Development and Validation of a 100 kW-Class Fuel Cell System Controller for Passenger Cars

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Abstract. Fuel cell (FC) vehicle is an important technology route to achieve carbon neutrality in transportation. This paper examines the integration, system control, and performance test of a high-power self-humidifying fuel cell system for passenger cars. Firstly, a high specific power FC system integration scheme is designed, and a highly integrated 100 kW self-humidifying fuel cell system is realized based on the installation requirements of passenger cars. Then, the system controller application layer is developed using Matlab/Simulink and the controller rapid development prototype for complete closed-loop control of each subsystem, such as hydrogen supply, air supply, cooling, and electrical management. Finally, the performance dynamics experiment of the 100 kW FC system is conducted based on the developed system controller. The results show that the developed system controller provides high-quality control effects of operating parameters such as air flow and pressure, hydrogen supply pressure, and cooling water temperature for the stack to meet different operating requirements. The highest efficiency of the system reaches 62%, and the coefficient of variation (C_V) of the cell voltages is controlled to be less than 1%. This study contribute to accelerate the deployment and application of high-power FC systems in passenger cars.

Keywords: Fuel cell system · System controller · Software development · Performance test

1 Introduction

Proton exchange membrane fuel cell is an energy conversion device with high power density, high efficiency, zero pollution, and good low-temperature starting characteristics, which is an important research orientation for the revolution of future automotive power systems [1]. Fuel cell vehicles equipped with fuel cell systems have the advantages of short hydrogen refueling time, long range and good environmental adaptability to become an important technological route to achieve carbon neutrality in new energy vehicles worldwide [2]. The performance and durability of automotive fuel cell systems during service are two extremely important objectives [3].

Currently, the development route of fuel cell systems for passenger cars is moving toward high integration, high power density, and long durability [4]. Toyota motor released its state-of-the-art fuel cell passenger cars in 2014 and 2020 [5–7], The 2nd-generation MIRAI has a volumetric power of up to 5.4 kW/L [6], and system components

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such as DC/DC converters, auxiliary components, and controller hardware are highly integrated with the electric stack. China's fuel cell vehicle technology is booming but still falls short of the world's most advanced level. FC systems are subject to variable environmental conditions and operating conditions, which is a huge challenge for performance and durability [8]. Innovative designs from the perspective of key materials and structures to achieve performance and endurance improvements from monolithic cells to systems have made significant contributions, but it takes a long lead-time as well as a great expense [9]. The development of superior controllers based on existing materials to improve the net power output, power generation efficiency, and durability of the system has been strongly demanded [10]. The system controller regulates the operating parameters such as airflow, pressure, and temperature at the macroscopic level to improve the electrochemical reaction efficiency and mitigate material degradation such as carbon corrosion, platinum agglomeration, and membrane dry cracking at the microscopic level [11–13]. The automotive fuel cell system controller consists of air supply subsystem, hydrogen supply subsystem, cooling subsystem, electrical management subsystem and monitoring subsystem. Coordinated control of each subsystem to achieve high performance and long life operation of the fuel cell system.

In this study, a 100 kW-class high specific power self-humidification fuel cell system is integrated for the R&D requirements of FC passenger cars. On the developed system bench, the system controller software is developed using Matlab/Simulink and Motohawk rapid development prototype. The developed FC system controller ensures optimal conditions in the FC stack by manipulating system components considering hardware limitations to achieve maximum system performance such as system efficiency and power.

2 FC System Integration

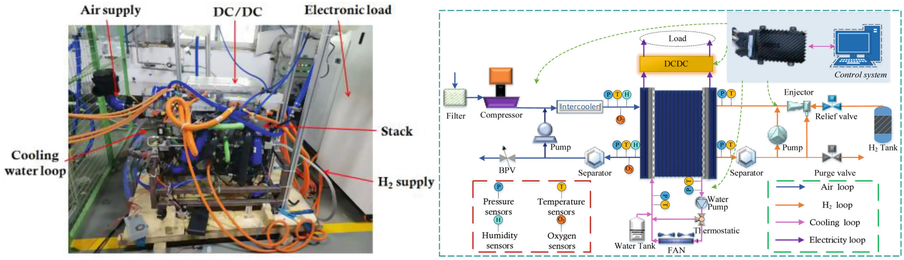

Fig. 1. 100 kW-class high specific power self-humidifying fuel cell system schematic and bench diagram.

