Research and Analysis on Cold Start of Fuel Cell Bus in Low Temperature Environment

Changhe Wei¹, Chao Wang²*, Dan Li³, Wenbo Wei⁴ and Hui Zhou⁵
¹,²,³,⁴Beijing Auv Bus, BeiQi Foton Motor Co.,LTD, Beijing, China
⁵Beijing Industry University, Beijing, China

*Corresponding author email: wangchao40@foton.com.cn

Abstract. Based on the characteristics of the components of the fuel cell bus, and on the premise of satisfying the best matching of fuel cell system, power cell system, driving system and transmission system, the purging control strategy of fuel cell system is designed. Taking the fuel cell system as the control variable, the conditions of the cold start heating energy source switching and the target temperature of the fuel cell system starting are determined by the total energy demand and the power cell energy. The integrated thermal management system and the purging control strategy of the fuel cell system proposed in this paper can meet the needs of the fast start of the fuel cell bus at -30°C. Through the energy compensation in the low temperature environment, the scheme can provide the heating energy needed for the start-up of the fuel cell. The experimental results show that the output power of the fuel cell is from 42% to 75% of the rated power, and the waste heat utilization accounts for 32% - 100% of the total power.

Keywords: Fuel Cell Bus; Water Content; Air Metering ratio; Purge Control Strategy; Integrated Thermal Management System; Cold Start.

1. Analysis of Cold Start of Fuel Cell System at Low Temperature
Through the start-up performance test of Maosheng Wu [1] at different temperatures of 5-30°C, it is found that the fuel cell system only needs less than 60 seconds to stabilize the output voltage after ventilation at room temperature, while at about 5°C, the time to stabilize the output voltage needs 6-8 minutes, and increasing humidity does not improve the output power. Y.Hishinuma [2] started the fuel cell at -10°C with a constant potential of 0.5V, the initial current density increased rapidly, and then declined sharply. The failure of cold start-up of fuel cell at low temperature is mainly caused by the freezing of water generated by cathode on the surface of catalyst [3]. Without external assistance, the minimum temperature for self-starting of PEMFC is -5°C. XM. Oszcipok [4] investigated the cold start ability of fuel cell monomer and module respectively at low temperature. It was found that the module could start successfully at -10°C under different current load conditions, but it was very sensitive to the load at -20°C, and the start-up failed. Through the analysis of the relationship between the parameters of electrode and diffusion layer and the cold start-up characteristics, it is found that the electrode quality, gas flow rate, diffusion layer structure and membrane resistance have great influence on the cold start-up. Keeping the film, catalyst layer and diffusion layer at a higher drying level before start-up is conducive to improving the cold start ability [5].

1.1. Research on Cold Start Strategy
There are three strategies for low-temperature self-starting of fuel cells: 1) constant pressure/constant current/constant power method; 2) reactant starvation method; 3) reactant mixed combustion method.
Constant power start-up can be divided into high current and low current. Constant power with high current can generate heat rapidly, and the fuel cell system has the fastest rate of temperature rise. However, due to the large amount of water production, if the temperature cannot rise above 0ºC, the catalyst layer will be blocked by ice quickly, resulting in the failure of start-up. When the constant power with low current starts, the output voltage is high and the heat production is small, the fuel cell system temperature rise rate is the slowest, the heat dissipation is more, and the fuel cell system is difficult to start, as shown in figure 1. In addition, they studied the effect of the initial water content in the proton exchange membrane on the low-temperature start-up of the fuel cell system in the constant power start-up mode, as shown in figure 2. The lower the initial water content in the proton exchange membrane, the longer the discharge time of the fuel cell system, the higher the corresponding heat production, and the easier the fuel cell system to start successfully at low temperature.

After investigation, at present, constant voltage/constant current/constant power mode is adopted for low-temperature startup, which can be successfully started above -10ºC. In addition, there must be ice formation during startup in this mode, which may cause damage to battery components and accelerate life degradation. Compared with the constant voltage/constant current/constant power starting mode, the reactant starvation method can usually generate more heat. There are two common ways: 1) reduce the metering ratio under constant current, generate greater over potential, thus generate more heat; 2) increase the current under constant metering ratio, and the output voltage will be reduced at the same time, and increase the heat production in both ways. However, it is easy to happen the reverse pole in case of lack of air when this method is used, which requires high control strategy and membrane electrode material. This is also the low-temperature starting strategy adopted by Toyota at present, and its mechanism is shown in figure 3 [6].

