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Analysis of the current status of control methods for fuel cell air supply systems

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Abstract

Proton exchange membrane fuel cells (PEMFCs) are highly efficient energy-conversion devices for hydrogen utilization and exhibit great potential in sustainable transportation. As a critical subsystem, the air supply system significantly influences stack performance, net power output, and operational reliability, whose control technology remains a major bottleneck hindering PEMFC industrialization. This paper systematically reviews classical, advanced, and special-operating-condition control strategies, evaluating their characteristics, merits, drawbacks, and engineering challenges. Conventional approaches, including PID, MPC, and SMC, are well-established in practice but exhibit weak adaptability to complex scenarios. Advanced algorithms incorporating fuzzy logic, neural networks, and reinforcement learning achieve superior control performance yet suffer from excessive computation and hardware constraints. Control schemes targeting dynamic load, cold start, and faults enhance environmental adaptability but are limited by high energy consumption and slow response. Finally, future directions such as algorithm fusion, lightweight design, digital twin, and standardization are prospected. This review provides theoretical support and engineering guidance for the development of PEMFC air supply control systems.

Keywords: PEMFCs, Air supply system, Control strategy, Classical control, Advanced control, Nonlinear system.

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Contents

Contribution of this paper to the literature

This study systematically establishes a unified control objective and evaluation system for PEMFC air supply systems, covering multi-condition adaptability, energy efficiency and robustness, which fills the gap of incomplete evaluation indicators in existing research.

1. Introduction

Nowadays, environmental issues such as global climate change and air pollution have attracted widespread attention worldwide. Fuel-powered vehicles, which consume non-renewable energy and emit serious exhaust pollutants, are facing increasingly severe energy conservation and environmental protection challenges [1]. Among various types of fuel cells, proton exchange membrane fuel cells (PEMFCs) have the advantages of light weight, high power density, and good stability. They operate at low temperatures and can start quickly at low temperatures, making them the most promising fuel cell technology with broad development prospects [2, 3]. As a core device for the efficient conversion of hydrogen energy, hydrogen fuel cells have significant characteristics such as short hydrogen refueling time (3–5 minutes), zero pollutant emissions during operation, and breaking through the limitations of the Carnot cycle.

Their theoretical energy conversion efficiency can reach more than 60%, far exceeding that of traditional internal combustion engines, thus becoming an important technical path for future sustainable transportation power systems. However, the air supply system is the only subsystem in the fuel cell power chain that requires an external energy supply. Its performance directly determines the oxygen supply quality of the stack, the net output power of the system, the energy consumption ratio, and the dynamic response capability, and has become one of the key bottlenecks restricting the energy efficiency, reliability, and cost competitiveness of the entire vehicle. Especially under real-world conditions such as frequent changes in vehicle operating conditions, large fluctuations in ambient temperature and humidity, and significant altitude differences, if the air supply system cannot accurately regulate the cathode oxygen excess ratio (λ), pressure, humidity, and flow rate, it is prone to induce "oxygen starvation," membrane drying, or flooding, leading to voltage drops, local corrosion, and even irreversible degradation.

Focusing on this key link, this paper systematically sorts out the representative methods in the field of fuel cell air supply system control at home and abroad from 2020 to 2026, aiming to provide a technical review with both theoretical depth and practical reference value for fuel cell system engineers, control algorithm researchers, and industrial policy makers.

2. Fundamentals of the Fuel Cell Air Supply System

2.1. System Composition and Working Mechanism

PEMFC is regarded as a clean and efficient energy device, and the air supply system is a key component to maintain the system's output efficiency [4]. The core components of the system mainly include: air compressor (commonly centrifugal or scroll type, providing stable high-pressure air for the system, which is the power core of air supply, and its speed directly determines the airflow rate and pressure), humidifier (using membrane or bubble humidification to adjust the air humidity to a suitable range, avoiding drying or flooding of the cathode proton exchange membrane and ensuring efficient electrochemical reactions), sensors (including pressure sensors, flow sensors, temperature, and humidity sensors, which collect air parameters in real time and provide feedback signals for control strategy adjustment).

