Modelling and Control of Fuel Cell and Micro Gas Turbine Hybrid Power System for Ship Application

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Abstract

A solid oxide fuel cell (SOFC) and micro gas turbine (MGT) hybrid power system is a newly developed and promising power technology for ship power systems. Compared to conventional power plants on commercial ship, the technology can achieve a high efficiency (up to 80 percent) and very low emission (up to zero). However, working as a marine power provider onboard ship, the control strategy of the hybrid system is one of the key challenges due to the requirement of balance between power generation from the SOFC's chemical reaction and the MGT's rotation mechanical power generation. In this paper, based on a system model, the control strategy for the hybrid power systems is presented. In order to get the maximum efficiency, the control of key parameters of the SOFC, such as stack temperature, fuel flow rate, fuel utilization and related power have been investigated and the control of power sharing between the two power sources of SOFC and MGT is proposed. The simulation results demonstrate that the control system can effectively control the SOFC and MGT subsystem and make them undertake their appropriate load separately with the forthcoming load.

Keywords: Fuel cell, Turbine, Control strategy, Electric power, Load change

1. Introduction

Facing the increasingly stringent worldwide anti-pollution regulations, it is more and more difficult for traditional marine diesel engines to meet the emission standards at national and international levels. On one hand, engine designers and users have to invest on engine design and management to improve the combustion quality of diesel engines; On the other hand, shipping companies have to invest money focusing on engines' exhaust treatment through all kinds of physical and/or chemical methods. At the same time, most SOFC research programs are currently targeting on the development of fuel cell systems for land-based use and have made some important technical successes. This paper is to present a project on developing a new type of marine power system which combines a SOFC fuel cell system with a micro gas turbine system. The SOFC produces electrical power from chemical reaction directly consuming natural gas and the MGT uses the thermal energy of exhaust gas from the SOFC to generate more electrical power, thus to increase the overall efficiency of the whole system.

2. SOFC and MGT Hybrid Power System Model

2.1 Tubular SOFC System Description

The SOFC-MGT hybrid power system shown in Figure 1 is developed based on a Siemens tubular SOFC fuel cell (CHP SOFC) which produces electricity and thermal energy contained in the SOFC exhaust gases (He, J et al., 2011). In this tubular SOFC system, through the valve (no. 2, 6) and the desulfurizer (3), methane (natural gas, 1) is transported to the reformer (9) where the reforming chemical reaction takes place; The hydrogen produces from chemical reaction of reforming then flows into the outside of the cell (11). On the other side, air (20) is pumped by the air blower (18), via the air filter (19), into the heat recuperator (16) where the air is heated by SOFC exhaust gases; The heated

air is passed to the air container (12), then distributed to cell stack via the air supply tubes (ast, 8). At the end of ast (8), the incoming air back flows to the inside of the cell (2) to react with the hydrogen outside of the cell. Thus, the chemical reaction between the oxygen and hydrogen within the cell stack takes place and electrical current is generated together with high temperature exhaust gases (24) discharged. There is also a combustor where, if required, excessive hydrogen and part of incoming natural gas burn to get more energy for gas turbine or to maintain the SOFC stack at an appropriate temperature.
The MGT system is used to generate electrical power. Thermal heat energy in the exhaust is extracted through the heat exchanger (25) and is converted into electric energy by micro turbine (26).

2.2 SOFC Model

There are mainly two components in the SOFC model: reforming sub-model and electrochemical sub-model. The former is to convert the methane (natural gas) into hydrogen, carbon monoxide and carbon dioxide as shown by the equation (1), (2) and (3). Hydrogen is let to the latter where hydrogen reacted with oxygen from air and hence, electric current is generated as shown in the equation (3) - (5).

$$CH_4 + H_2O(x) \rightarrow CO + 3H_2 \quad (1)$$

$$CO + H_2O(y) \rightarrow CO_2 + H_2 \quad (2)$$

$$H_2 + \frac{1}{2}O_2(z) \rightarrow H_2O \quad (3)$$

$$H_2 \rightarrow 2H^+ + 2e^- \quad (4)$$

$$O_2 + 2e^- + 2H^+ \rightarrow H_2O \quad (5)$$

Where x, y and z are the conversion rates (molar flow rate) of CH_4, CO, and H_2, respectively.
The following assumptions are made in developing the SOFC system:
(1) All gases are to be ideal gas and no phase change during the reaction
(2) All the exterior walls of the cells are perfectly insulated. There is no heat exchange across the cells
(3) Gas distribution within a cell is uniform and no variation of gas distribution among cells
(4) One-dimensional behaviour along the stream direction
Based on the above assumptions and according to the characteristics of the physical and chemical reaction under certain temperature and pressure conditions, the output of hydrogen from the reformer can be calculated by the above equation (1) and (2). In equation (3) reaction, electric current (power) generated through outside circuit, other related ingredients including H_2, CO, CO_2 and H_2O also be produced. Using the above mentioned mathematical equations, together with the Matlab-Simulink software, reforming and electrochemical process can be modeled. The main equation of actual voltage and current of the fuel cell can be expressed separately as:

