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Design of New Test System for Proton Exchange Membrane Fuel Cell

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Abstract: A comprehensive test system for proton exchange membrane fuel cells (PEMFCs) is designed and developed for monitoring and controlling the inlet and outlet parameters and safety issues of fuel cells. The data acquisition and output instruction rely on the connection between PLC (programmable logic controller) and OPC (object linking and embedding for process control). Based on Siemens S7-200 series PLC and PID (proportion integration differentiation) technology, the margin of error in relative humidity of inlet air is controlled at less than 0.7%. Furthermore, a hydrogen recycling system and an alarm module are introduced, considering the hydrogen or nitrogen solenoid valve power failure, cooling fan power failure, temperature anomaly, and hydrogen leakage. This developed test system is evaluated by the experimental investigation of PEMFC performance. The results show that the test system has very good test and control performances. At a cell temperature of 40 °C, enhanced performance in the polarization tests is depicted at a high humidification temperature of 60 °C.

Keywords: proton exchange membrane fuel cell; test system; programmable logic controller; LabVIEW; object linking and embedding for process control; inlet/outlet parameters; safety issue; test and control performance

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1. Introduction

In recent years, renewable energy has been rapidly developed under the background of the increasing pressure of fossil fuel depletion and environmental protection. Compared with solar energy and wind energy, with the disadvantage of intermittency, the employment of electrochemical generators, such as fuel cells, is needed to improve the utilization rate and stability of renewable energy [1]. A proton exchange membrane fuel cell (PEMFC) has unique characteristics, such as fast startup at ambient temperature, high energy conversion efficiency, low noise, zero emission, easy maintenance, etc. [2–15]. The research on PEMFC for power supply and new energy vehicles involves material development, water and heat management, temperature, humidity optimization, etc. The cell output performance and service life are affected by the working conditions, including reactant concentrations, gas pressure, temperature, and humidity [16,17].

The proton exchange membrane, such as Nafion® and Dow®, is used as the polymer electrolyte, and the water content in the membrane directly affects the performance of fuel cells [18]. Low relative humidity results in slow electrode kinetics, including slow electrode reaction and mass diffusion rates, and high membrane resistance [19–21]. The commonly used methods to maintain a certain amount of water content in the membrane depend on external humidification by introducing water from the inlet. However, too much water could flood the electrode and lead to materials degradation. It was reported that local flooding could accelerate carbon corrosion, while the corrosion of PEMFC catalysts resulted from the reactant starvation due to the water flooding process [22]. In the work of Fan et al., the detachment or agglomeration of Pt particles from the carbon supports were found in the TEM images under a high potential and water flooding, especially at the outlet [23]. The accuracy control of inlet humidity for water management has been an essential task in PEMFC investigation.

PEMFC test systems, with some basic functions, including gas supply, temperature and humidity management, have been developed with the devices, such as solenoid valve, mass flow controller, temperature and humidity sensors, etc. In order to meet different testing requirements, modules with various functions were designed [24–26]. Kuo et al. [24] designed a self-humidification system with an air humidity of more than 95% to solve the problem of insufficient humidification and to avoid the dehydration of the polymer membrane. Zhang et al. [25] built a control system to enable a safe start and shutdown while monitoring the sensor signals. The G60 test platform is a commercial fuel cell test system developed by Greenlight Innovation Company (Burnaby, Canada), which combines the gas control function with the visual presentation of a polarization curve and power curve of the fuel cell through the internal electronic load [26].

The automatic fuel cell test system is developed by introducing a control module based on the connection between lower machine and the upper computer [27–30]. Cheng et al. [27] proposed a hydrogen fuel cell test system using the joint control of PLC (programmable logic controller) and MATLAB/Simulink to improve the gas control performance. Liu et al. [28] designed a high-power PEMFC test system that used LabVIEW software and a fuel cell controller unit to achieve real-time monitoring, control, and fault diagnosis and to ensure a stable operation. Based on the PLC and LabVIEW platform, Peng et al. [29] designed a test system for air-cooled self-humidifying PEMFC with the function of start and stop timing control, hydrogen exhaust alerting, etc. Rosli et al. [30] designed a high-temperature PEMFC test system using LabVIEW and channel frame processor hardware, which could monitor the voltage and current generation and the inlet and outlet temperatures.

