



Overview of Electric Ship Propulsion and Fuel Consumption*

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1. Introduction

In this paper, the electric propulsion has been discussed and evaluated from various viewpoints, for example, fuel saving effect, decreasing sound noise for crew and passenger, optimizing engine room space for making cargo space bigger, improving redundancy of navigation, reducing maintenance work, and suppressing initial cost. After dual fuel engine was developed for 2 cycle marine diesel engine, the electric propulsion has gone to second position or less because of fuel economy and initial cost, especially for merchant cargo ship. On the other hand, it is inevitable system for large cruise liner due to low vibration, low noise, high redundancy, and large hotel load. Recently, autonomous navigation technology has become attractive themes for not only car industry but also marine sector. A part of engineers believe that the electric propulsion system is necessary to realize it. However, it is hard to find reasonable discussions why the electric propulsion is in main stream of the autonomous vessel. Many topics to be discussed has appeared and disappeared in our marine sector.

Before talking about new approaches for clean future of marine industry and the environment, it is effective to make sure that what we can expect for the electric propulsion system, and what have to be done, although we need to know not only energy saving but also recycling problem of lithium ion battery, child labor problem of mining company of cobalt if we think the battery propulsion ship.

In order to focus only technical terms, however, this paper discuss the energy saving effect of the electric propulsion system for large vessel so that we know how to design the future better. Small boats are not in main theme in this paper.

The electric propulsion system provides shaft horse power (SHP) by using electric motor for driving main thruster including FPP, CPP, and pump jet. In general, the electric propulsion system is classified to diesel electric system using diesel gensets, battery propulsion system using secondary lithium ion battery, and hybrid propulsion system which consist of the diesel engine and the electric motor. Some candidates for energy carriers of the hybrid electric propulsion system are main diesel engine, diesel gensets, secondary battery, fuel cell, and auxiliary generators taking power from exhaust gas thermal energy. There are a few cases that combination of solar cell and secondary battery interconnects to AC line system which is provided by gensets⁽¹⁾. However, such multi energy source AC grid system is out of scope in this paper because its system is not for the propulsion.

2. Power system architecture for electric propulsion

2.1 AC power system

Figure 1 shows representative samples of the electric propulsion system which uses AC power system or AC switchboard. The system a) to c) has DC link between power electric converters. However, these are sorted to AC bus system because the load which means inverter has only one power source which means rectifier in DC link.

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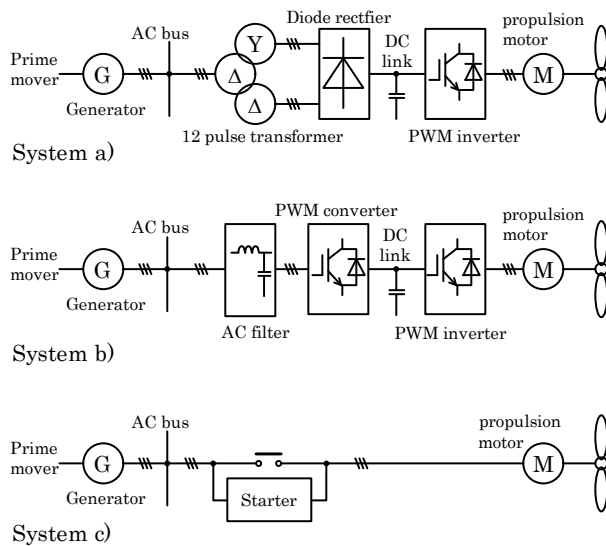


Fig.1 Electric propulsion system with AC switchboard.

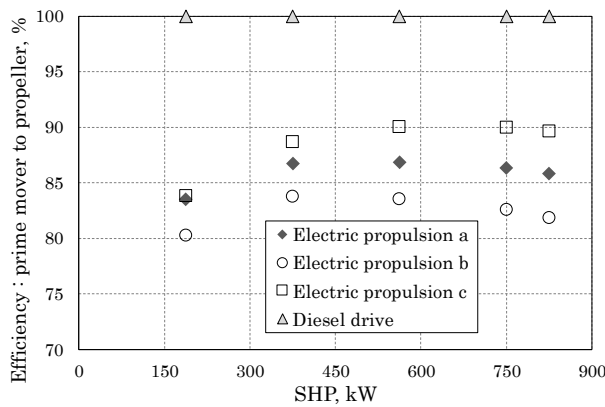


Fig.2 Estimated results of total efficiency from prime mover to propeller shaft as diesel drive system's efficiency