The integrated solution of FC system starts from the demand of the whole vehicle, targeting high specific power density, and puts forward the requirements for fuel cell system, power stack, and components level by level. The schematic and the integrated system are shown in Fig. 1. The innovation of the system integration is the removal of the traditional external humidifier and instead the self-humidification function through material and structural innovation, hydrogen recirculation and hydrogen-air counter-flow configuration, which is significant for the high integration of the whole system.

3 FC System Controller Development

Figure 2 shows the software architecture of the FC controller application layer and the Simulink flow diagram. SECM-112 controller has 33 analog input interfaces for all temperature, pressure, flow and other sensors in the fuel cell system. The system contains 7 CAN signals for air compressor, circulation pump, thermostat, DCDC, PTC, CVM, and water pump. The information interaction between FCU and each component is realized through CAN bus. Some valves and fans involved in the system are driven by low-side output (Boolean or PWM) and H-bridge.

In this developed system controller, setpoint of the FC-system net power, the ambient temperature, and atmospheric pressure are inputs. The calculated system net power is the output as well as the other values in the FC system, the polarization state of the stack, such as current, voltage, the state variables of system, such as flow rate, pressure, temperature, humidity, and oxygen concentration, the actuation values of components, such as compressor speed, pump speed, valve position, and fan speed. According to the vehicle operating conditions, the system state machine consists of nine states: power on, self-test, standby, automatic operation, purge, discharge, shutdown, and emergency stop. Different control calculations are performed within each state, and then the components are driven to achieve the appropriate function. The controllers in Fig. 2 consist of the electric power controller, the monitoring controller, and the actuator controllers for the system components in air, H2, and cooling subsystems. Such a hierarchical and simple controller architecture enables independent investigation of optimal stack operating conditions and hardware specifications.

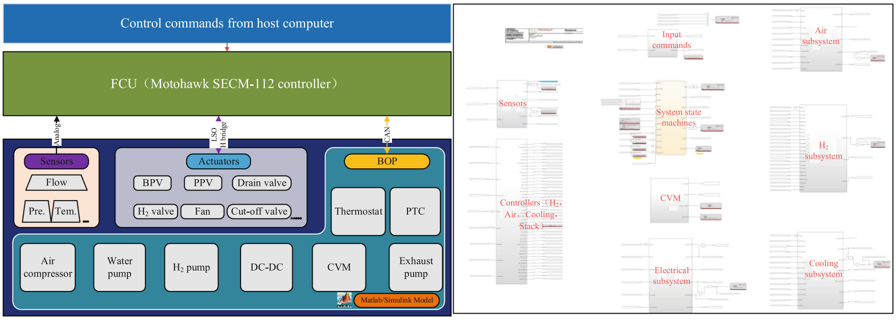

Fig. 2. Software development architecture and closed-loop control procedures for the entire FC system.

In general, the control of the air subsystem is the key to determine the high efficiency, high performance and long life of the FC system [14]. The control goal is to quickly provide precise air flow and pressure to the stack during cyclic load changes to avoid oxygen starvation and excessive air compressor power consumption. In this study, a decoupled flow and pressure control algorithm is implemented for the air subsystem. The stack current and is given to the pre-determined functions, which are built based on experimental data to achieve the maximum system net power considering the stack power, compressor power loss, and pump power loss. Then, the setpoints of air pressure and flow are is determined. The setpoints of the flow and pressure are converted to the compressor speed and back pressure valve opening by a double PI controller including the supplemental functions of integral anti-windup and feedforward compensation methods for the stable operation.

Figure 3 shows the results of the close-loop setpoint tracking performance of the air flow rate and pressure by a series of step load profile. The current operation curves are shown in Fig. 5(a), and the results show that the DC/DC responds to the set current command almost indistinguishably, indicating that the reactant supply adequately meets the current loading demand. It is also confirmed that the air flow rate could trace the setpoint within an acceptable deviation less than ± 2.5 g/s as shown in Fig. 5 (b), the OER fluctuation range within 0.2 as shown in Fig. 5(c), and pressure fluctuation within ± 1.5kPa. It indicates that the error effect is within the acceptable range and meets the practical application requirements considering the influence of sensors and controllers in acquisition, measurement, and noise.