While most of the commercial PEMFC test systems focus on the convenience improvement with basic functions, the instrument development on strictly controlling the working condition is rare, especially the gas humidity. In this study, we provide a resolution for accurate humidity control by mixing the dry air with humidified air in the bubble humidifier. Otherwise, we design a comprehensive test system, with the hydrogen recycling and back pressure control, meanwhile considering the electrical safety and hydrogen safety issues. Based on the previous works, OPC (object linking and embedding for process control) technology is used to connect PLC and LabVIEW for the automatic control of the test system.

2. Design of Test System

A PEMFC test system, including the gas control module and safety alarm module, was designed with the compositions, as shown in Figure 1. The gas control module was for the inlet control, hydrogen recycling, and back pressure control. The safety alarm module was consisted of the hydrogen leakage alarm, power failure alarm, and temperature alarm.

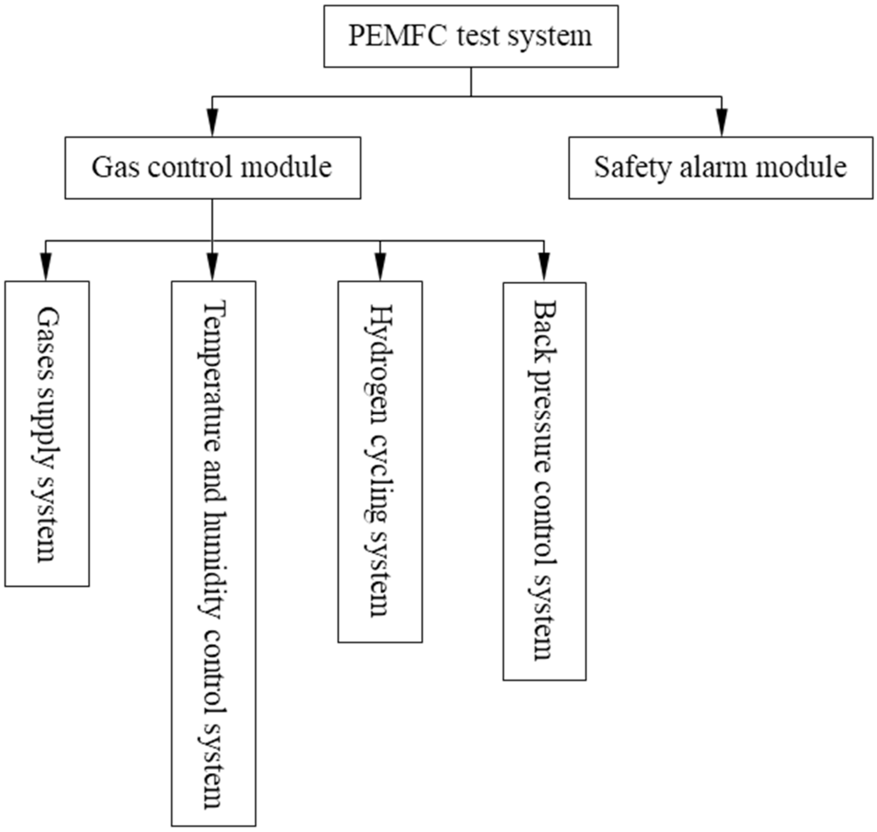

Figure 1. Basic composition diagram of the PEMFC test system.

2.1. Gas Control Module

The gas control module of PEMFC test system was composed of PRV (pressure reducing valve), S (solenoid valve), MFC (mass flow controller), CV (check valve) and PT (pressure transducer), THS (temperature and humidity sensor), GWS (gas–water separator) and VP (vacuum pump). The diagram is shown in Figure 2.

