1. Introduction

Harbor tugboat has two middle-high speed and high power engines than general cargo vessel of similar size so that it pushes and pulls large vessels. Fig.1 shows a sample of real data which was measured a trend of a demanded output power while the tugboat is operated in one working cycle for about three hours. This data is classified to analyze the tugboat's operation into two situations. In service situation, the tugboat works to push or pull the large vessel under pilot order. Not in service situation shows the left of the working time including transit time between tug's base and the working spot and waiting time for starting service.

Fig.2 illustrates the demanded propulsion power and its frequency in use. As is clear from Fig.2, a wide range of propulsion power is required in service situation. On the other hand, in transit and waiting situation, a demanded propulsion power is not high but low power less than 20%. In other words, the duration time that tugboat's main engines are operated at low loaded condition is long in both situations.

Generally, the thermal efficiency of engine for ship is low in low loaded condition. Tugboat’s engine tends to be operated in low load and low efficiency for a long time. For this reason, it is effective to improve the thermal efficiency in low loaded condition. By focusing on this characteristic, several challenging projects have implemented to save fuel by employing hybrid propulsion system (1) - (3).

It is reported that an efficiency of propulsion system is improved by using large capacity rechargeable battery as one of power source and an energy buffer when the demanded power is low. However, an initial cost for ship building goes up in price since it is necessary to add several apparatuses which include battery, motor generators, electric power converters, and their controller for realizing the system. Thus, many of

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Fig. 1 Trend of demanded propulsion power in tugboat
projects received some sort of subsidy. On the other hand, authors have studied a hybrid propulsion system without using large battery for reducing cost \cite{4,5}. This hybrid system does not have any energy buffer to accumulate surplus energy and to cover power shortage for a short time. Therefore, controlling energy flow is important to make characteristics of the hybrid propulsion system effective. This paper describes management method of the energy flow in the hybrid propulsion system when the tug boat is not in service.

To clarify the relation between fuel saving effect and the energy flow, a simulation which authors have been developed is used \cite{6,7}. It consists of several efficiency estimation modules for variable speed engine, constant speed engine, gear box, slip clutch, alternator, electric motor, and electric converter. In the simulation, it can provide SFC (Specific Fuel Consumption) [g/kWh] of whole system including the propulsion system and electric system for not only engine direct drive system but also electric propulsion system and hybrid propulsion system. By using the developed simulation, several energy flows are evaluated from the view point of SFC.

2. Propulsion system and FOC simulation

2.1 Conventional system

Fig. 3 shows a line diagram of conventional propulsion system. In general, it has two middle speed and high power engines and two azimuth thrusters in order to push and pull large vessels. Each Main Engine (M/E-1,2) drives mechanically Azimuth Thruster Drives (ATD-1,2) via Slip Clutches (SC-1,2) and intermediate shafts. Diesel Generators (D/G-1,2) supply electric power to the onboard load (Load).

2.2 Hybrid propulsion system

Fig. 4 shows a line diagram of hybrid propulsion system which authors have proposed before \cite{4,5}. In this system, two Motor Generators (M/G-1,2) and three Electric Power Converters (EPC-1,2,3) are combined with the conventional propulsion system. The circuit configuration of EPC-1,2,3 is full bridge circuit with IGBT modules, which has a DC terminal and three phase AC terminal. EPC-1 and 2 connect each M/G and DC bus. The electric power can flow in bidirectional way by using these devices. EPC-3 also connects DC bus and three phase AC bus in bidirectional way. Consequently, D/G can assist M/E through these electric power converters in this system. M/G-1 can be operated also as a shaft generator. Therefore, the number of diesel generator is reduced to one. A changeover gear (Gear) is installed into starboard side intermediate shaft for adjusting load torque to M/E-1. Gear ratio is 1.0 when M/E-1 and M/E-2 drives each ATD.