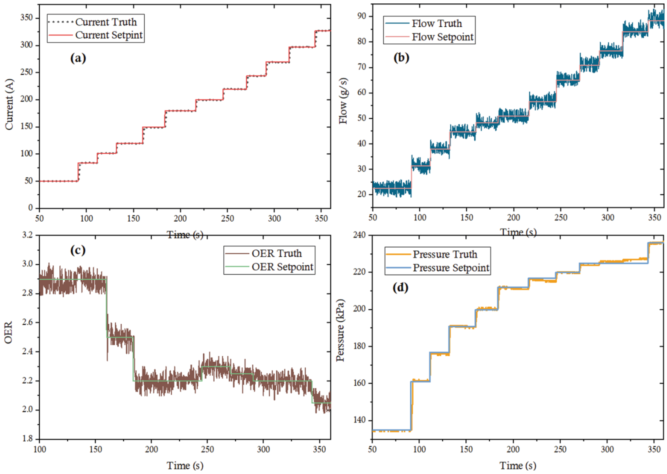

Fig. 3. Performance evaluation of closed-loop setpoint tracking with decoupled air flow and pressure.

4 FC System Performance Discussion

4.1 System Power and Efficiency

The developed system control algorithm is written into the fuel cell system controller, and performance experiments of the 100kW system are conducted. Figure 4 shows that the average output voltage of the individual cell is 0.62 V when the current density is loaded to 1781 mA/cm^2, and the output power of the stack reaches a peak of 120.2 kW, at which the peak net power of the system reaches 97.8 kW and the power consumption of the auxiliary components accounts for 18.6%.With the rise of the net power of the system, the efficiency shows a decreasing trend. The maximum efficiency of the system reaches 62%, which is the advanced level of current FC systems for passenger cars.

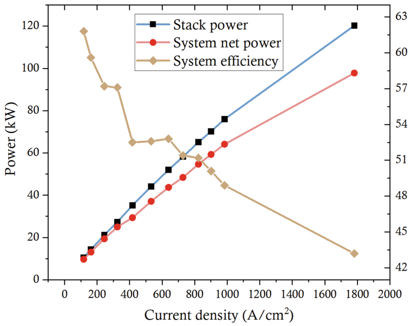

Fig. 4. 100 kW-class FC system output performance analysis with the implementation of the developed system controller.

4.2 Stack Consistency

Figure 5 shows the cell voltage coefficient of variation (C_V) during the load variation. The trend of C_V is observed during the period when the stack is loaded from start-up to 70 kW. In the start-up phase (around 0 s), the instability of the cell voltage is due to the lagging response of the hydrogen and air supply, which results in a C_V of 4.5%. Afterwards, the voltage stabilizes quickly and C_V drops rapidly. The C_V is kept within 1% during the entire load variation, which is a really bright result and provides the basis for the high reliability and durability of the system operation. After 2100 s, the system enters into the shutdown procedure, the reactants are cut off and start discharging, thus C_V increases.

5 Conclusions

In this paper, we developed a system controller for high efficiency and long durability on an integrated 100 kW passenger car fuel cell system. The complete control program is developed in conjunction with Matlab/Simulink and the Motohamk rapid control prototype. The closed-loop control performance of the controller is discussed, represented by the air subsystem. With the implementation of the developed FC system controller, the dynamic performance of the entire system is investigated. The results show that the FC system demonstrates excellent potential in terms of net power, system efficiency, and consistency. The implementation of this study is important for advancing the commercialization of fuel cell passenger vehicles.

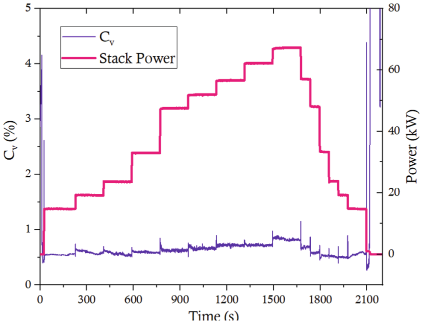

Fig. 5. Consistency analysis of 100 kW-class FC system under dynamic conditions output performance analysis with the implementation of the developed system controller.

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