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Design and simulation of LNG-fueled SOFC-GT Hybrid System for ship application

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ABSTRACT

The solid oxide fuel cell-gas turbine (SOFC-GT) hybrid systems are thought to be the most attractive energy conversion systems in future energy markets because of high efficiency 60~70%, low emission, and fuel flexibility. Which are vary suitable for mobile applications due to they could be installed in a standalone manner to supply power with a high electric efficiency. In this context, this paper designed a LNG-fueled SOFC-GT hybrid system for all-electric ship application. And proposed the control structure of power feedback and temperature feedforward for the ship used SOFC-GT system. Also, a 5000t class of river-to-sea cargo ship which is sailed from Nanjing to Shanghai along the course of the Yangtze River is conducted as a case study. The results show that the total amount of 2724kg fuel is consumed by the ship in the whole course, meanwhile, the CO_2 emissions is reduced by almost 48.8% compares to the conventional propulsion technology.

Keywords: Solid oxide fuel cell, Gas turbine, Hybrid system, Ship application

NONMENCLATURE

Abbreviations	
D	Diameter
E^{OCP}	Reversible cell potential
P	Partial pressure of spices
Q	Torque
R	Gas constant
T	Temperature Trust
U	Cell potential

Symbols	
η	Overpotentials

1. INTRODUCTION

As the amount of greenhouse gas that is produced by the ship power system increase, the strict regulations has been introduced by the International Maritime Organization (IMO) aiming at reducing the total amount of GHG emissions from shipping by 50% before 2050 [1]. In this context, the all-electric ship which is integrated with electric propulsion becomes a promising solutions to reduce the fuel consumption and emissions [2]. The solid oxide fuel cell-gas turbine (SOFC-GT) hybrid systems have a great potential to act as a power source for all-electric ship owing to their high efficiency, low pollution and fuel flexibility. In addition, they show a high electrical efficiency at medium-low load, which is much suitable for propulsion because ships are most often operated in this conditions during their lifetime [3].

Although the SOFC-GT powered electric ship has been investigated by several researches [4], most of which ignores the influence of operation condition on the system performance in the design process. Therefore, this paper proposed an approach for designing a LNG fueled SOFC-GT hybrid system for ship application based on the built models of SOFC-GT, ship resistance and propeller load. And proposed the control structure of power feedback and temperature feedforward for the ship used SOFC-GT systems. Meanwhile, in order to investigate the adaptability of the SOFC-GT for ship application, the target ship is sailed from Nanjing to Shanghai along the course of the Yangtze River is conducted as a case study.

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2. POWER SYSTEM DESCRIPTION

The typical SOFC-GT hybrid power system for electric propulsion ship is given in Fig.1. The power produced by two set of SOFC-GT systems is used to propulsion and other ship services. Although the SOFC is identified as the most potential technology for ship application due to their high efficiency and low pollution, the high operation temperature of SOFC results in slow start-up and load shifting. Therefore, the battery is necessary in the SOFC based ship power sources to achieve power tracking in transient process.

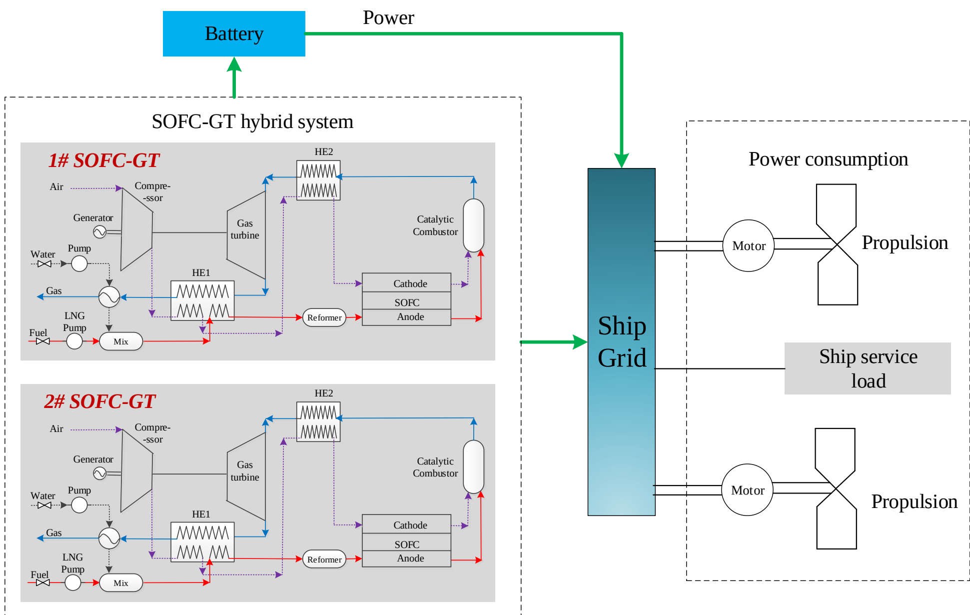

Fig.1. Schematic of SOFC-GT hybrid propulsion system for ship application

3. MATHEMATIC MODELLING

3.1 SOFC-GT

Generally, the thermodynamic models are built based on the mass and energy balance equations. Due to the existing of various losses inside SOFC, the actual potential of fuel cell is always lower than the theoretical open-circuit potential, and the theoretical open-circuit potential and operation potential of SOFC are written as follows [5]:

$$E^{OCP}=E^{0}+\frac{RT}{2F}\ln\left(\frac{P_{\mathrm{H_2}}P_{\mathrm{O_2}}^{0.5}}{P_{\mathrm{H_2O}}}\right) \tag{1}$$

$$U=E^{OCP}-\eta_{\mathrm{act}}-\eta_{\mathrm{ohm}}-\eta_{\mathrm{con}} \tag{2}$$

The detail parameters and validation with experiment results of this model can be found in our previous research [6]. In addition, the gas turbine models can be obtained by the characteristic maps of compressor and turbine respectively. The detail models and parameters about the gas turbine, heat exchanger, pre-reformer, catalytic combustor and other components can be found in our previous literatures [6].

3.2 Ship resistance and propeller load

There is a close relationship between propulsion power and ship resistance. The external resistance of ship mainly consists of the frictional resistance and residual resistance in calm water and the added resistance in wind and wave [7].

Meanwhile, the propeller has to overcome the resistance moment generated by water during sailing. And the thrust and torque of propeller can be given as [8]:

$$T=K_T\rho n^2D^4 \tag{3}$$

$$Q=K_Q\rho n^2D^5 \tag{4}$$

3.3 Battery storage system

The current battery energy can be obtained based on the charge/discharge power, given as,

$$E_{B,t}=E_{B,t-\Delta t}+\int_0^{\Delta t}\left(P_{cha}\eta_{cha}+\frac{P_{dcha}}{\eta_{dcha}}\right)dt \tag{5}$$

Where, Δt is the time interval, P_{cha} and P_{dcha} are charge and discharge power respectively, here, we assumed that the discharge power is a negative value for easy calculation.

4. DESIGN SHIP USED SOFC-GT SYSTEMS

4.1 Design SOFC-GT hybrid power system for ship

In this work, a 5000t class of river-to-sea cargo ship is selected as the target ship for case study. Generally, the electric propulsion power accounting for 70%-80% of ships power capacity, even reach 90% [9]. Based on the built models of SOFC-GT, ship resistance and propeller load. The power sources of two set of SOFC-GT hybrid systems (Each of 1000kW) is designed for the target ship. The average current density, fuel utilization, steam to carbon ratio of the design hybrid system are 4000A/m^2, 0.75 and 2 respectively.

4.2 Design control structure

In actual operation, the frequently fluctuation in working temperature of fuel cell stacks will extend the time of power tracking and shorten the cycle life of SOFC. In order to achieve a better trade-off between thermal management and system performance, the control system with ability of minimize the temperature difference in transient operation is necessary. Therefore, the control structure of power feedback and temperature feedforward is designed in this work to improve the transient performance of SOFC-GT.

Fig.3 and Fig.4 exhibit the transient behavior of maximum and average temperature at SOFC PEN structure (Max.T_{PEN} and Ave.T_{PEN}) respectively. Both two temperatures firstly decrease and then increase during the time. It is clear that the proposed control strategy can significantly reduce the temperature fluctuations in transient process. A 20% load step down operation will only cause the maximum 1.29% of Max.T_{PEN} and 1.43% of Ave.T_{PEN} change. Furthermore, the reduction in temperature fluctuation is very beneficial to prolong the cycle life of SOFC.