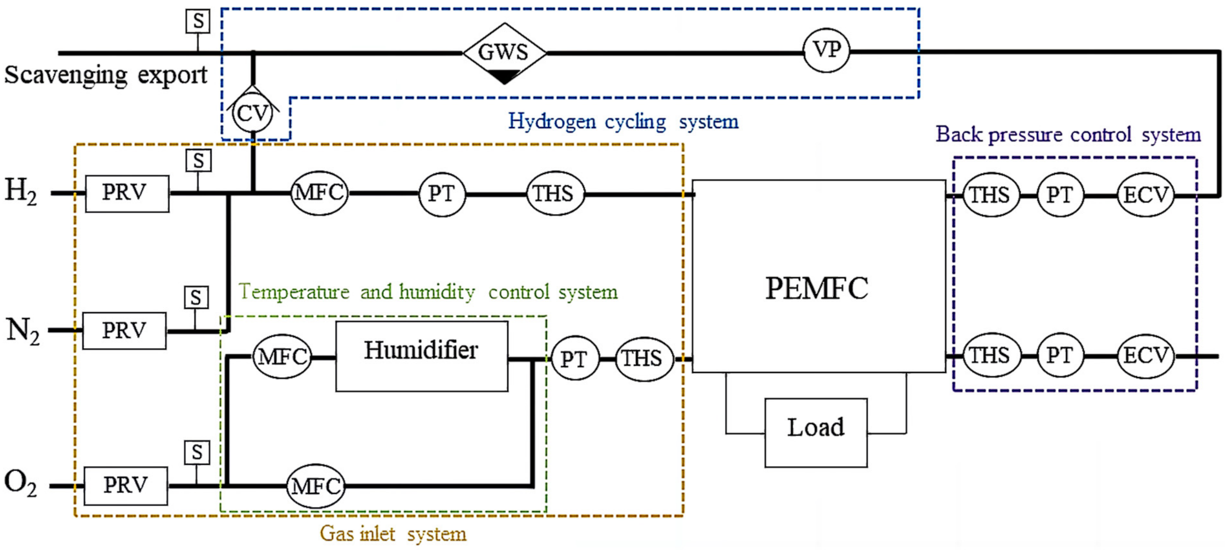

Figure 2. Schematic diagram of the gas control module.

2.1.1. Gases Supply System

Hydrogen and nitrogen came from the hydrogen and nitrogen cylinders, respectively. They both passed through the pressure relief valve, solenoid valve, and mass flow controller to the PEMFC anode. Nitrogen was used for purging the system after the hydrogen supply. Air was provided by the air compressor with a certain pressure. After flowing through the solenoid valve and mass flow controller, air entered the PEMFC cathode after heating and humidification. The temperature, humidity and pressure sensors were used to monitor the parameters of the inlet gases.

2.1.2. Temperature and Humidity Control System

Based on a self-designed bubble humidifier with temperature and humidity regulation, the inlet humidity was controlled by mixing the dry air with humidified air. The profile of the humidifier is shown in Figure 3. First, the heating belt heated up the system according to the set temperature. Then, according to the difference between actual humidity and set value, the mass flow rates of dry air and humidified air were regulated based on PID technology via two mass flow controllers.

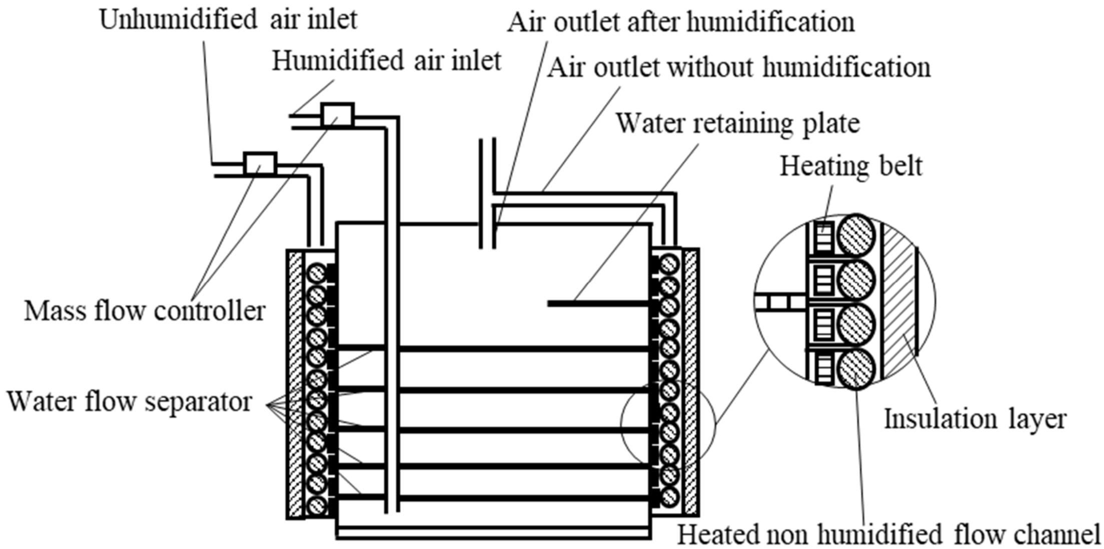

Figure 3. Section view of the humidifier.