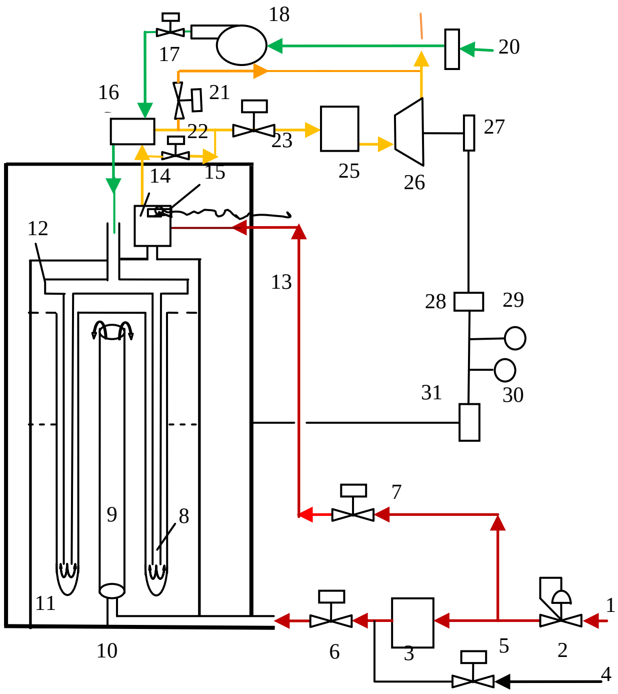


Figure 1: SOFC and micro gas turbine hybrid system

1-Natural Gas 2-Regulator 3-Desulfurizer 4- Purge Gas 5, 6, 7,17,20,21,22,23-Flow Control Valve 8-Air Supply Tube 9-Reformer 10-Fuel Cell Stack 11-Cell 12-Air Container 13-To Combustor 14-Comb. Zone 15-Igniter 16-Heat Recuperator 18-Air Blower 19-Air Filter 20-Air 24-Exhaust Gas Exit 25-Heat Exchanger 26-MG Turbine 27-Generator 28,31 – Inverter 29, 30-Load

$$V = E_0 + \frac{RT}{2F}\ln\frac{p_{H2}\,p_{O2}^{\;1/2}}{p_{H2O}} - \eta_{act} - \eta_{conc,a} - \eta_{conc,c} - \eta_{\Omega} \quad (6)$$

$$I = 2\dot{n}_{H2}F \quad (7)$$

Where, E_0 is the standard potential which almost lineally changes with temperature T; R and F are gas constant and Faraday constant; η_{act}, η_{conc} η_{Ω} are activation losses, concentration losses, ohmic losses respectively; $\dot{n}$ is molar flow rate.

2.3 MGT Model

The work output of the MGT can be calculated from the enthalpy change and the SOFC exhaust gas flow rate. The isentropic power W_{ise}, actual power output W_{act} and outlet temperature of the turbine $T_{t,\,out}$ can be expressed as:

$$W_{ise} = \dot{m}(\bar{h}_{t,in} - \bar{h}_{t,out})$$

$$= \dot{m}c_{t,p}T_{t,in}(1 - \frac{1}{(p_{t,in}/p_{t,out})^{\frac{1-r}{r}}} \qquad (8)$$

$$W_{act} = \eta_t * W_{ise} \qquad (9)$$

$$T_{t,out} = T_{t,in}(1 - \eta_t(1 - (p_{t,in}/p_{t,out})^{\frac{1-r}{r}})) \qquad (10)$$

Where $\dot{m}$ is the SOFC exhaust gas mass flow rate; $\bar{h}_{t,in}$, $\bar{h}_{t,out}$ are gas turbine inlet and outlet enthalpy respectively; $c_{t,p}$ is the gas mean specific heat; $T_{t,in}$, $T_{t,out}$, $p_{t,in}$, $p_{t,out}$ are gas turbine inlet and outlet temperature and pressure respectively; r is gas expansion index and η_t is the isentropic efficiency of the turbine.