In conventional propulsion system, both side M/E and D/G must be kept running for driving both side ATDs even if high power is not required. Total propulsion power of tugboat tends to be low as
mentioned before. Therefore all prime movers are forced to run in low load condition long time. On the other hand, all power source including the main engine and the diesel generator are connected each other in the hybrid propulsion system. According to the demanded load, optimal combination of the power sources can be selected.

When M/G-1 and D/G-1 provide electric power to M/G-2, ATD-2 is driven by only M/G-2 without M/E-2. As a result, it is possible to stop M/E-2 although total propulsion power is limited. In this case, the reduction ratio of Gear is switched to 1.33 in order to prevent M/E-1 from driving on torque rich condition.

All M/E can also be suspended if D/G-1 supplies sufficient electric power to both M/Gs for driving ATDs. Consequently, it is possible to reduce the number of running main engines and diesel generator depending on the situation.

This paper focuses on a case which M/E-1 and D/G-1 are RUN and M/E-2 is STOP. In this case, M/E-1 drives not only ATD-1 mechanically via intermediate shaft but also M/G-1 to generate electric power for M/G-2 and ATD-2. Generated three phase electric power in M/G-1 is converted into DC power through EPC-1. DC power is also supplied to DC bus from D/G-1 by using EPC-3. DC power is converted into variable-voltage variable-frequency electric power through EPC-2 because M/G-2 needs to drive ATD-2 in variable speed and variable torque.

2.3 Energy consumption simulation

The developed simulation makes a virtual model of propulsion system in computer. The simulation has a number of efficiency data banks of actual onboard apparatuses including diesel engine (constant speed and variable speed), slip-clutch, alternator, motor-generator, and electric power converter. From these data banks, the efficiency characteristic modules of all apparatus are estimated. Inputting the rated power and the load ratio into each module, these give the efficiency value of apparatuses. Virtual model of energy consumption in propulsion system consists of these efficiency characteristic modules. By using this virtual model in the following conditions, SFC characteristic of whole propulsion system is calculated.

<table>
<thead>
<tr>
<th>a. conventional propulsion system</th>
<th>Symbol</th>
<th>Rating</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Engine</td>
<td>M/E-1,2</td>
<td>1,500 kW</td>
<td>400-750rpm</td>
</tr>
<tr>
<td>Diesel Generator</td>
<td>D/G-1,2</td>
<td>100 kW</td>
<td>220V/PF:0.83</td>
</tr>
<tr>
<td>Slip Clutch</td>
<td>SC-1,2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Azimuth Thruster Drive</td>
<td>ATD</td>
<td>1,500kW</td>
<td>-</td>
</tr>
<tr>
<td>Average onboard load</td>
<td>Load</td>
<td>30 kW</td>
<td>assumed to be constant</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>b. hybrid propulsion system</th>
<th>Symbol</th>
<th>Rating</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Engine</td>
<td>M/E-1,2</td>
<td>1,350 kW</td>
<td>400-750rpm</td>
</tr>
<tr>
<td>Diesel Generator</td>
<td>D/G-1</td>
<td>300 kW</td>
<td>440V/PF:0.83</td>
</tr>
<tr>
<td>Slip Clutch</td>
<td>SC-1,2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Azimuth Thruster Drive</td>
<td>ATD</td>
<td>1,500kW</td>
<td>-</td>
</tr>
<tr>
<td>Changeover Gear</td>
<td>Gear</td>
<td>-</td>
<td>1.0 / 1.33</td>
</tr>
<tr>
<td>Motor Generator</td>
<td>M/G-1,2</td>
<td>730 kVA</td>
<td>PF:0.95</td>
</tr>
<tr>
<td>Electric Power Converter</td>
<td>EPC-1,2</td>
<td>800 kVA</td>
<td>fs: 2.5kHz</td>
</tr>
<tr>
<td></td>
<td>EPC-3</td>
<td>267 kVA</td>
<td>fs: 5.0kHz</td>
</tr>
<tr>
<td>Average onboard load</td>
<td>Load</td>
<td>30 kW</td>
<td>assumed to be constant</td>
</tr>
</tbody>
</table>
d) In the case that one main engine is STOP, another main engine which is RUN needs to supply the propulsion power to the both side azimuth thruster. Therefore the motor generators should be designed to satisfy about half power of main engine’s rated power. Furthermore, considering power losses in the motor generators and electric power converters, these rated are set to over half of rated power of main engine.

