A Study on Control Method and Fuel Saving Effect of Hybrid Propulsion System for Tugboat

◎Takaaki Nishio, Hiroyasu Kifune

1. Introduction

Harbor tugboats assist large vessels to enter and exit a port. Fig.1 shows a line diagram of conventional propulsion system. It has generally two middle to high speed and high power engines and two azimuth thrusters which are turnable over 360 degrees in order to push and pull large vessels (Fig.1). Each main engine (M/E-1,2) drives mechanically azimuth thrusters (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). Authors measured tugboat's operation data to clarify a characteristic of tugboat's operation. Fig.2 shows a sample of measured data which was a trend of a demanded propulsion power. As is clear from this figure, a wide range of propulsion power is required when the tug boat is on service. On the other hand, the demanded propulsion power is not high but low power less than 20% when it is out of service situation. On the basis of this characteristic, authors have studied and proposed hybrid propulsion system for tugboat [(1)-(2)]. In proposed system, a main engine system and a diesel generator system are combined by using motor generators and electric power converters. Thus, when the diesel generator supplies the electric power to the motor generator, the main engine can be assisted. As a result, it is possible to share the propulsion power between the main engine and the diesel generator. The share ratio of propulsion power can be controlled.

In this paper, the optimal control methods for hybrid propulsion system are proposed. In addition, the effect of saving fuel consumption which is calculated by FOC (Fuel Oil Consumption) simulation is reported.

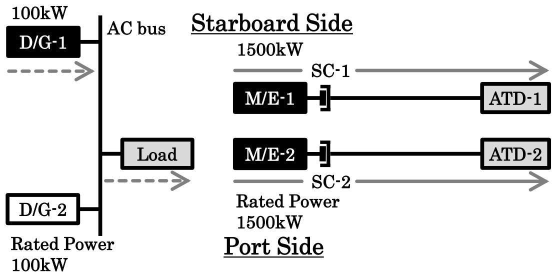

Fig.1 Conventional propulsion system and energy flow

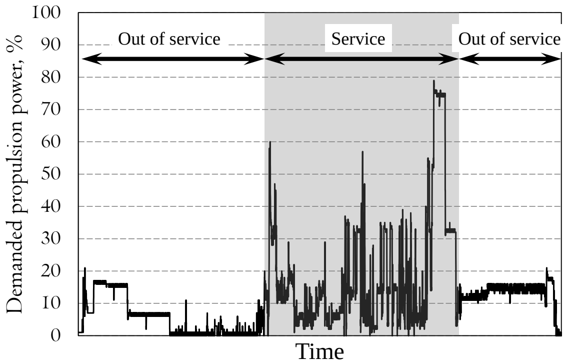

Fig.2 Sample of measured propulsion power

2. Propulsion system and FOC simulation

2.1 Hybrid propulsion system

Fig.3 shows a line diagram of hybrid propulsion system which authors have proposed before. In this system, two motor generators (M/G-1,2) and three electric power convertors (EPC-1,2,3) are combined with conventional propulsion system. EPC-1 and 2 connect DC bus and each M/G. The electric power can flow in bidirectional way by using these devices. EPC-3 also connects DC bus and 3 phase AC system in bidirectional way. Consequently, D/G can assist M/E through these electric power converters in this system.

In conventional propulsion system, M/E-1 and 2 drive each ATD. D/G supplies electric power to the onboard load. M/Es and D/G must be kept running whenever any propulsion power is required.

In the hybrid propulsion system, M/G-1 can be operated also as a shaft generator in the hybrid propulsion system. 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.

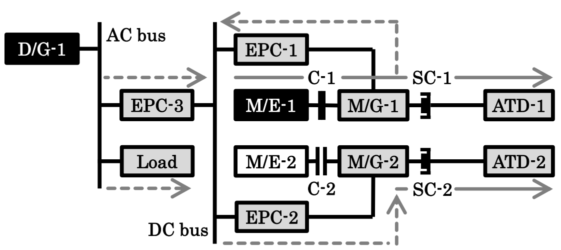

Fig.3 Proposed hybrid system and sample energy flow

As a result, it is possible to stop M/E-2 as is shown in Fig.3. In addition, M/E-1 and 2 can be stopped when D/G-1 provides electric power to both M/Gs in order to drive each ATD. Consequently, it is possible to reduce the number of running main engines and diesel generator depending on the situation.