2.1.3. Hydrogen Cycling System

During the operation of PEMFC, the utilization rate of hydrogen is about 65–95%, and the direct emission will not only cause a waste of resources, but also bring huge safety risks [31]. The designed hydrogen cycling system was composed of a hydrogen circulation pump, a gas–water separator, and a check valve, as shown in Figure 4. The hydrogen circulating pump was used to pressurize the outlet gas, which would pass the gas–water separator to prevent excess water from the flooded membrane. The check valve was employed to prevent the gas counterflow.

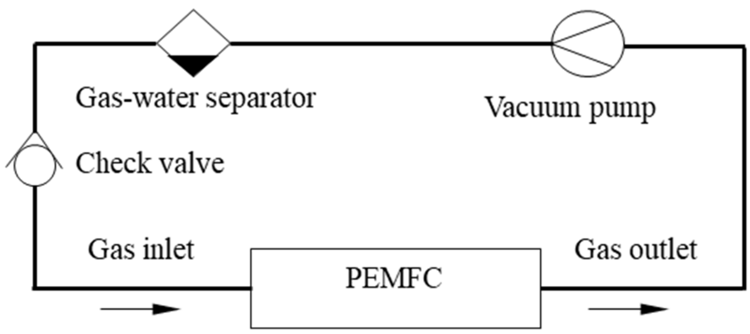

Figure 4. Diagram of the hydrogen cycle module.

2.1.4. Back Pressure Control System

The back pressure system for regulating the internal pressure of PEMFC was designed by controlling the outlet flow at the anode and cathode. Meanwhile, the two mass flow controllers worked in coordination with each other to prevent the membrane damage caused by a high pressure difference. The flow chart of the back pressure control module is shown in Figure 5.

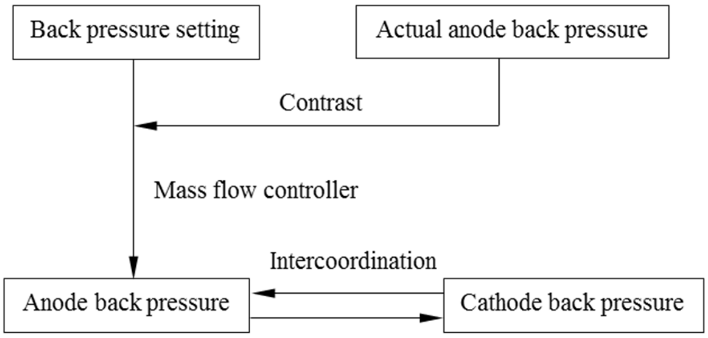

Figure 5. Flow chart of the back pressure control module.

2.2. *Safety Alarm Module*

In order to avoid a potential safety accident during the operation of the PEMFC test system, an alarm module was designed to monitor the possible anomalies and make corresponding responses to hydrogen or nitrogen solenoid valve power failure, cooling fan power failure, temperature anomaly and hydrogen leakage. The specific workflow of the safety alarm module is illustrated in Figure 6.

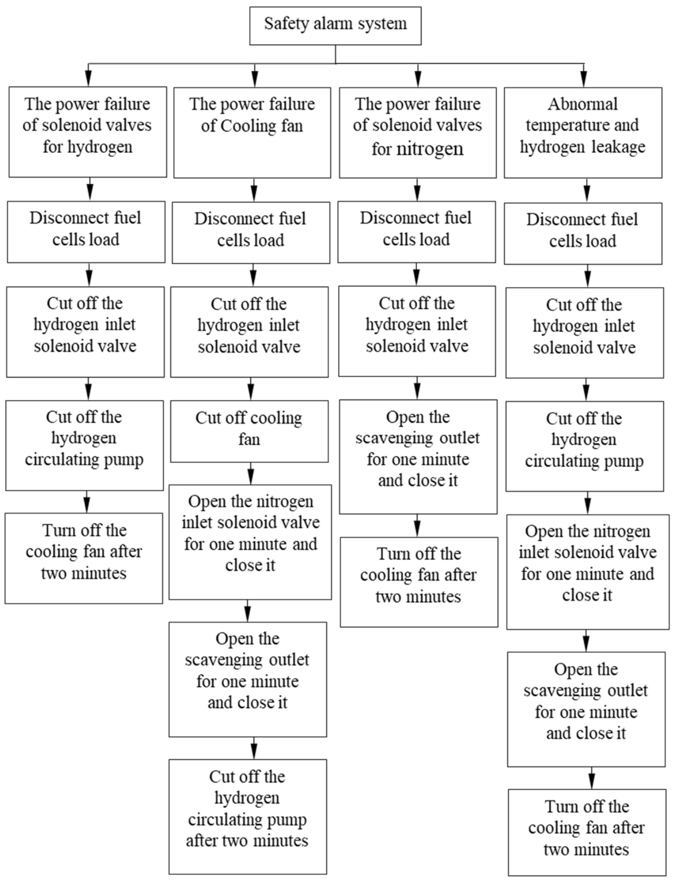

Figure 6. Flow chart of the safety alarm module.