3. Control of SOFC/MGT Hybrid Power System

3.1 Control Strategy during Start-up and Shutdown Process

It is very important to design a control system to maintain the appropriate fuel and air flow rate to produce the desire output power. Before start the hybrid system, both the SOFC, MGT subsystem and other related equipments should be checked in appropriate states or positions both manually and automatically, including stack, purge gas tank, fuel, valve position, filter, blower, pump, and battery, as well as lubrication oil, cooling water (or oil).

During the start-up process, the SOFC stack must be pre-heated slowly to reach a temperature which is high enough for the chemical reaction between CH_4 and H2O to take place in the fuel reformer, where additional fuel may be required to burn to supply heat energy to preheat the SOFC stack to an appropriate temperature. Then the hybrid system is ready to start under the following control strategy and function:

1) Activate the start-up procedure;

2) Close fuel bypass valves smoothly by a liner ramp function. Decrease the auxiliary fuel from the initial value (flow control valve 7). To raise the stack temperature to about 1273 K by a combination of adjusting the valve 23 and the air flow rate into the stack.

3) Close the purge gas valve 5 to stop the inert gas supply.

4) When the stack temperature has reached to the desired value, ramp down the fuel and air flow rate to the burner to zero. In the meantime, fuel utilization in the cell stack should reach to about 0.85 when the fuel and air supply to the burner is reduced to zero.

5) Slowly increase the output power of the fuel cell by increasing the CH4 flow-rate.

6) Start MGT subsystem operation after the operation of SOFC reaches to a steady state.

On the contrary, in the shutdown process, the MGT subsystem should be decoupled first and then stop the SOFC subsystem gradually. This control may also include the following control strategy:

1) In the early phase of the shutdown, reduce the power output of MGT through decreasing the exhaust gas flow rate and pressure into MGT system by slowly open the by-pass throttle valve (21 on Fig.1) until the MGT power output is reduced to zero. Then, decouple the inverter (29) from the power line.

2) Turn off the SOFC system power output, including the burner, depower the inverter (31) and close the fuel valves (6, 1). Then, the SOFC system enters the cooling state where the fuel cell is supplied with inert purge gas by valve (5) to prevent the cell anode material from oxidation while the stack temperatures are still above a defined limit.

3) Continuously increasing the opening degree of exhaust throttle valve (21) to control the air flow rate until the valve (21) is fully open. To further cool down the cell stack to a lower temperature via slowly opening the bypass valve (22) of recuperation (16) by a ramp function.
4) Once the stack has been successfully cooled below a defined temperature, the SOFC subsystem will be transited to the idle state.

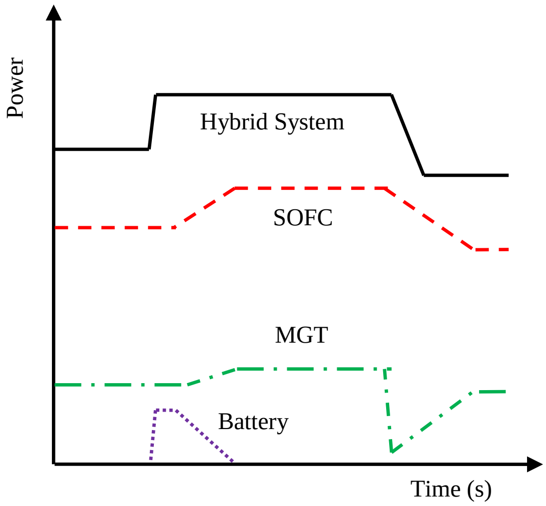


Figure 2: Power output changes of the system components with the load control strategy