The system a) consists of the electric propulsion motor, PWM inverter, diode rectifier, and 12-pulse transformer ⁽²⁾. It is often seen that 24-pulse transformer is used for suppressing THD in large cruise liner. The system b) has higher performance to suppress THD than system a) because PWM rectifier is equipped for PFC (power factor correction) operation ⁽³⁾. The systems of a) and b) can use not only CPP but also FPP, because shaft speed control is available by using power electronics converters. It is required to install a break resistor in DC connection point between the rectifier and the inverter for protecting inverter from back power in system a). System b) also can have a break resistor. On the other hand, if onboard electric load is big enough in this system, it has another option to convert the back power to AC power grid. These

systems can use PM (permanent magnetic) synchronous motor instead of induction motor. In generally, PM motor has good efficiency characteristics in wide range from low load to high speed torque condition compared to the induction type one. Additionally, PM motor is smaller than bulky induction type one. It utilizes permanent magnet to provide high intensity magnetic flux as field system of synchronous motor. Therefore, it is necessary to pay attention for high intensity magnetic flux when it needs to be opened for periodical maintenance.

The system c) is most simple configuration, just uses a starter circuit to start the induction motors. It can drive only CPP because the speed of electric motor cannot be changed for controlling SHP.

2.2 Energy conversion loss in AC system

It is difficult to compare and to discuss the energy conversion loss in the propulsion systems shown in Figure.1 because each system tends to be applied to different power scale plant. For example, system a) is often used for large scale propulsion system like LNG carrier, large cruise liner, and ice-class cargo vessel. On the other hand, system c) is seemed to be used for middle to small cargo ship and research vessel less than several 1000 ton because it's difficult to install the panel of electric converters in the limited machinery space. In this paper, however, it is assumed that SHP is 750kW for comparing them in same condition. In addition, to make the discussion simple, this paper neglects the electric demand of onboard load and side thrusters, although it is necessary to consider both of them for clarifying the electric propulsion system. To evaluate the energy conversion efficiency and their power loss from the power source to the propeller, a simulation scheme which has been developed by author's group was utilized.

Figure 2 shows the efficiency comparing to the conventional diesel drive propulsion system. The power transmission efficiency from the prime mover to the propeller shaft in the conventional system is set to 100% conveniently. The system a) and b) uses FPP generally, system c) uses only CPP. Induction motor was applied to the main propulsion motor for driving propeller shaft in this simulation. PWM

converter and inverter consist of 4 units which use IGBT (1200V/600A) at switching frequency 4kHz. AC grid voltage is 440V. Its power factor is assumed to be constant 0.8 regardless of the electric load condition.

As generally said, power dissipation is inevitable when the energy is delivered in the electric propulsion system because there are several energy conversion processes from the prime mover to the propeller shaft. For example, in system b), generator, AC line filter, PWM converter, PWM inverter, and the induction motor dissipate energy to some extent respectively. The system c) can maintain high efficiency comparing to other system over middle SHP range due to less components in the propulsion system because it does not need to employ the electric power converters. However, when required SHP is low, advantage of system c) is decreased, because the efficiency of induction motor in system c) becomes lower than system a) and b). Power factor tends to be low in constant speed condition comparing to variable speed condition when the induction motor is operated in low load. Although AC line power factor is assumed to be constant in this simulation, it fluctuates depending on the load factor of the induction motor for propulsion in actual system c). Figure.3 shows a sample data of measured power factor in actual electric propulsion ship which has same topology as system c). The simulation does not have a function to estimate the generator's efficiency in low power factor condition. However, it is natural to think that copper loss and iron loss increase in generators in low power factor condition because reactive current becomes large. It will be additional factor to decrease total efficiency of system c) from the prime mover to the propeller shaft in low load condition.

The efficiency of system b) is lowest in whole SHP range. The reason that efficiency of system b) is low in low load condition is different from system c). In almost case, inverter and converter using IGBTs which are silicon power devices have such a feature due to IGBT's saturation characteristics. If permanent-magnetic motor is used as the propulsion motor instead of the induction motor, the efficiency of system a) and b) can be improved by 1-2%.