3. Design of Control System

The PEMFC test system based on PLC, LabVIEW and OPC technology was developed for comprehensive functions such as the data acquisition and output of PEMFC, real-time monitoring, as well as the system fault alarm and data curve display.

3.1. PLC Technology

PLC is an important tool for developing independent automation systems, which has been widely used in implementing automated fuel cell test systems. In this study, a Siemens PLC S7-200 with CPU 224XP was used, which integrated 14 inputs/10 outputs for 24 digital I/O points, 2 inputs/1 outputs for three analog I/O points and seven expansion modules. The maximum expansion value was 168 digital I/O points or 38 analog I/O points. Two RS485 communication/programming ports had a PPI communication protocol, MPI communication protocol and freeform communication capability, with internal analog I/O, bit control feature, linear ramp pulse command, diagnostic LED, data logging, recipe function, etc. The electrical connection diagram and physical connection diagram are shown in Figures 7 and 8, respectively. The data collected by PLC was the analog signal converted by the sensor, and the analog signal need to be converted into the corresponding physical values, including flow rate, temperature and humidity, pressure, etc. In addition, PLC control technology was used for the manual/automatic control, safety alarm and parameter-setting.

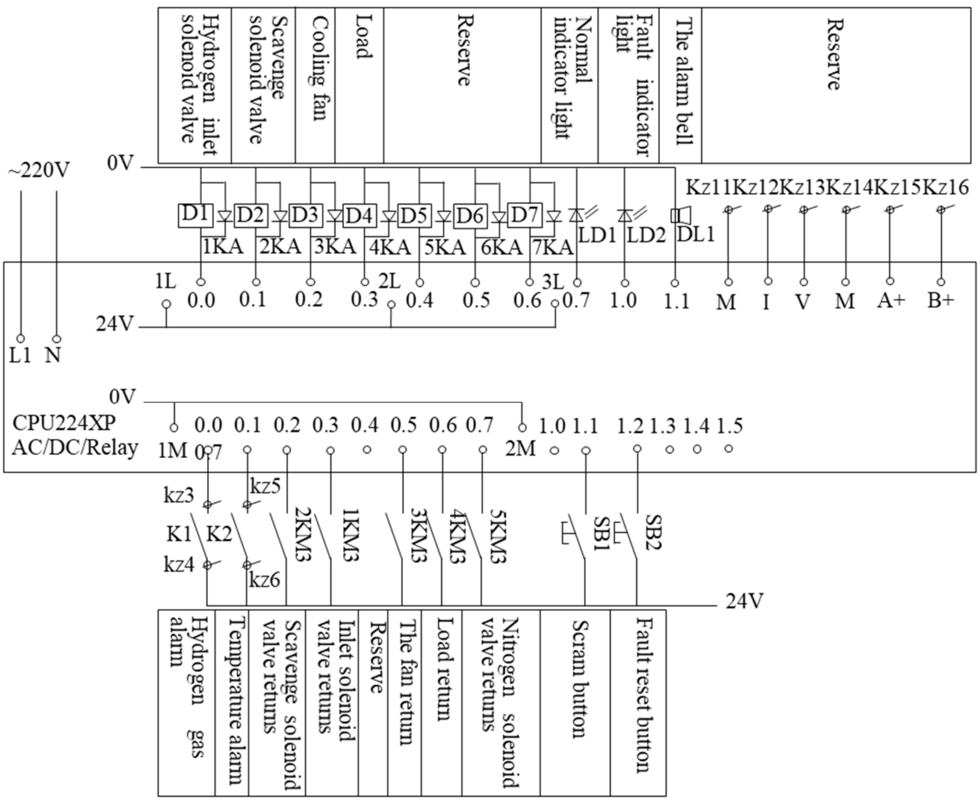

Figure 7. Main electrical connection diagram of the PLC.