This paper picks up one of sample case which M/E-1 and D/G-1 are RUN and M/E-2 is STOP. In this case, M/E-1 drive not only ATD-1 mechanically via intermediate shaft but also M/G-1 to generate electric power for M/G-2. Generated three phase electric power 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 VVVF (Variable Voltage Variable Frequency) electric power through EPC-2 because M/G-2 drives ATD-2 in variable speed and variable torque.

It is possible to change the power ratio which is provided from EPC-1 and EPC-3 because both EPCs can provide electric power to EPC-2 in order to drive M/G-2. When EPC-1's output power increases and EPC-3's one decreases, M/E-1's output power increases and D/G-1's one decreases. As the result, the efficiency of whole propulsion system which includes M/E, D/G, M/G, EPC and SC are changed. In other words, the SFC (Specific Fuel Consumption [g/kWh]) characteristic of the whole propulsion system is affected by change of the power ratio. This SFC characteristic means the value that is calculated based on the whole propulsion system's efficiency. FOC simulation was implemented to clarify a relationship between the power ratio and the SFC characteristic of the whole propulsion system.

2.2 FOC simulation

The efficiency of whole apparatus which are included in propulsion system can be estimated in order to calculate the SFC characteristic of the whole propulsion system. When some conditions which are shown below are set, the SFC characteristic is estimated in FOC simulation.

1) Each demanded propulsion power of starboard and port side is assumed to be same in FOC simulation.

In actual tugboat's operation, each propulsion power is normally not same because each engine is controlled separately so that tugboat gets thrust to all direction. However, the difference of each propulsion power was not large, as long as authors measured the load factor of main engine in actual tugboat over three months.

2) The onboard load is set to constant 30kW in FOC simulation.

Authors measured onboard electric power for one year in the conventional tugboat. As the result, fluctuation range of onboard electric power is limited around several 10 kW.

3) Ratings of both main engines are set to 1500kW and a rating of diesel generator is set to 100kW in the conventional propulsion system.

The majority of tugboats have two main engines of around 1500kW rating and two diesel generators of around 100kW rating. It is reported that they account for 70% of total amount of tugboats which were built during the past five years in Japan. For this reason, total rated power of the main engines and the diesel generator is set to around 3,000kW.

4) In hybrid propulsion system, ratings of each apparatus are set as Table 1.

In this system, the main engine can be assisted by supplying electric power from the diesel generator to the motor generator. Accordingly, even smaller engine can be employed on the main engine only if the total ratings of main engine and diesel generator satisfy demanded power load. In this paper, each apparatus constituting propulsion system is set on condition that total rating of main engines and diesel generator is 3000kW.

Table 1 Rating and number of each apparatus

Item	Symbol	Rating	Number
Main Engine	M/E-1,2	1,350 kW	2 equiped
Diesel Generator	D/G-1	300 kW	1 equiped
Motor Generator	M/G-1,2	860kVA	2 equiped
Electric Power Converter	EPC-1,2	880kVA	4 blocks
	EPC-3	270kVA	2 blocks

In hybrid propulsion system, the number of running main engines and diesel generator can be decreased as described in Chapter 2. In this paper, a sample case which one main engine and one diesel generator are RUN as shown in Fig.3 is reported. In this case, it is necessary that electric power is supplied to M/G-2 through EPC-2 in order to drive ATD-2. This electric power is provided by EPC-1 and EPC-3. It is possible to change the ratio of these EPCs' output power. By changing this ratio as parameter, the SFC characteristic of hybrid propulsion system is calculated in FOC model.

3. Control method and fuel saving effect

3.1 Control method of each EPC

FOC simulation is implemented in order to find an optimum control method for minimising fuel consumption as the first priority. Fig.4 shows one of calculated result about propulsion power sharing in each electric power convertor. The vertical axis indicates absolute values of EPC-1 and EPC-3's output power and EPC-2's input power. The horizontal axis indicates the propulsion power of ATD-2.