In this paper, as mentioned above, onboard electric

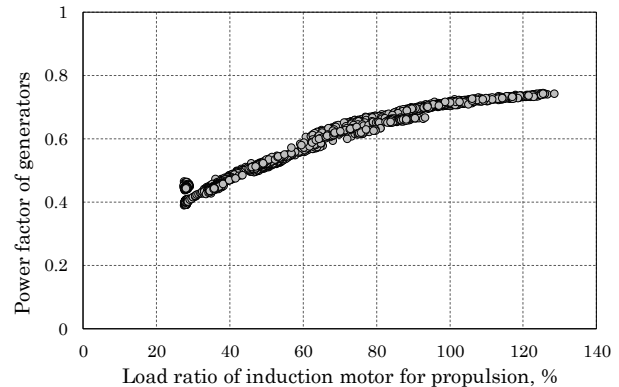


Fig.3 Sample of measured power factor to load ratio of propulsion motor measured by system c) in actual sea condition

load and side thruster's load are neglected. Generally speaking, the electric propulsion system can save fuel consumption by controlling the number of diesel-gensets depending on load condition. If the number of genset are controlled appropriately and its effect reach to 10~15%, the electric propulsion system can be good candidate from the view point of reducing FOC and CO₂ emission.

2.3 DC power system

DC power system has been attractive for vessels of marine research, marine resource investigation, and development because it is expected to reduce fuel consumption by controlling speed of diesel generators appropriately⁽⁴⁾. But in this paper, prime mover's thermal efficiency is not included. In addition, other DC voltage source like battery and capacitor can be connected as the power source and/or energy buffer⁽⁵⁾. Furthermore, DC power system has several power sources and/or several loads in parallel. To simplify the discussion, however, this paper assumes three types of the electric propulsion systems using DC power system or DC switchboard, which are shown in Fig.4. The induction motor is applied as the propulsion motor.

In system d), thyristor converter control DC bus voltage. In output side of generator, THD tends to be large when the load ratio is low. However, it does not affect any other electric machine because generator's load is only the thyristor converter.

System e) is similar topology as system b). It has DC bus to be connected to several DC power sources

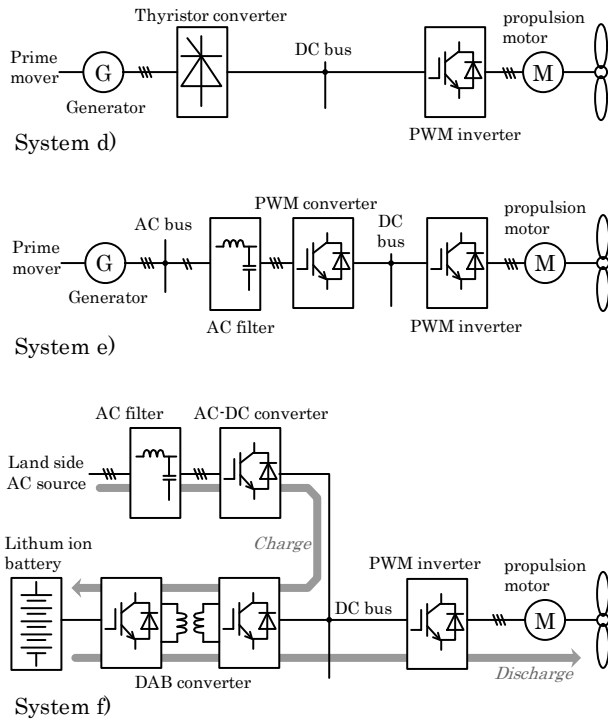


Fig.4 Electric propulsion system with DC bus

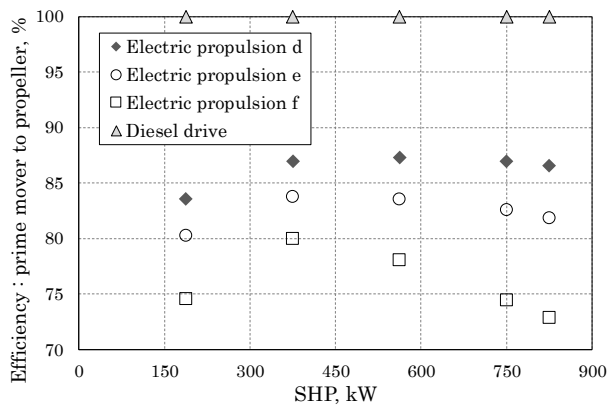


Fig.5 Estimated results of total efficiency from prime mover or AC line to propeller as diesel drive system's efficiency is 100%