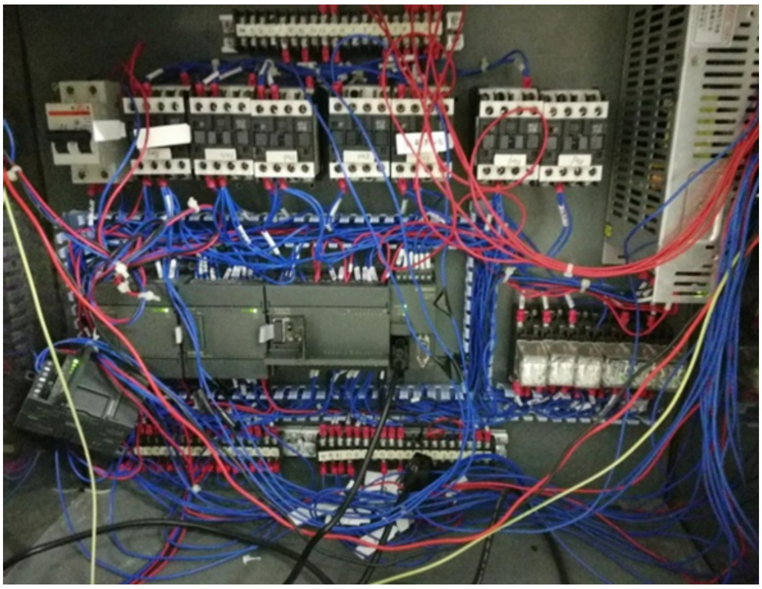

Figure 8. Physical connection picture of PLC.

3.2. LabVIEW Technology

The human–machine interaction interface of the PEMFC test system was developed by LabVIEW as shown in Figure 9, including parameter-setting, manual/automatic switch, liquid water level display, start/stop switch, alarm signal light indicator, fuel cell I-V curve display, etc.

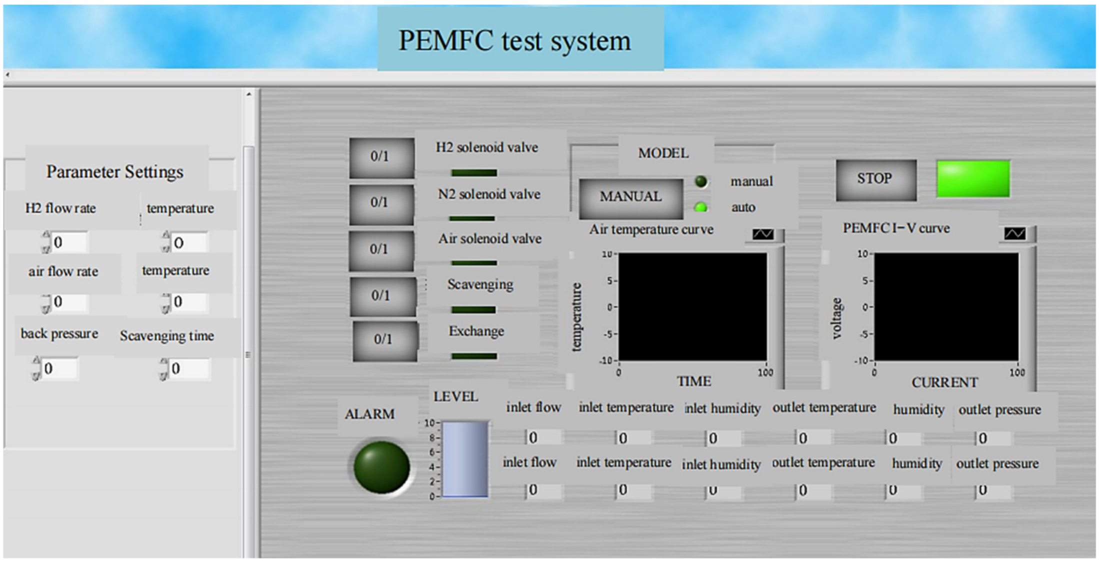

Figure 9. LabVIEW human–machine interface.

3.3. OPC Technology

OPC technology bridges the Windows-based applications and on-site process control applications [31]. It is used for the standardization of interfaces between the devices and applications with different supply vendors, making the data exchange simpler. OPC Data Access (DA) interface can read, write and monitor the variables, including the current process data. It can also transfer the real-time data from PLC to the LabVIEW interface.

The EM232 module in Siemens PLCS7-200 was used to convert the analog signal collected by the sensor into the corresponding digital signal, which was stored in the PLC register, and then transmitted to the upper computer through the Siemens programming cable and RS232 to USB serial port. After processing the data results, the upper computer sent control instructions through the PLC and converted them into analog signals by D/A to control the execution components. The communication flow chart is displayed in Figure 10.