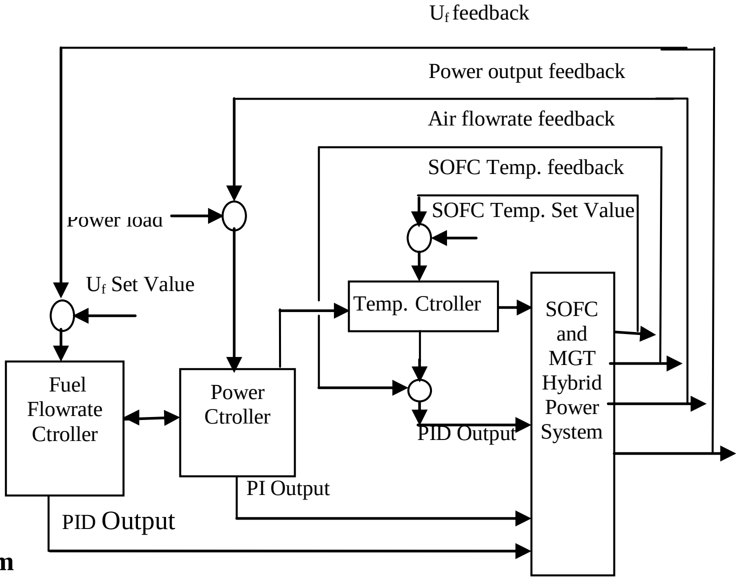


Figure 3: SOFC-MGT Hybrid Power Control System

3.2 Part-load Control Operation Strategies

Regarding how to control the fuel flow-rate and air flow-rate, there are 2 control strategies being considered here (Li, Y et al., 2011).
Strategy 1: keep on adjusting the air flow rate according to the fuel flow rate to maintain the SOFC stack operating temperature constant; Strategy 2: keep on adjusting the air flow rate based on the fuel flow rate to maintain the air-to-fuel flow rate ratio a constant. In each strategy, the fuel flow rate can be regulated through a flow control valve while the air flow rate can be controlled by the air supply valve.

3.3 Power Control Strategy during Load Changing Process

In order to avoid shock of SOFC load change suddenly, the main purpose of the power control strategy is to maintain SOFC subsystem working in a stable condition or to control change rate at an acceptable level. During a normal operation, when the external load increases, the controller will instantly connect the battery or super-capacitor to the power board as shown in Figure 2. Hence, the power output of the SOFC can be increased to the set-point power slowly within a short period of time after load changes and the MGT will produce the remaining demanded power accordingly. The battery power output will be undertaken to fit the rest of the load. On the contrary, when the power load decreases, the MGT output will be decreased instantly by opening the exhaust gas bypass valve (21) to reduce the amount of exhaust gas flowing into the MGT. This gives the SOFC some time to drop down its power output smoothly in a liner ramp way and then the bypass valve closes in a liner ramp way to gradually increase the MGT power output until it reaches a lower power balance. The controller will calculate the power drop from the SOFC system, the opening degree of bypass valve, ramp extension for the SOFC and MGT when a sudden load decrease takes place. Also the transition process in Figure 2 is simplified as a linear line process.

3.4 Development of SOFC/MGT Hybrid Power Control System

Since there are chemical reactions taking place at a high temperature in the SOFC and mechanical rotor rotating with a high speed in the MGT, plus the utilisation of energy from the SOFC exhaust gases by the MGT, how to control both the SOFC and MGT subsystems working harmoniously is a challenge task for all designers. Zhu, Y and Tomsovic, K, 2002 have studied the MGT and fuel cell system models separately and combined them as a combined system. Stiller, C et al., 2006, Jiang, W et al., 2010 and Milewski, J et al., 2010 also developed a control strategy for SOFC and GT hybrid system separately. The power sharing strategy with load change for an SOFC and MGT hybrid system has never been investigated. Based on the control strategy described by the authors of this paper, an SOFC-MGT hybrid power control System has been developed. As shown in Figure 3, there are mainly 3 controllers which perform temperature control, fuel utilisation control and power control.

3.4.1 Temperature Control

One of the main objectives of temperature control is to maintain a proximate constant temperature of SOFC. This is because when SOFC operating temperature exceeds the maximum value or the temperature rises too fast, the thermal stress and thermal fatigue will degrade the fuel cell performance and even the cell lifetime (Larminie, J and Dicks, A, 2003). Here, the temperature control of SOFC stack is carried out by adjusting the air flow rate into system and the burner output. The set temperature is about 1000^0C and a small fluctuation of the temperature is permitted at a temperature below 1050^0C. As showed in Figure 3, if the stack feedback temperature is lower or higher than the set value, its deviation value will be sent to the temperature controller, the controller then send a PID output signal to adjust air flow-rate to the stack based on above deviation value and the signal from power controller. The power controller signal reflects the relationship of SOFC power output and its corresponding air flow-rate. If the stack temperature too low, the temperature controller may start up the auxiliary burner to increase its fuel flow-rate.