In addition, it also includes an air filter (filtering impurities in the air to prevent damage to the stack and components), intercooler (cooling the high-temperature air at the outlet of the air compressor to avoid high temperatures affecting the stack performance), and throttle valve (adjusting the airflow to achieve precise parameter matching) [5, 6] with the schematic diagram shown in Figure 1. The specific air circulation process is as follows: ambient air is filtered by the air filter and then enters the air compressor, heated by compression and then cooled by the intercooler, adjusted to appropriate humidity by the humidifier, and then sent to the cathode of the fuel cell to participate in electrochemical reactions, and the exhaust gas after the reaction is discharged through the exhaust system [7]. There is a strong coupling relationship between key air parameters such as pressure, flow rate, humidity, temperature, and electrochemical reactions: insufficient air flow rate will lead to cathode air shortage, reduce the output power of the stack, and accelerate catalyst aging; excessive pressure will increase the energy consumption of the air compressor and may damage the proton exchange membrane; too low humidity is likely to cause membrane drying, and too high humidity will cause cathode flooding, both of which will inhibit the electrochemical reaction rate.

Excessive pressure will increase the energy consumption of the air compressor and may damage the proton exchange membrane; too low humidity is likely to cause membrane drying, and too high humidity will cause cathode flooding, both of which inhibit the electrochemical reaction rate. Based on the above coupling relationship, researchers usually establish the core logic of a simplified dynamic model, taking air flow rate and pressure as the core state variables, correlating control variables such as air compressor speed and throttle opening, quantifying the dynamic correlation between parameters, and providing theoretical support for the design and performance analysis of various subsequent control methods [8]. Based on the above coupling relationship, researchers usually establish the core logic of a simplified dynamic model, taking air flow rate and pressure as the core state variables, correlating control variables such as air compressor speed and throttle opening, quantifying the dynamic correlation between parameters, and providing theoretical support for the design and performance analysis of various subsequent control methods [9].

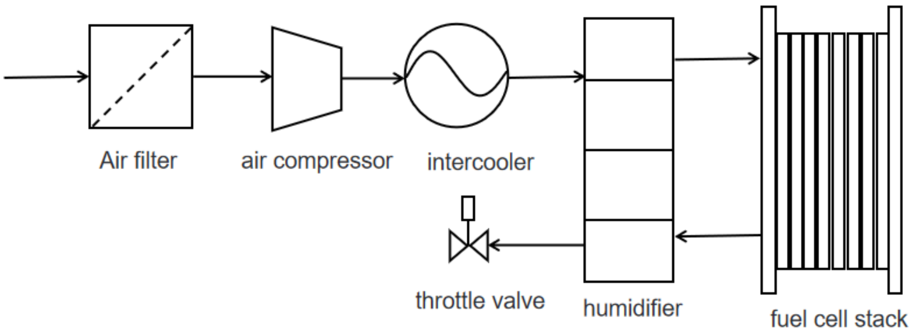

Figure 1. Schematic diagram of the fuel cell air supply system.

2.2. Control Objectives and Evaluation Indicators

The core control objectives of the proton exchange membrane fuel cell (PEMFC) air supply system focus on ensuring the efficient and stable operation of the stack, specifically covering four dimensions [10]: first, precise parameter tracking, which requires rapid following of the set values by air flow rate, pressure, and oxygen excess ratio (OER/AER) to match the stack load change demand and avoid local air shortage or membrane damage; second, dynamic balance control, solving the strong coupling characteristics between flow rate and pressure, maintaining the dynamic stability of the cathode inlet and outlet parameters, and ensuring continuous and efficient electrochemical reactions; third, strong anti-interference capability, resisting internal and external disturbances such as load mutations, ambient temperature and pressure fluctuations, and system model distortion, to ensure robust control performance under complex operating conditions; fourth, low energy consumption optimization, reducing the power loss of core components such as air compressors on the premise of meeting control accuracy, and improving the net output efficiency of the system [11]. To scientifically evaluate the performance of various control methods, the key evaluation indicators are defined as follows [12]: dynamic response time, referring to the time from the occurrence of disturbance to the stabilization of parameters, including rise time and adjustment time, reflecting the system's rapid adaptation capability to changes in operating conditions, such as the steady-state compliance time of parameters after adjusting the air compressor speed and throttle opening; steady-state error, that is, the deviation between the actual value and the set value after the parameters are stabilized (including absolute error and relative error), quantifying the control accuracy, usually requiring the flow deviation to be less than 3 g/s and the pressure deviation within ±1 kPa; reliability, referring to the system's trouble-free operation capability under long-term variable load conditions, which is related to the robustness of the control algorithm and hardware adaptability, and can be evaluated by the fluctuation range of stack voltage and power (such as voltage fluctuation $\leq$1V, power fluctuation $\leq$0.4kW) and continuous operation time in bench tests. The above control objectives and evaluation indicators lay a core foundation for the performance comparison, advantage analysis, and applicability judgment of various subsequent control methods.