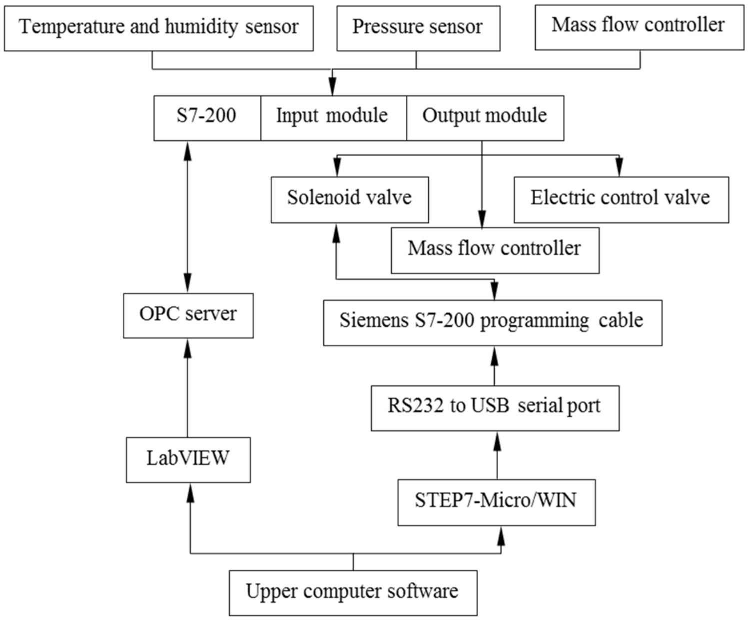

Figure 10. Communication flow chart.

4. Test System Test

4.1. Start/Stop Test

The startup processes of the test system were described as follows: the cooling fan was first turned on; after a delay of 10 s, the scavenging solenoid valve and hydrogen inlet solenoid valve was opened; the scavenging solenoid valve was cut off after 60 s; the load was turned on after another delay of 20 s.

The shutdown processes of the system included the fuel cell load and the hydrogen inlet solenoid valve were first cut off at the same time, and the nitrogen inlet solenoid valve and scavenging solenoid valve were opened; after one minute, the scavenging solenoid valve and nitrogen inlet solenoid valve were cut off. After another minute, the cooling fan was turned off.

4.2. Gas Tightness Test

The PEMFC test system works with hydrogen and air as reactants for the anode and cathode, respectively. Hydrogen is a flammable and explosive gas, which is easy to leak at the joint of the test system, so the gas tightness test is important and necessary. Air was used for the gas tightness test, with each joint coated with a leakage testing agent. The pressured air was supplied into the system for a period of time to observe whether there were bubbles at the joint. Due to the large size of the equipment, the gas tightness test was repeated several times, and the subsequent experiments were carried out only when the requirements of gas tightness were met.

4.3. Humidification Effect Test

The self-designed bubbling humidifier was used to humidify the cathode inlet air, and the flow rates of humidified air and non-humidified air were adjusted to accurately control the humidity based on the PID control algorithm. The humidifier temperature and the relative humidity were set at 80 °C and 80% after opening the air circulation pump, air inlet solenoid valve, and humidifier. The optimal PID parameters were obtained after automatic debugging, with a proportion coefficient of 2.8, integration time of 3 min, and differential time of 1 min. The humidity control speed was fast, and the margin of error in relative humidification was less than 0.7%. The variation curve of humidity with time is shown in Figure 11.

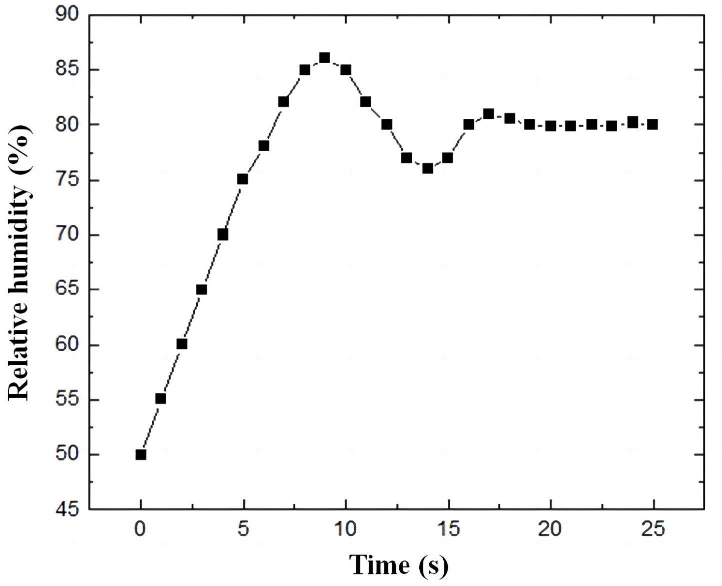

Figure 11. Variation curve of the relative humidity with time.