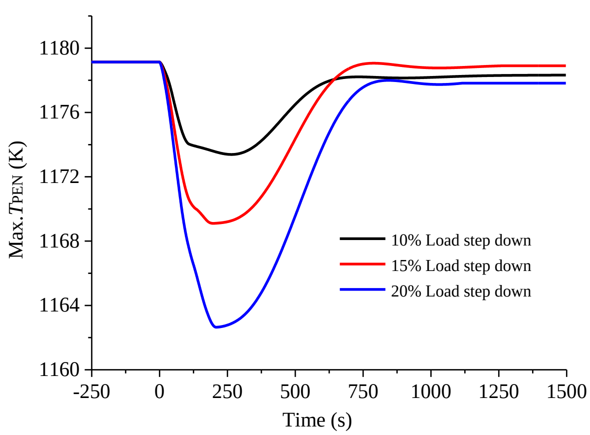

Fig.3 Transient behavior of Max.T_{PEN} in the designed control strategy

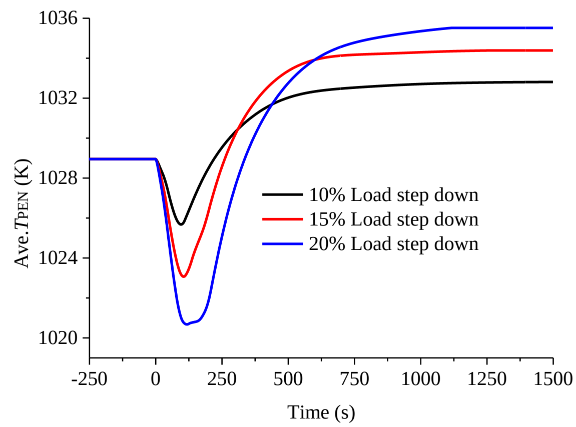

Fig.4 Transient behavior of Ave.T_{PEN} at PEN structure in the designed control strategy

Fig.5 describe the battery stored energy in these three transient processes. Generally, the battery charge process corresponding to the load decreases operation, and the battery discharge corresponding to the load increases operation. Almost 2.60MJ, 3.91MJ and 5.31MJ of energy are stored by the battery during the process of load step decreased from the design value to 90%, 85% and 80% load respectively.

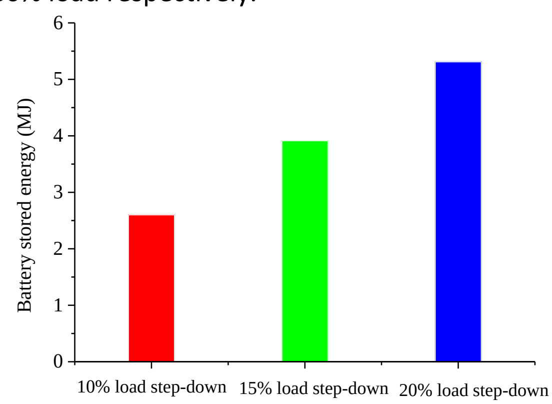

Fig.5 Battery stored energy

5. CASE STUDY

To investigate the adaptability of the proposed SOFC-GT hybrid system for ship application, a 5000t class river-to-sea cargo ship is sailed from Nanjing to Shanghai along the course of the Yangtze River is selected as a case study. We assumed that the ship is started off at 6am with the average velocity of 13knots (downstream), and it will arrive at about 7pm. And the average velocity in the lower reaches of the Yangtze river is assumed as 4km/h.

5.1 Energy management strategy

Because this work aims at investigating the adaptability of SOFC-GT hybrid system for ship application, we assumed that the operation conditions of the target ship within one hour remains the same for simplify the analysis. Based on the weather conditions along the course, we can easily obtain the hourly consumed power of the selected ship. This work mainly using the SOFC-GT to following the load, and the battery is used to support the transient power. However, the optimal power tracking path can be obtained based on the optimization solutions, and this is an interesting topic in further research work.

5.2 Operation characteristic of ship power system

Based what is discussed above, the configuration of 2×1000kW hybrid SOFC-GT systems is supplied for the selected 5000t class river-to-sea cargo ship. We assumed that each set of SOFC-GT supplied the same power to meet the load demand, although this method of power split is not the optimal one, it is reasonable and commonly used at the initial design stage. The optimal load distribution can be obtained based on an optimization algorithm, but this is not the focus of the work.

In this course, almost 2724kg fuel is consumed by the ship power system in the whole course, with an average electrical efficiency of 60.8%. According to a report from the Department for Business, energy & Industrial strategy [10], the marine diesel oil and LNG have the carbon emission factor of 3.223 kg CO_2/kg and 2.808 kg CO_2/kg respectively. Comparison with the diesel engine with the fuel consumption of 200g/kWh, the total CO_2 emissions is reduced from 14.95 tons to 7.65 tons in the whole course.

6. CONCLUSIONS

This paper designed a LNG-fueled SOFC-GT hybrid system for all-electrical ship application. Also, the control strategy of power feedback and temperature feedforward is designed for the ship used SOFC-GT. Moreover, a 5000t class of river-to-sea cargo ship is sailed from Nanjing to Shanghai along the course of the Yangtze River is conducted as a case study in this paper. The results shown that the total amount of 2724kg fuel is consumed by the ship in the whole course, meanwhile, the CO_2 emissions is reduced by almost 48.8% compares to the conventional propulsion technology. This have proven that the solid oxide fuel cell-gas turbine (SOFC-GT) hybrid systems have a great potential to act as a power source for all-electric ship.

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