In this system, the main engine can be assisted by supplying electric power from the diesel generator to the motor generator. Accordingly, even small engine can be employed as the main engine only if the total ratings of main engine and diesel generator satisfy the demanded power load.

In these propulsion systems, ratings of each apparatus are set as Table 1 respectively.

3. Control method and fuel saving effect

3.1 Control method of each EPC

The energy consumption simulation is implemented in order to find an optimum control method for minimizing fuel consumption as the first priority. In the case that the propulsion system is in a state shown in Fig.4, EPC-2 outputs electric power to the M/G-2 by getting DC power. DC power is supplied by EPC-1 and EPC-3.

EPC-1 rectifies the electric power taken from M/G-1. M/G-1 converts a part of shaft horse power of M/E-1 to electric power. Consequently, DC output power of EPC-1 is related to M/E-1’s load factor.

EPC-3 delivers DC power by rectifying AC bus power which is supplied by D/G. In result, the load factor of D/G has relation to DC power of EPC-3 since onboard load is set to constant in this paper. Therefore, it is key to know the converting electric power by EPC-1 and EPC-3 so that the load factor of M/E-1 and D/G are clarified.

3.2 Control pattern for minimizing SFC

Fig.5-a shows one of simulation result that EPC-1 and EPC-3 share the propulsion power to ATD-2. Vertical axis shows the input power to EPCs. Horizontal axis shows the total propulsion power to ATD-1 and ATD-2. Fig.5-b shows the required power of the main engine and the diesel generator. This trend is a result of giving and calculating in two conditions. One is to minimize SFC as a first priority. Another is to make load fluctuation of prime movers smooth and continuous. If it can control the electric power and direction of EPCs respectively as shown in the figure, it might be expected to keep high efficiency in the propulsion system without discontinuous load fluctuation to the prime movers. This control pattern shown in Fig.5 is named as Pattern A.

In this Pattern A, EPC-1 and EPC-3 maintain DC bus voltage as CVS (Constant Voltage Source) simultaneously. Thus, it’s necessary to have an integrity controller for governing whole converter’s power and its direction in addition to each independent controller. If some problems occur in this integrity controller, EPC-1 and EPC-3 have to work separately. In this case, each electric power of EPC-1 and EPC-3 turn to be unstable, which make difficult to maintain DC bus voltage in an appropriate range, even if each control function operates normally in these converters. As a result, EPC-2 cannot drive M/G-2 in stable since DC bus voltage is unstable. Therefore, the control system has to be designed more carefully from the viewpoint of propulsion system’s redundancy. For
these reasons, more simple control pattern should be considered.

3.3 Simple control pattern for realizing redundancy

To solve these problems, two simple control patterns are proposed (see Figs.6 and 7). By switching the duty for maintaining DC bus voltage between EPC-1 and EPC-3, the integrity controller is not necessary.

As shown in Fig.6-a, the duty for controlling DC bus voltage is shifted between EPC-1 and EPC-3 at around 510kW in pattern B. EPC-1 has a duty for maintaining DC bus voltage as CVS when the propulsion power is under 1,020kW. In this range, EPC-3 is idling. When propulsion power reaches to 1,020kW, control principle of EPC-1 turns to CCS (Constant Current Source) from CVS. In addition, EPC-3 starts working as CVS for maintaining DC bus voltage instead of EPC-1.

In Pattern C, the control duty on DC bus voltage is shifted around 450kW (refer Fig.7-a). EPC-3 maintains DC bus voltage as CVS when the propulsion power is under 450kW. In this situation, EPC-1 is idling. On the other hand, the control principle of EPC-3 turns to CCS from CVS at range over 450kW. EPC-1 takes a duty to maintain DC bus voltage as CVS.