3. Classification and Current Status of Control Methods for the Air Supply System

3.1. Classical Control Methods

As a widely used basic control method, the core of proportional-integral-derivative (PID) control is to realize closed-loop control of key parameters such as airflow rate and pressure through parameter adjustment of three links: proportional (P), integral (I), and derivative (D), which is suitable for the steady-state control needs of the system. However, it has weak anti-interference capability and is difficult to cope with parameter coupling characteristics. Therefore, improved algorithms such as fuzzy PID, adaptive PID, and sliding mode PID have been derived. By introducing fuzzy reasoning, parameter self-tuning mechanisms, etc., the adaptability to system nonlinearity and disturbances is improved, and it is widely used in air supply systems of small and medium-power fuel cells [13]. Model predictive control (MPC) is supported by a simplified system model, realizing multi-variable coordinated control through a rolling optimization strategy, which can effectively handle the coupling constraints between airflow rate and pressure and accurately track set values. However, its control performance depends on model accuracy, and it has high computational complexity and insufficient real-time performance, so it is mostly used in fixed operating conditions with high control accuracy requirements [12]. Sliding mode control (SMC) is based on the robustness design principle. By designing the sliding mode surface and reaching law, it can effectively resist external disturbances such as load mutations and environmental fluctuations, with fast control response, and is suitable for complex dynamic operating conditions. However, it has obvious chattering problems, which are likely to affect the service life of components such as air compressors. At present, most improved schemes, such as high-order sliding mode and terminal sliding mode, are used to mitigate chattering, and they have significant application advantages in dynamic load scenarios [14]. Combined with relevant literature cases, all three types of classical control methods have achieved initial engineering applications, each with its own advantages and disadvantages, and need to be reasonably selected according to specific operating conditions.

3.2. Advanced Control Methods

Advanced control methods mainly integrate two major technical systems: intelligent control and coordinated control. Among them, intelligent control is centered on fuzzy control, neural network control, and reinforcement learning control, while coordinated control focuses on multi-system coupling scenarios. The following focuses on outlining the design ideas and composite control strategies of various methods, and in-depth analyzes the core bottlenecks (real-time performance, complexity, cost) in their engineering applications. The core design of fuzzy control does not rely on an accurate mathematical model of the system. It fuzzifies control parameters such as air flow rate and pressure, as well as adjustment quantities into linguistic variables such as "large, medium, and small," formulates reasoning rules based on expert experience, and outputs continuous control signals through three steps:

fuzzification, reasoning, and defuzzification, which is suitable for system nonlinear characteristics [15]. Neural network control designs a network model based on simulating the structure of human brain neurons, realizes the approximation of system nonlinear relationships through sample training, and can complete parameter modeling and adaptive control, with commonly used network structures such as BP and RBF. Reinforcement learning control adopts the core framework of "agent-environment-reward function," optimizes the control strategy through continuous interaction between the agent and the system environment, and has self-learning and self-adjusting capabilities under dynamic scenarios, suitable for uncertain operating conditions. In practical applications, the three types of intelligent control methods are often combined with classical methods such as PID and MPC to form composite control strategies, such as fuzzy PID, neural network coordinated MPC, and reinforcement learning combined with sliding mode control, to compensate for the shortcomings of a single algorithm and improve control performance [10]. Coordinated control technology designs distributed topology structures and node communication mechanisms for multi-stack fuel cell systems or coupling scenarios between the air supply system and other subsystems, such as cooling and hydrogen circulation, achieving multi-objective coordinated optimization and ensuring the efficient and stable operation of the overall system [16]. From an engineering perspective, various advanced control methods face significant bottlenecks, which further restrict their large-scale application in special operating conditions. Specifically, in terms of real-time performance: neural networks, reinforcement learning, and complex composite strategies have large computational loads, making it difficult to meet the real-time control needs of high-speed dynamic operating conditions such as vehicle use; in terms of complexity: the design of relevant parameters and rules lacks uniform standards, relying on extensive experimental data and expert experience, resulting in high debugging difficulty; in terms of cost: advanced control strategies require high-performance hardware such as controllers with substantial computing power and high-precision sensors, significantly increasing system industrialization investments.

