At sea, ships receive sunlight without any obstacles or shading from the surrounding and therefore, an ideal place for erecting solar panels. However, as the amount of power that can be captured from sunlight depends on the available surface area there is a limitation on the amount of PV power generated in ships. Despite this space limitation PV power systems are becoming popular in cruise ships as a green energy source that supplies electricity to the ships' shopping districts [9]. In another implementation, PV panels are erected vertically which increases the effective surface area [10]. In these applications the power captured from solar panels are used to offset the power from fossil fuel and thereby reduce fuel consumption. Studies have shown that PV technologies have the potential to contribute up to 3% improvement of the fuel efficiency in ships [11, 12].

2.1.2 Fuel Cells

In fuel cells, Hydrogen and Oxygen act as fuel which are combined inside a special membrane. The electrochemical reaction between Hydrogen and Oxygen produces electricity and H_2O (water). Since the by product is water, this technology does not emit any obnoxious gasses. Apart from that, large scale production of Hydrogen and Oxygen is economically feasible. Therefore, the use of Hydrogen as an alternative fuel is considered as a promising solution [2]. However, safe and efficient hydrogen storage technologies are still at the development stage and therefore, large scale deployment of fuel cell power systems in ships are yet to come. Apart from that, response of fuel cells for changing power demands is slow and therefore they are more suitable to use as an auxiliary power source in ships for supplying slow changing loads [13]. Recently, the ship "Viking Lady" has been equipped with a Fuel cell system as a pilot project [14].

2.1.3 Thermoelectric energy recovery

Ships generate large amount of waste heat which is partly recovered as thermal energy through waste heat recovery systems. The conversion of waste heat into electricity is an alternative that can help further improve the fuel efficiency [11, 12]. Nevertheless, the conversion of waste heat into electrical energy is still at the development stage mainly due to the high cost, low efficiency (≈15%) and low voltage levels of the thermoelectric cells that are used to convert heat into electricity. In addition to the low voltage, the output voltage varies with the temperature and thus power electronic converters are required to interface thermoelectric modules into the power grid. New thermoelectric materials and high efficiency power electronic converter technologies are currently being researched to make thermoelectric generation efficient and cost competitive with the other technologies.

2.2 Energy storage

Energy storage has been identified as a key technology that can improve engine efficiency. For example, pulse loads or large power demands that last for short periods can effectively be supplied with energy storage elements such as batteries or supercapacitors without running the motor into non-optimal conditions. Recently, a vast amount of research has been carried out on the efficient use of energy storage technologies in ships. This growing interest and relevant technology development have made energy storage an essential part in future ships.

Lead acid is the most common, widely available and relatively cheap battery technology used in ships. Nevertheless, their efficiency and cycle life are low compared to the alternative battery technologies such as Lithium-ion, molten-salt and flow batteries. Out of these technologies, Lithium-ion batteries have the highest efficiency and cycle-life. Therefore, they have become the number one choice in consumer electronic and automobile industries. However, the cost of Lithium-ion batteries are still at the high side and therefore not a very popular choice for large scale shipboard applications. Flow battery technologies such as Zinc-Bromide, Vanadium- Redox and Iron-Chromium and molten-salt battery technologies such as Sodium-Sulfur and Sodium-Nickel are moderate in cost, efficiency and cycle-life. Therefore, these technologies are gaining attention as suitable energy storage technologies for ships.

2.3 Variable speed drives

Pumps and fans are widely used in ships which accounts for a reasonable share of shipboard electrical loads. The traditional approach is to connect the motors directly to the AC supply and run them closer to the synchronous sped. However, the required flow rate might be lower at certain conditions and therefore running closer to the synchronous speed is inefficient. In such cases variable speed operation can effectively reduce the power consumption. In order to realize variable speed operation frequency converters are used which is generally in the form of AC-DC-AC power conversion stages. In the past, diode and thyristor based power converters were used to build these converters. Nowadays, insulated gate bi-polar transistors (IGBTs) have become the popular choice to build frequency converters due to their high frequency switching and high power handling capabilities. In addition, advanced control technologies such as model predictive control and adaptive control are actively being researched to improve the performance of variable speed drives in steady state and transient conditions. Owing to these technological advancements and efficiency improvements, variable speed drives have become the industry norm for pumps and fans.