3.4 Evaluating SFC characteristics

To evaluate these control patterns from the viewpoint of SFC characteristics, simulation was implemented. Fig.8 shows calculated characteristics of SFC ratio. SFC ratio shows an effect of improved SFC in the hybrid propulsion system comparing to the conventional one. The vertical axis indicates the SFC ratio that hybrid propulsion system’s SFC divided by the conventional system’s one. Therefore, hybrid system has fuel saving effect in case that SFC ratio is less than 100%. The horizontal axis indicates the total propulsion power which is sum of the propulsion power in ATD-1 and ATD-2. Both sides propulsion power are assumed to be same in this calculation result for the sake of convenience. Black solid line indicates SFC ratio of the conventional propulsion system as a base line. These calculated SFC data include efficiency characteristics of not only the main engine but also the diesel generator. Thus, it is though that the
hybrid propulsion tugboat consumes fuel less than the conventional one when the SFC ratio is fewer than 100%.

As is clear from Fig.8, efficiency of hybrid propulsion system is better than the conventional one under 450kW range. In conventional system, slip clutches on both sides are slipped to control power for ATDs so that the main engines keep minimum speed under low load condition. On the other hand, in hybrid propulsion system, ATD-2 can be driven by only M/G-2 as shown in Fig.4. Driving power of M/G-2 is transmitted to ATD-2 without slipping SC-2 since M/G-2 outputs variable speed and variable torque power. For this reason, in hybrid propulsion system, ATD-2 can be driven without slipping loss on SC-2, which improves the hybrid propulsion system's SFC.

Under 450kW range, electric power is taken from M/G-1 through EPC-1. The operation of M/G-1 and EPC-1 increase electric power loss on them. In addition, the load factor of D/G in pattern C is higher than pattern B as shown in Fig.6-b and Fig.7-b. The thermal efficiency of generator's diesel engine is improved effectively at this condition. However, contribution of thermal efficiency improvement on M/E-1 is small, while the load factor of M/E-1 in pattern B becomes higher than pattern C. Consequently, it is thought that pattern C can improve SFC ratio comparing to pattern B.

Over 450kW range in Fig.8, it was expected that whole system's efficiency is improved by suspending M/E-2 and raising the load factor of M/E-1. But energy is trickled out and dissipated when it goes through several apparatuses M/G-1, EPC-1, EPC-2, and M/G-2. Resultantly, it is clarified that the hybrid propulsion system is not effective for improving SFC in the condition that the slipping loss does not occur in the slipping clutch.

M/G-1 starts to generate electric power when the total propulsion power exceeds 450kW in pattern C. Efficiency of M/G-1 and EPC-1 is low since the load factor of these apparatuses is also low in a range of 450kW to 900kW. M/E-1 needs to output not only the propulsion power but also the electric power dissipation on EPC-1 and M/G-1. Thus, it is thought that SFC ratio of pattern C gets worse comparing to pattern B.

The total propulsion power does not exceed 20% (600kW) in most of cases when the tugboat is not in service (see Fig.2). The longer tugboat is not in service, the higher fuel saving effect is expected. As mentioned above, the rating of motor generator is set to around half of the rating of main engine. The motor generators tend to be operated in low load condition, which makes system's efficiency low.

4. Conclusion

The characteristic of the hybrid propulsion system without large battery is analyzed for applying to the tugboat. Three control patterns were evaluated from the view point of controllability, redundancy, and its efficiency. From the calculation results, the followings were clarified.

1. The integrity controller for a group of electric power converters is necessary in pattern A which gives a priority to the efficiency. The problems of controllability and redundancy of it are not negligible.
2. The integrity controller is not necessary in control pattern B and C.
3. Reducing the mechanical loss in the slipping clutch contributes to improve efficiency of the hybrid propulsion system.
4. Hybrid propulsion system achieves the fuel saving effect in low power condition.

For the future study, optimizing the ratings of apparatuses which consist of the hybrid propulsion system is effective for improving the fuel saving potential.

Acknowledgment

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