3.3. Control Strategies for Special Operating Conditions

Combined with the classical and advanced control methods mentioned above, aiming at the three typical special operating conditions of dynamic load, low-temperature startup, and fault in the operation of the fuel cell air supply system, this section sorts out the design points and application effects of the adaptive control strategies, and emphasizes the core impact of operating condition adaptability on the system control performance. As the most common operating scenario, the core control difficulty of dynamic load conditions is that the air parameters need to quickly match the stack load mutation demand. The adaptive strategies mostly adopt the aforementioned adaptive PID, sliding mode control, or composite strategies of reinforcement learning combined with MPC. By identifying the load mutation signal in real time and dynamically adjusting the air compressor speed and throttle opening, the dynamic response time of parameters can be shortened by 10%-20%, effectively suppressing pressure and flow fluctuations [17]. The core difficulties of low-temperature startup conditions are the freezing of the air humidifier, the large starting resistance of the air compressor, and low cathode reaction activity. The adaptive strategy is mainly based on air preheating control combined with fuzzy PID humidity adjustment, coupled with a low-speed air compressor smooth startup scheme, which can avoid membrane drying or freezing damage at low temperatures and significantly improve the stack startup success rate [18]. For fault conditions, focusing on typical problems such as air compressor faults, pressure/flow sensor faults, and pipeline leaks, a combined strategy of fault diagnosis and passive/active fault-tolerant control is adopted. For example, when a sensor fails, neural network prediction is used instead of measured values; when a pipeline leaks, pressure compensation control is activated to ensure trouble-free operation of the system and reduce the damage of faults to the stack [19]. The control strategies for the three types of special operating conditions need to balance pertinence and robustness. At present, there are still problems such as high energy consumption during low-temperature startup and lag in fault-tolerant response, which are also the key directions for subsequent research and form a connection with the engineering bottlenecks below.

4. Engineering Application Bottlenecks and Research Deficiencies of Control Methods

The engineering application bottlenecks mainly focus on four aspects: first, insufficient hardware adaptability. Although classical control methods are suitable for conventional hardware, they cannot fully utilize the performance of high-precision sensors and high-efficiency air compressors; advanced control methods (such as neural networks and reinforcement learning) require high controller computing power, which existing low-cost vehicle controllers cannot meet for real-time computing needs. The application of high-precision sensors further complicates hardware adaptation, aligning with the real-time and cost bottlenecks of advanced control mentioned earlier [20]. Second, significant cost constraints. The hardware investment needed for advanced control strategies, such as high-performance controllers and multi-dimensional sensors, is relatively high. Compared to traditional control methods, the industrialization cost increases by over 30%, making it difficult to meet the large-scale application needs of small and medium-power fuel cells, further restricting the promotion of advanced control technologies in engineering [21]. Third, lack of a standardization system. The parameter design and performance testing of various control methods lack uniform standards. For example, the design of fuzzy control rule bases, the selection of neural network structures, and the setting of control thresholds under special operating conditions all rely on experimental data and expert experience, resulting in difficulty in horizontal comparison of different research results, low engineering debugging efficiency, and hindering the large-scale deployment of technologies [22]. Fourth, insufficient adaptability to multiple scenarios. Most laboratory studies are based on ideal operating conditions, while complex conditions such as large fluctuations in temperature and humidity, frequent load mutations, and pipeline aging in actual vehicle scenarios lead to obvious deviations between the actual control effect of control methods and laboratory simulation results, resulting in the problem of disconnection between theory and practice. At the same time, it further exacerbates prominent problems such as high energy consumption during low-temperature startup and lag in fault-tolerant response. The common deficiencies in current research mainly include: insufficient in-depth research on the coordinated optimization of multiple control objectives, making it difficult to balance the dual needs of control accuracy and energy consumption optimization; control strategies under special operating conditions still need to be further improved, and the adaptability to complex scenarios such as low temperatures and extreme faults needs to be enhanced; the lightweight optimization of advanced control methods is insufficient, and it is difficult to achieve a balance between real-time performance and engineering practicality. These deficiencies also clearly point out the key breakthrough directions for future development trends below.