The mixed combustion method of reactants is to burn reactants, generate heat and heat the fuel cell system to achieve the purpose of low-temperature start-up. Therefore, the current use of this method is less.
1.2. Secondary Purging Strategy

Low temperature purging is mainly to remove the freezing water and free water in MEA and reduce the damage of MEA caused by freezing at low temperature. Therefore, purging is very important. The selection of purging strategy involves system matching, the structure of vacuum purging is complex, and the cost performance of vehicle is not high. As the pressure difference often forms instantaneously, it will cause mechanical damage to MEA and affect the service life. Therefore, in order to better fit the actual vehicle use and reduce the impact on MEA, we choose the secondary low-temperature purging strategy [7].

The actual operation of the fuel cell system is about 60ºC, while the room temperature is set to 25ºC, so the purging test is first verified under the above temperature conditions. In order to keep consistent with the actual operation of the vehicle, nitrogen is not used during the test, hydrogen is used as anode and air is used as cathode. The purging curve of fuel cell system at 60ºC is shown in figure 4. According to the results, the larger the purge gas flow is, the shorter the time for the internal resistance of the fuel cell system to reach the equilibrium point is. Considering the acceptance of the purge time after shutdown in the actual use process, this paper determines the strategy of large flow purge [8].

![Figure 4. Change curve of internal resistance of purging gas with different flow rate at 25ºC](image1)

![Figure 5. Change of internal resistance of fuel cell system under secondary purging strategy](image2)

According to the vehicle conditions, in this paper, the purging of fuel cell system at 25ºC is studied. At this time, both hydrogen and air use dry gas, which is consistent with the environment. The change curve of internal resistance is shown in figure 5, which is consistent with the purging rule of 60ºC. Under the condition of air volume purging, the internal resistance of fuel cell system increases rapidly, indicating that the internal moisture removal of fuel cell system is faster. On the basis of the above purging experiments, by matching the operation conditions of the system, combining the energy consumption and purging time requirements of the system, the secondary purging strategy suitable for the fuel cell system is determined. The determined purging curve of fuel cell system is shown in figure 6, and the total purging time is less than 5 minutes.

2. Effect of Purging on Fuel Cell System Performance

The specific operation of the purge durability test scheme designed in this paper is as follows: 1) 5kW fuel cell system operates normally for 30 minutes under rated current to ensure the internal condition of fuel cell system is consistent before each purging; 2) Purge according to the secondary purging strategy determined above, and reduce to room temperature after purging; 3) Repeat steps 2 and 3 under normal load to rated current at room temperature to carry out purging durability test; 4) After 100 times of purging durability test, the polarization test of fuel cell system was carried out to investigate the effect of low temperature secondary purging on the performance of fuel cell system; 5) A total of 500 purge durability tests and 6 polarization tests were conducted. The performance and internal resistance curve of 5 kW fuel cell systems in the whole test cycle are shown in figure 7. It can be seen from the figure that the performance of the fuel cell system changes little in the whole test cycle, and there is basically no attenuation, while the internal resistance curve of the fuel cell system also basically coincides. There is a slight difference under the condition of small current, because the fuel cell system is relatively dry under the condition of small current and greatly affected by the operating conditions.
3. Integrated Thermal Management System and Control of Fuel Cell Bus

3.1. Design of Integrated Thermal Management System

The preliminary design scheme of the vehicle integrated thermal management system is shown in figure 8. The system retains the original thermal management system of fuel cell and power battery (including heat dissipation and heating), and the vehicle heating system adopts water heating mode. The heat exchanger of liquid-liquid heat exchange is used to exchange the cooling water of fuel cell, the medium of heating system and power cell insulation system, so as to realize the utilization of waste heat under low temperature and reduce the heating energy consumption.

3.2. Optimal Control of Power System in Low Temperature Environment

Under normal conditions, the fuel cell system is not required for heating and insulation in the passenger compartment and power battery, so the heat exchanger is disconnected by valve control, the cooling systems of fuel cell system and power cell system operate in normal working mode, as shown in figure 9.

At low temperature, fuel cells outlet temperature is about 80ºC, some of which are exchanged with the heating system through heat exchanger. The heating system needs to provide hot water at 70ºC for the heat exchange with defroster and radiator in passenger compartment. After heat exchange, the water temperature is about 50~ 60ºC, and then used for thermal insulation of power battery, as shown in figure 10 and 11.