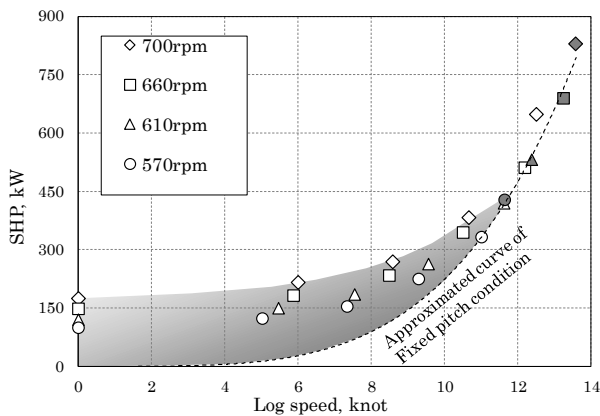


Fig.6 Sample measured data of SHP to log speed in ship equipped with CPP

and/or several PWM inverters as electric load ⁽⁶⁾.

System f) is often said as battery propulsion system which uses AC power source of land side for charging onboard battery ⁽⁷⁾. DAB converter is used to control charging and discharging current of the battery system. It has a high frequency transformer for insulation, which brings essential safety to the system when unexpected accident like short circuit occurs in DC bus.

To compare these systems from the view point of energy consumption, the simulation was implemented at the following condition that DC bus voltage was set to 690V. The land side AC was assumed to be 440V/60Hz.

In system d), it is often used variable speed diesel-gensets as mentioned before. Therefore, there is possibility to improve its total efficiency including the prime mover comparing to other systems. The total efficiency of system e) is same as system b) because the topology is same in this simulation. In system f), the energy flows through lots of devices. The electric power from land side AC line is delivered to the battery through AC line filter, PWM converter, and dual active bridge type DC-DC converter when the battery is charged. Then, the battery power is delivered to the propeller shaft as the mechanical power through DC-DC converter, PWM inverter, and the induction motor. Hence, its total efficiency from AC power source of land side to the propeller shaft becomes lower inevitably. Additionally, this simulation result does not include efficiency of lithium ion battery. The battery gets warm when the battery is charged and discharged because of internal impedance. In general, it is often said that charge/discharge efficiency of lithium ion battery is over 95%. But it is not 100% unfortunately. Thus, there is possibility that the total efficiency of system f) will get worse.

3. Propeller effect

In chapter 2, we have discussed the power transfer efficiency from the prime mover to the propeller shaft. Talking about the propulsion system, however, the efficiency of propeller should be taken into account ⁽⁸⁾⁽⁹⁾ because the propeller's efficiency is not so high compared to the load on the electric car powertrain.

Figure 6 is a sample of measured data which shows relation between SHP and log speed in actual sea condition. The propeller speed and pitch angle of CPP were changed as the parameters. CPP consumes certain energy even if the ship speed is zero unlike FPP. As is clear from the figure, power dissipation which is not converted to the thrust becomes over 100kW. As far as author's group investigated, around 15% of maximum SHP is wasted in low speed condition which shows hatched area in the figure. It can be said that the thrust force of CPP is controlled by changing its efficiency to zero. This is not small issue for the electric propulsion system because low speed condition is frequently used in the electric propulsion ship due to operations of dynamic positioning, marine investigation, and off-shore engineering. From these considerations, if the ship with electric propulsion system is used often in low load condition, it is a good way to save fuel that the propeller speed is controlled for controlling thrust force and ship speed.

4. Load fluctuation effect

Figure 7 shows a sample measured data of the propulsion motor power in system c) when the ship went rough sea condition (see Table 1). CPP was driven by the induction motor in almost constant speed around 592.6 rpm. The motor power is fluctuated largely because the motor torque is varied cyclic. Torque is affected by the depth of CPP from sea surface changing by the wave which the ship encountered. In this case, the motor power cannot be controlled because any power electric converters are not employed. Decreasing pitch angle dynamically for reducing propeller load, which is called as ALC (auto load controller), can shave the peak load to some extent. But it cannot be used for smoothing the motor load.