5. Future Development Trends and Conclusions

5.1. Future Trends

First, multi-algorithm fusion has become the core direction. Aiming at the shortcomings of a single control method, we focus on promoting the in-depth integration of advanced intelligent control and classical control methods, such as reinforcement learning combined with sliding mode control, neural network-coordinated MPC, and fuzzy PID composite strategies, to achieve the coordinated optimization of control accuracy, real-time performance, and robustness, accurately adapting to complex vehicle operating conditions, and solving the problem of insufficient coordinated optimization of multiple objectives.

Second, accelerated breakthroughs in lightweight intelligent control technology aim to address bottlenecks such as high computational complexity, insufficient real-time performance, and poor hardware adaptability of advanced control methods. We will carry out lightweight algorithm optimization, simplify neural network structures, optimize reinforcement learning training processes, reduce controller computing power requirements, adapt to low-cost vehicle hardware platforms, and alleviate cost constraint issues simultaneously.

Third, in-depth empowerment of digital twin technology. Construct a digital twin model of the air supply system, integrate real-time sensor data and simulation analysis, realize virtual debugging, operating condition prediction, and fault early warning of control strategies, improve the intelligence level of system control, effectively alleviate the problem of disconnection between theory and practice, and provide technical support for the optimization of control strategies under special operating conditions.

Fourth, coordinated advancement of integration and standardization. On the one hand, promote the integrated coordinated control of the air supply system with other fuel cell subsystems such as cooling and hydrogen circulation to optimize overall system performance; on the other hand, accelerate the establishment of uniform standards for control method parameter design and performance testing, standardize debugging processes, improve the compatibility of different research results and the efficiency of engineering debugging, and solve the bottleneck of lack of standardization.

In addition, aiming at problems such as high energy consumption during low-temperature startup and lag in fault-tolerant response, we will continuously optimize control strategies for special operating conditions, promote the upgrading of control technologies towards high efficiency, low energy consumption, and high reliability in line with the development needs of new energy vehicles, and provide core technical support for the industrialization of fuel cells.

5.2. Conclusions

Focusing on the current status of control methods for fuel cell air supply systems, this paper systematically analyzes the core principles, applicable scenarios, advantages, and disadvantages of various methods by combining classical control, advanced control, and special operating condition control strategies. It systematically summarizes the engineering application bottlenecks and current research deficiencies, and finally draws the following conclusions: classical control methods (PID and improved algorithms, MPC, SMC) are the basis of engineering applications, each with its own advantages and disadvantages. PID and improved algorithms are suitable for small- and medium-power steady-state scenarios, MPC for high-precision fixed operating conditions, and SMC for dynamic load scenarios, which need to be reasonably selected according to specific needs; advanced control methods (fuzzy, neural network, reinforcement learning control) and coordinated control technologies effectively make up for the shortcomings of classical control methods, adapt to system nonlinearity and multi-coupling characteristics, but face three core engineering bottlenecks of real-time performance, complexity, and cost; control strategies for special operating conditions have formed targeted schemes for dynamic load, low-temperature startup, and fault scenarios, improving the system's adaptability to operating conditions, but there are still problems such as high energy consumption at low temperatures and lag in fault response. The core obstacles to the engineering landing of current control methods are concentrated in insufficient hardware adaptation, significant cost constraints, lack of standardization, and disconnection between theory and practice. At the research level, there are still shortcomings, such as insufficient in-depth research on the coordinated optimization of multiple control objectives and imperfect control strategies under special operating conditions.

In summary, the development of control methods for fuel cell air supply systems needs to focus on the above-mentioned engineering bottlenecks and research deficiencies, take multi-algorithm fusion, lightweight optimization, digital twin empowerment, and integrated and standardized advancement as the core directions, continuously improve the control strategies for special operating conditions, and achieve the coordinated improvement of control accuracy, real-time performance, reliability, and economy. Subsequent research can focus on directions such as lightweight advanced algorithm design, multi-subsystem coordinated control, and extreme operating condition adaptation, to provide technical support for the large-scale application of fuel cells.

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