3.4.2 System Power and Fuel Utilisation Control

In the SOFC and MGT hybrid system, the former generates up to almost two-thirds of the system power output as electricity. The output power of the SOFC also affects the power output of the GMT. Thus the power control of a SOFC and MGT hybrid system is mainly focused on the control of the SOFC output. The function of the power controller is mainly to control the fuel flow-rate. However, fuel utilisation (U_f) must be controlled as well (Larminie, J and Dicks, A, 2003), since at the same power output, an SOFC may have different fuel flow-rate and different U_f. As shown in Figure 3, the power load (as a set value) is compared with the power output (feedback) and its deviation signal being sent to power controller. The controller has three output signals, one is sent to the fuel flow-rate controller where it combines with the deviation signal of U_f set value and U_f feedback value to send a PID signal to control the system fuel flow-rate; One is sent to the above mentioned temperature controller; The third output (PI) regulates the SOFC cell voltage to control the SOFC power output. Normally, U_f value is set around 85%. Based on U_f, the power controller regulates the fuel flow with the load changes.

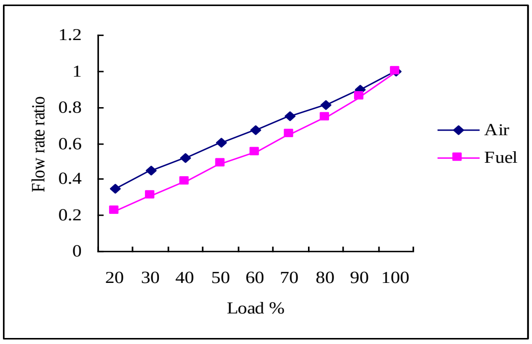
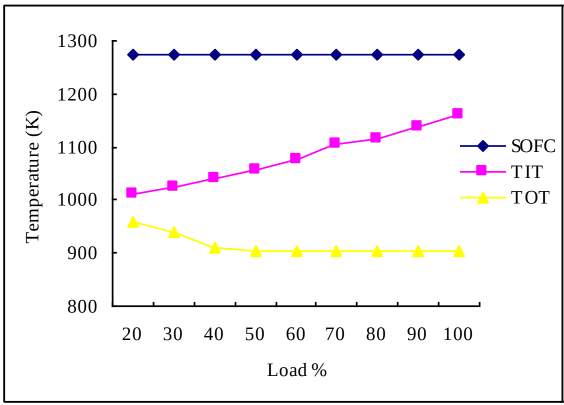


Figure 4: Air and fuel flow-rate vis with power

4. Result and Discussion

Figure 4 shows the designed flow-rates change with the power output when control strategy 1 is applied. The temperatures of the SOFC stack, the turbine inlet (TIT) and outlet (TOT) at different power outputs are shown in Figure 5. It can be seen that the SOFC stack temperature maintains almost



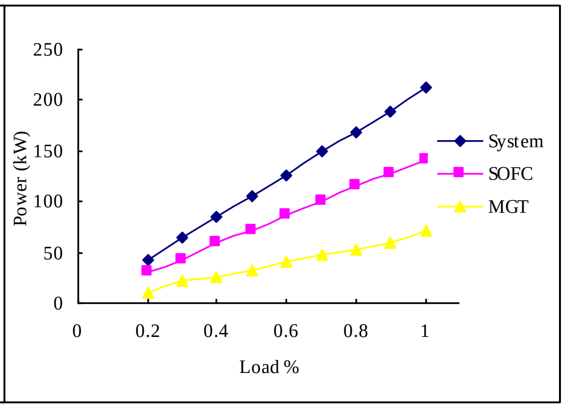


Figure 5: Temperature of SOFC, MGT TIT and TOT with different power output

Figure 6: The hybrid system, SOFC and MGT power output at different load

the same and the MGT inlet temperature increases when the power output increases. However, the MGT outlet temperature drops down as the output power increases due to the increase in the MGT efficiency. The power output distribution between SOFC and MGT in a steady state operation at different loads is shown in Figure 6. In the designed load, the total electric output power of the hybrid system is 210kW, where about 150 kW is generated by the SOFC and 60kW by the MGT.

5. Conclusions

The main components of the SOFC and MGT hybrid power system for ship application, including the SOFC reformer, cell stack, has been discussed. Based on the developed hybrid power system, its dynamic models with the novel control strategies have been introduced and discussed. The newly developed control strategies for start-up, shutdown, part load and load change processes are able to protect the SOFC cell stack from sudden the change of load. The controlled fuel flow rate, air flow rate, SOFC stack temperature and MGT inlet and outlet temperatures offer the hybrid system a high efficiency

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