When the vehicle stops or runs at low speed, the heat dissipation power is less than the heating demand power, turn on the electric heater of the heating circuit for auxiliary heating. In the start-up process of low-temperature condition, the fuel cell and the thermal management system of power cell work in small cycle by controlling the valve. The power cell heats up rapidly with heater to improve the output capacity; while the fuel cell heats itself, the electric heater can be used to accelerate the temperature rise.
4. Low Temperature Start Test and Performance Evaluation of Fuel Cell Bus

For real vehicle application, combined with the low-temperature control strategy of fuel cell engine, low-temperature start strategy, low-temperature vehicle thermal management strategy, adaptive energy management strategy of power system, braking feedback strategy, etc., the whole vehicle control algorithm for real vehicle is developed, as shown in figure 12. Parameters optimization results and real-time control strategy are applied to vehicle design and control, the system design and control strategy are improved through the test results feedback, and the degradation of fuel cell and power cell in low temperature environment is obtained through the analysis of data.

This paper proposes the performance and durability evaluation method of fuel cell high-speed bus in low temperature environment, and the test report is obtained by analyzing the results of the real vehicle test.

In Hailar's extremely cold experiment, we found that after a long time shutdown, comparing the internal temperature of the stack with the ambient temperature for a second low-temperature purging, according to the internal temperature of the stack and ambient temperature, carry out the secondary low temperature purging. It can not only effectively control the internal freezing water, but also more accurately control the water content of MEA at the current temperature. As shown in figure 13, the loading power and temperature rise speed of the stack after the secondary purging are faster than that after the single shutdown purging and no purging.

The extreme cold test data of Hailar show that the integrated thermal management system of Foton's 12 meter fuel cell bus can greatly reduce energy consumption at ambient temperature from -25°C to -30°C. As shown in figure 14, under the ambient temperature of -25°C to -30°C, the coolant of the bus radiator is heated to 70°C within 20 minutes (at this time, the temperature in the compartment reaches 10-15°C), and at least 30kW PTC heater is required. However, this model is only equipped with a 10kW PTC heater, the PTC heater only needs to heat the coolant temperature to 10°C before the
integrated thermal management system is started to ensure that after the integrated thermal management system is started, the residual heat of the fuel cell system can quickly heat the temperature in the compartment to 10-15ºC. The integrated thermal management scheme proposed in this paper can not only ensure the comfort of passengers, but also reduce the energy consumption and cost of the bus. It can be seen from the experimental data that the higher the actual output power of the fuel cell, the greater the proportion of waste heat utilization in the total heating power.

5. Conclusions
The main purpose of this paper is to break through the technical bottleneck of fast start, power performance, economy, and passenger comfort of fuel cell bus in extremely cold environment. The integrated thermal management system and the purging control strategy of the fuel cell system proposed in this paper can meet the needs of the fast start of the fuel cell bus at -30°C. The experimental results show that the output power of the fuel cell is from 42% to 75% of the rated power, and the waste heat utilization accounts for 32% - 100% of the total power. The research results of integrated thermal management of fuel cell stack are applied to fuel cell bus. The research results are verified by extreme cold test and analyzed by experimental data, it has a guiding role for the design of fuel cell bus in the future.

References
[1] Maosheng Wu, Datai Yu, Guo Li, Yangping Zhang. Effect of environmental conditions on performance of proton exchange membrane fuel cell [J]. Journal of Beijing University of science and technology, 2003, 25(6): 584-586.
[2] Tabe, Yutaka Saito, Mastaka Fukui K, et al. Cold start characteristics and freezing mechanism dependence on start-up temperature in a polymer electrolyte membrane fuel cell[J]. Journal of Power Sources, 2012, 208: 366-373.
[3] Ali Akrem Amamou, Sousso Kelouwani, Loic Boulon, Kodjo Agbossou. "A Comprehensive Review of Solutions and Strategies for Cold Start of Automotive Proton Exchange Membrane Fuel Cells", IEEE Access, 2016.
[4] Hongye Tang, Anthony Santamaria, John Bachman, et al. Vacuum-assisted drying of polymer electrolyte membrane fuel cells [J]. Applied Energy, 2013, 107: 264-270.
[5] R. Lin, Y.S. Ren, X.W. Lin, Z.H. Jiang, Z. Yang, Y.T. Chang. "Investigation of the internal behavior in segmented PEMFCs of different flowfields during cold start process", Energy, 2017
[6] Maruo, Tsuyoshi, et al. "Development of Fuel Cell System Control for Sub-Zero Ambient Conditions." Wcx™ 17: Sae World Congress Experience.
[7] YS Kim, SANG Young, IL Kim, et al. Study on a purge method using pressure reduction for effective water removal in polymer electrolyte membrane fuel cells [J]. International Journal of Hydrogen Energy, 2015, 40: 9473-9484.
[8] Qian Guo, Yueqi Luo, Jiao K. Modeling of assisted cold start processes with anode catalytic hydrogen–oxygen reaction in proton exchange membrane fuel cells [J]. International Journal of Hydrogen Energy, 2013, 38: 1004-1015.