Total required power of diesel generators is also fluctuated (see Fig.8). When the load is changed rapidly and widely, turbo charger speed does not follow to the required level sufficiently. Inlet boost pressure cannot reach to appropriate level, then the engine speed comes down. For keeping the engine speed and frequency of generator to constant, amount of fuel injection is increased. As the result,

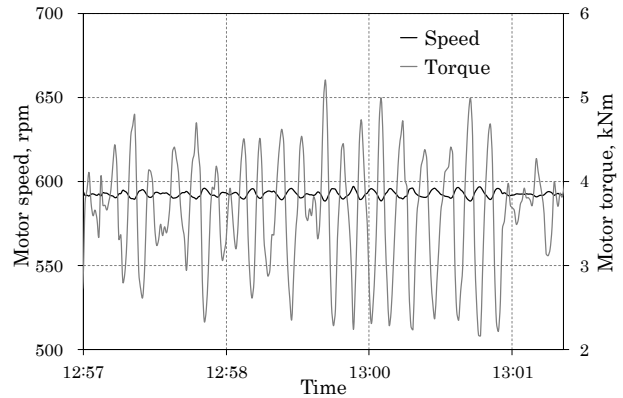


Fig.7 State of one propulsion motor driving CPP in rough sea condition.

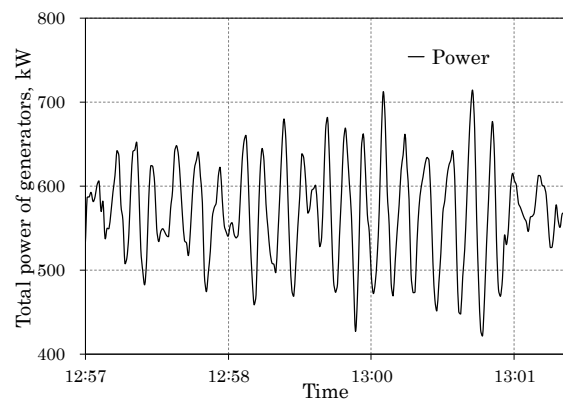


Fig.8 Total power of generators in rough sea condition

Table 1 Environment condition

Measured item		Value
Wind (relative)	Speed	15.0 m/s
	Direction	255 °
Wave (relative)	Height	6.0 m
	Cycle	17.5 sec
	Direction	249 °

Table 2 FOC at different sea condition

Sea condition	Measured FOC
Calm	160.6 L/h
Rough sea	193.0 L/h

the thermal efficiency of diesel engine gets worse and FOC is increased (see Table 2). It should be noted that this phenomenon occurs in engine room. Another consideration is required that the fluid resistance of hull will be increased in rough sea condition.

On the other hand, if the inverter is adopted to the electric propulsion system like system a), b), d), e),

and f), the power of propulsion motor can be controlled to be constant. Then, the load ratio of diesel generators is not affected by sea condition. Therefore, it is natural to think that the thermal efficiency of diesel engine comes close to ideal state which is like shop trial data provided in the finished drawing book. Consequently, the inverter driven electric propulsion systems may have a benefit to control fuel consumption comparing to CPP propulsion system, in frequently load fluctuating condition like going in rough sea.

5. Summary

When the propulsion system is discussed for saving fuel, it is necessary to consider not only electric devices but also the power source and the propeller. The thermal efficiency diesel engines are different in constant-speed / variable-torque operation and variable-speed / variable-torque operation, even if their rated power is same. From the view point of operating the propeller in high efficiency, speed of the propulsion motor should be controlled by the inverter. And also, it is better to employ the inverter for suppressing the load fluctuation of diesel generator in actual sea condition.

Total efficiency of battery propulsion system depends on the type of electric power plant. If the land side of AC power is supplied by only renewable energy source, it will be effective solution for reducing CO₂ emission from vessel and society. But if the energy source depends on fossil fuel, the society's overall CO₂ emission might be increase. The total efficiency of battery propulsion system including efficiency of electricity generating plant is not attractive comparing to other type of the electric propulsion. Of course, it is non-sense to utilize the nuclear power plant positively to supply the electric power to the battery propulsion system in narrow sight for reducing CO₂ emission.

In this paper, the induction motor is adopted as the propulsion motor in all system. However, if permanent-magnetic motor is used as the propulsion motor instead of the induction motor, the efficiency of systems a), b), d), e), and f) can be improved by 1-2%.

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