This control pattern shown in Fig.4 is named as Pattern 1. According to the simulated result, it is expected that SFC can be minimised by controlling the power and its direction of the electric power converters like Fig.4. However, the output power of these electric power converters changes steeply around 500kW. Resultingly, it is nature that the main engine and generator's engine have to accept sharp load change. This is hardly realised from the viewpoint of engine operation and control.

Furthermore, in this Pattern 1, EPC-1 and EPC-3 maintain DC bus voltage as CVS (Constant Voltage Source) at the same time. Thus, it's necessary to have an integrity controller for governing whole converter's power and its direction in addition to each independent controller. Propulsion system including electric power convertors and this governing controller will be complicated.

If some problems occur in this integrity controller, EPC-1 and EPC-3 have to work separately. In this case, it is difficult to maintain DC bus voltage within a certain range even if each control function operates normally in these converters. As a result, EPC-2 cannot drive M/G-2 in stable because 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.

Consequently, authors proposed two simple control patterns which do not need to control output power of EPC-1 and EPC-3 simultaneously (see Fig.5). As is clear from the figure, the output power of main engine and diesel generator change continuously.

In Pattern 2, the duty for controlling DC bus voltage is shifted between EPC-1 and EPC-3 at 500kW. EPC-1 is controlled to maintain DC bus voltage as CVS when propulsion power of ATD-2 is under 500kW. In this range, EPC-3 is idling. When propulsion power reach to 500kW, control principle of EPC-1 is shifted from CVS to CCS (Constant Current Source). In addition, EPC-3 starts working as CVS instead of EPC-1 for maintaining DC bus voltage.

In Pattern 3, the control duty on DC bus voltage is shifted around 250kW. EPC-3 maintains DC bus voltage as CVS when propulsion power of ATD-2 is under 250kW. In this system, EPC-1 is idling. On the other hand, the control of EPC-3 is changed from CVS to CCS over 250kW. EPC-1 has a duty to maintain DC bus voltage as CVS.

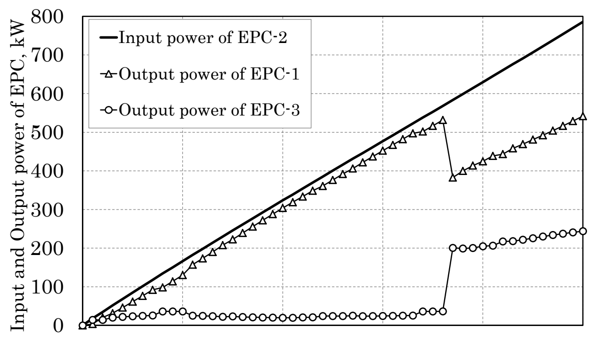

Fig.4 Calculated sample of propulsion power sharing in EPC-1 and EPC-3 (Pattern 1)

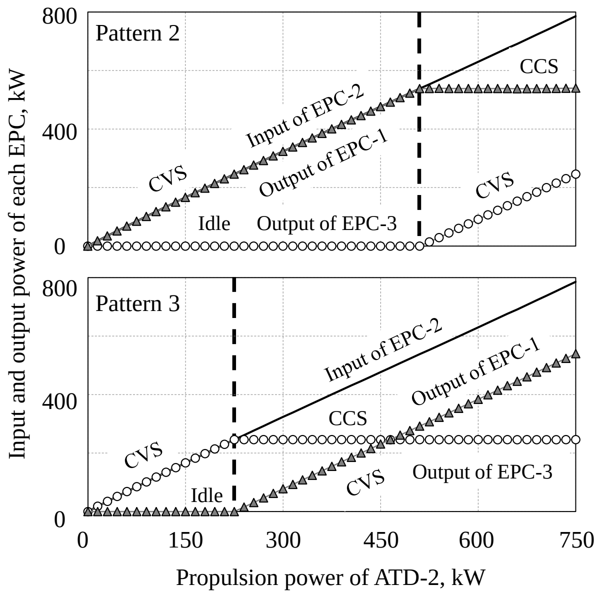

Fig.5 Proposed power pattern of each EPC (Pattern 2 and 3)

Each SFC characteristics are calculated in FOC simulation to compare with these control patterns.

3.2 Simulation Result

Fig.6 shows simulated characteristics of SFC ratio. The vertical axis indicates the SFC ratio that hybrid propulsion system's SFC divided by conventional system's one. The horizontal axis indicates the total propulsion power.