5. Fuel Cell Performance Investigation and System Evaluation

The polarization performance of a 2 × 2 cm^2 single cell under various humidified temperatures with relative humidification of 100% was studied and tested by the above-mentioned test system, as shown in Figure 12. The Pt loading at the anode and cathode was 0.20 mg cm^{-2}. As the cell temperature was 40 °C, the humidifier temperature was set as 30, 40, 50, and 60 °C, respectively. It is found that an enhanced performance was depicted at a high humidification temperature, which was mainly attributed to the high humidification of the membrane. Evidently, the as-developed test system demonstrated good test and control performances during the experiment.

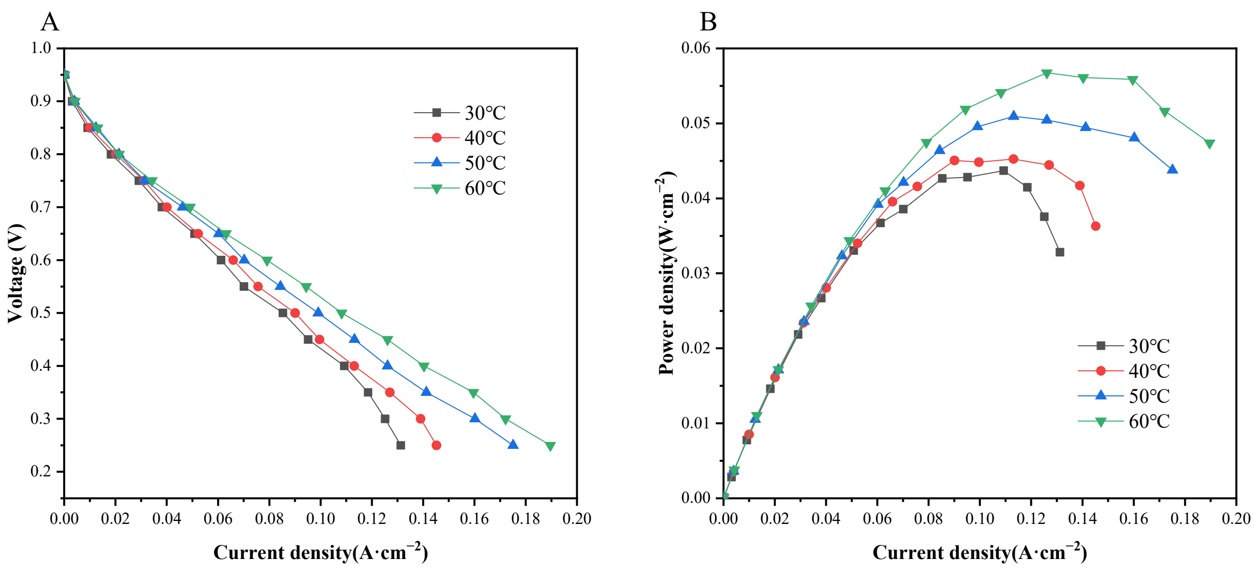

Figure 12. Fuel cell performance curves at different humidification temperatures. (**A**) Polarization curves and (**B**) power density curves.

6. Conclusions

A PEMFC test system with comprehensive functions was built using the combination of PLC and OPC technologies. The multiple functions were implemented as follows:

1. Data acquisition and output instruction. The input module and output module of PLC S7-200 combined with the LabVIEW software of the upper computer were used to collect and save multichannel data.
2. Hydrogen recycling. Under the premise of ensuring system security, the maximization of energy utilization could be realized.
3. Accurate control of humidity. The relative humidity of inlet gas with a margin of error of less than 0.7% was achieved by the PLC programming PID technology combined with the mass flow controller and temperature and humidity sensor.
4. Back-pressure control. The controller of the mass flow rate and pressure sensor worked together to control the back pressure.
5. The as-developed test system demonstrated good test and control performances during the fuel cell performance experiment.

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