2.4 Electric propulsion

In simple terms, electric propulsion refers to the generation of propeller torque by means of an electric motor. In fully electric propulsion systems, motor is the only unit that generates the torque. In hybrid electric propulsion systems, an engine generates major portion of this torque and the motor assists it. Electrical power required for spinning the motor comes from a prime mover driven single generator or set of generators. The prime mover can be either a diesel engines or a gas turbine. When the power is transmitted in the electrical forms, the placement of generators and engines become flexible, whereas in traditional mechanical transmission based systems, engine is required to be placed at a particular location. Apart from that, the motor can be placed very close to the propeller so that mechanical transmission and associated problems such as tear, wear and fatigue can be minimized. This has been further extended in pod propulsion systems by putting the motor into a pod outside the ship and attaching the propeller directly into the rotor. This gives the flexibility to turn the entire pod and thereby change the direction of the thrust. This enables rudderless maneuvering. Since the response of electrical systems are faster than mechanical systems, ship maneuvering has become easier with electric propulsion.

Compared to the traditional mechanical driven propulsion system where a specific large engine has to be coupled to the propeller, in electrical propulsion systems, a number of small generators can be connected into the common electrical power bus and run them efficiently based on the power demand [15]. An extension of this technology is the integrated shipboard power system where the same set of generators are used to power the hotel loads as well [15, 16]. This enables engines to be used in an optimal manner based on the operating profile. Therefore, from the overall system point of view, introduction of electric propulsion and integrated power systems help improve fuel efficiency and control flexibility.

2.5 High voltage shipboard power systems

In the last few decades there has been a global trend to build a few number of bigger ships than building large number of small ships. This trend seems to be continuing in the future as well. Consequently, the power requirement of the ships also increases with the size. This in turn requires bigger power cables to transmit more current to the loads increasing the cost of the conductors and power loss within the conductors. The promising solution to reduce conductor size and power losses is increase of the system voltage. As a result, modern ships come with high voltages systems such as 11 kV and 6.6 kV compared to the traditional 690 V low voltage distribution systems. Power converters used to drive propellers and other motor loads such as tunnel thrusters should either be capable of operating at these high voltage levels or should use locally installed step down transformers. The latter is the most common approach while the former is currently being in the research, development and testing stages. The move from low voltage to high voltage in shipboard power systems is capable of reducing power losses and thereby improve the fuel efficiency. Nevertheless, it comes with certain challenges that have to be addressed with suitable supporting technologies such as high voltage power converters, high voltage motors, advanced control techniques protection mechanisms, and appropriate power system architecture [15].

In addition to the above mentioned applications and scenarios, dynamic positioning, slow speed maneuvering, and supplying pulse loads such as radar are other areas, where more electric technologies can make a significant contribution in terms of energy efficiency.

3 ENERGY EFFICIENCY IMPROVEMENTS IN HYBRID ELECTRIC SHIP PROPULSION

In hybrid electric propulsion systems, diesel engine is the main source of power for the propeller while the electric motor supports the main engine to drive the propeller especially at maneuvering or during peak power demand. This can effectively reduce the peak power requirement of the engine and thereby reduce the overall size of the engine. This assistance from the motor is known as power take-in (PTI). Similarly, it is possible to take some of the main engine power out through a shaft generator so that electrical loads in the ship can be supplied from the main engine. This is re-