Each characteristic is approximately equal regardless of control pattern when total propulsion power is under 450kW. In this range, the hybrid propulsion system consumes less fuel oil compared with the conventional one. In conventional system, slip clutches on both sides are slipped to control power for ATDs under a minimum speed of M/E. On the other hand, in hybrid propulsion system ATD-2 can be driven by only M/G-2 as shown in Fig.3. Driving power of M/G-2 is transmitted to ATD-2 without slipping SC-2 because M/G-2 outputs power in variable speed and variable torque. For this reason, in hybrid propulsion system, ATD-2 is driven without slipping loss on SC-2. In addition, the fuel oil consumption in M/E-2 can be also decreased. Consequently, the hybrid propulsion system can improve the SFC ratio around 20% compared with conventional one under 450kW.

In a range from 450kW to 1000kW, the SFC characteristic of Pattern 3 gets worse around 5% than other pattern. In Pattern 3, D/G-1 supplies electric power to not only onboard load but M/G-2 through EPC-2 so that M/G-2 drives ATD-2. Thus, D/G-1 is operated in high loaded condition compared with Pattern 2. Generally, the thermal efficiency of internal combustion engine is high in high loaded condition. As a result, D/G-1 runs efficiently in Pattern 3 compared with in Pattern 2 when the total propulsion power is below 450kW.

In Pattern 3, M/E-1 drives ATD-1 under 1000kW. On the other hand, in Pattern 2, M/E-1 drives both ATDs by using M/G-1, M/G-2, EPC-1 and EPC-2 in this range. Thus, in Pattern 3, M/E-1 runs in low loaded condition compared with in Pattern 2.

In Pattern 3, M/E-1 runs in low efficiency condition although D/G-1 is operated in high efficiency compared with Pattern 2 under 1000kW. For this reason, SFC characteristic of Pattern 3 gets worse than Pattern 2 when total propulsion power is in a range between 450kW and 1000kW.

Additionally, it is sure that energy loss on EPCs and M/Gs is not zero, although the conversion efficiency of these apparatuses is higher than prime mover and slip clutch. Thus, the fuel consumption of hybrid propulsion system tends to be increased compared with conventional one when the total propulsion power is over 450kW.

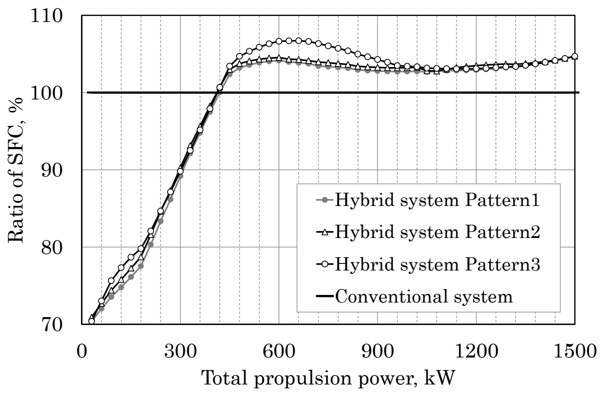

Fig.6 Characteristic of proposed hybrid system's SFC compared with conventional one

4. Conclusion

In this paper, two optimal control methods of electric power convertor are proposed in condition that one main engine and one diesel generator are RUN. In these proposed patterns, the integrity controller which governs each electric power convertor's power is not required because the electric power convertor's power does not change at the same time. Therefore, the hybrid propulsion system is not complicated. The SFC characteristic of hybrid propulsion system is calculated in FOC simulation when each electric power converters is controlled as Pattern 2 and Pattern 3. As the result, it is expected the hybrid propulsion system has the fuel saving effect compared with the conventional one when the total propulsion power is low.

References

(1) Hiroyasu Kifune and Takaaki Nishio, 2015 A study of Fuel Consumption Model Using Tugboat's Propulsion System, Journal of The Japan Institute of Marine Engineering, Vol.50, No.4 pp. 129-136.

(2) Takaaki Nishio and Hiroyasu Kifune, 2014 A Study on Simulations of Fuel Consumption in Hybrid Propulsion System for Tugboat, The International Symposium on Marine Engineering, Harbin, PID150.