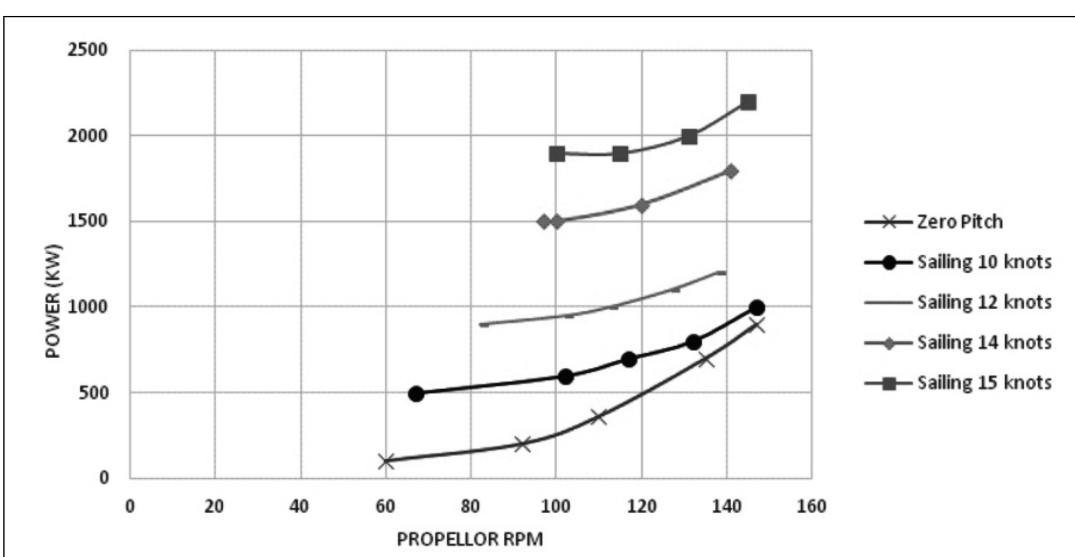

Figure 1
Propeller shaft input power requirement as a function of the propeller speed [16]

ferred to as power take-out (PTO). The shaft generator and the motor can be the same machine, where in the PTI mode generators coupled to the auxiliary engines provide electrical power to the machine to operate as a motor. In the PTO mode, power is taken out from the main engine and fed to the electrical system. In this situation, auxiliary engines can be turned off if the main engine is capable of supplying the propulsion load as well as the other electrical loads of the ship.

In traditional hybrid systems, the shaft generator is coupled to the main engine through a gear box and the output of the generator is directly connected to the power bus. Since the power bus requires a constant voltage at constant frequency, the engine runs at a constant speed. In order to get required thrust to propel the ship and maintain the ship speed, the pitch angle of the propeller blades are varied. When the ship is not moving, pitch angle is set to zero which results in zero thrust on the propeller. However, as shown in Figure 1, spinning a zero pitched propeller at a constant speed requires certain amount of power that increases rapidly with the increase of the required speed. This power is lost at the propeller without doing any useful work and thus reduces the overall efficiency. For example, if the required engine speed is 145 rpm, then the power loss, is about 900 kW. This power loss can be reduced if the engine speed can be reduced, e.g. 90 rpm where the loss is only 200 kW.

This variable speed operation can be realized by placing a frequency converter between the shaft generator and the power grid. This can effectively reduce the power loss by 700 kW and thereby reduce the fuel consumption and GHG emissions.

4 CONCLUSIONS

The rise of the fossil fuel price and emissions are the major motivations for exploring alternative fuel and fuel efficiency improvement technologies in maritime industry. PV power systems, fuel cells and thermo-electric generation are considered as promising alternative energy technologies that can help reduce greenhouse gas emissions. These emerging technologies heavily depend on development of associated electro-technologies. Apart from that, through efficiency improvement, by means of electrical technologies, fuel consumption can be reduced. Electric and hybrid electric propulsion technologies are found to be more efficient and flexible compared to traditional mechanical power transmission systems. With an example of a hybrid electric propulsion system, this paper has shown that power losses can be greatly reduced with the appropriate use of modern electro-technologies. Therefore, in conclusion, it can be envisaged that electro-technologies will play a significant role in fuel efficiency improvement and greenhouse gas emission reduction in future ships.

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