Yang et al.
Protection and Control of Modern Power Systems (2022) 7:36
https://doi.org/10.1186/s41601-022-00251-0

Protection and Control of Modern Power Systems

REVIEW

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Comprehensive summary of solid oxide fuel cell control: a state-of-the-art review

Bo Yang[1], Yulin Li[1], Jiale Li[1], Hongchun Shu[1], Xinyu Zhao[2], Yaxing Ren[3*] and Qiang Li[4]

Abstract

Hydrogen energy is a promising renewable resource for the sustainable development of society. As a key member of the fuel cell (FC) family, the solid oxide fuel cell (SOFC) has attracted a lot of attention because of characteristics such as having various sources as fuel and high energy conversion efficiency, and being pollution-free. SOFC is a highly coupled, nonlinear, and multivariable complex system, and thus it is very important to design an appropriate control strategy for an SOFC system to ensure its safe, reliable, and efficient operation. This paper undertakes a comprehensive review and detailed summary of the state-of-the-art control approaches of SOFC. These approaches are divided into eight categories of control: proportional integral differential (PID), adaptive (APC), robust, model predictive (MPC), fuzzy logic (FLC), fault-tolerant (FTC), intelligent and observer-based. The SOFC control approaches are carefully evaluated in terms of objective, design, application/scenario, robustness, complexity, and accuracy. Finally, five perspectives are proposed for future research directions.

Keywords: Solid oxide fuel cell, Control, Hydrogen energy, Artificial intelligence

1 Introduction

With the continuous depletion of nonrenewable resources and deterioration of the environment, countries all over the world are accelerating the pace of their energy structure reform [1–7]. Leading the innovation and application of high efficiency and clean energy are hydrogen, geothermal, wind, and solar energy [8–18]. The fuel cell (FC) is also a member of the renewable energy family. It has a simple working principle, high efficiency, and fewer disadvantages than other clean energy sources. Thus FC has attracted a lot of global attention [13, 14]. Compared with traditional power generation methods, the FC does not require a thermal engine process and is not restricted by the Carnot cycle, and therefore has higher energy conversion efficiency. Generally, depending on the electrolytes, FCs are divided into alkaline (AFC) [19, 20], phosphoric acid (PAFC) [21], proton exchange membrane (PEMFC) [22], molten carbonate (MCFC) [23], solid oxide (SOFC) [24], and direct methanol, etc. [25, 26].

SOFC is an energy exchange device which can directly convert the chemical energy of fuel and oxidant into electrical energy through an electrochemical reaction [24]. It can have a wide variety of fuels, and has high efficiency, zero emission, and waste heat utilization. Because of these benefits, SOFC is considered to be one of the most promising FC technologies [27, 28]. With the continuous development and progress of FC technology, SOFC can serve a large variety of applications, including mobile [29], auxiliary power units (APU) [30, 31], backup power systems, stationary small-scale combined heat and power systems, and medium-large scale power generation systems [32]. Therefore the commercial application of SOFC is very broad.

In the operation of an SOFC, an appropriate control strategy is very important to ensure its safe and reliable operation and to achieve the expected objectives. In the control of an SOFC, it is necessary to ensure that:

*Correspondence: yaxing.ren@outlook.com

[3] Warwick Manufacturing Group, University of Warwick, Coventry CV4 7AL, UK
Full list of author information is available at the end of the article

- The power supply is sufficient when the load fluctuates frequently, and the system output voltage has good robustness;
- There is safe and efficient operation of the entire system;
- Unnecessary battery loss is reduced with improvement in operation [33].

In addition, an appropriate SOFC model is very important for research and development. According to whether the dynamic behavior is considered, the models of SOFC can be divided into steady-state models and transient models. From the perspective of dimension, models can also be divided into zero-, one-, two-, and three-dimensional [34, 35]. Appropriate models need to be used for different control objectives, such as constant output voltage [36–38], improving dynamic response speed [39, 40], and prolonging system service life [41].

Reference [42, 43] reviews SOFC control, with the control objectives and control variables of SOFC described in detail, while the control strategies of various hybrid SOFC systems are introduced. However, the main attention is on the traditional control methods while modern control strategies (such as adaptive control (APC), robust control, model predictive control (MPC), etc.) are not introduced nor summarized [42, 43]. Reference [44] sorts out and summarizes the performance evaluation, fault diagnosis, and health control of SOFC in relative detail, and points out the shortcomings of the current research on the fault diagnosis and control of SOFC. However, it does not focus on the controller itself, and does not classify and evaluate various control strategies. Reference [45] focuses on the SOFC system with anode exhaust gas recirculation and summarizes the representative control strategies. However, it lacks generality and does not describe the control strategy in detail. In addition, artificial intelligence (AI) has opened a new round of rapid development in recent years. This is gradually developing from a single technology to an integrated approach with new technologies such as big data and high-performance computing, and from shallow learning to deep learning. Research on the application of AI technology in SOFC control is of great research value due to the difficulties of SOFC control [46].

This paper aims to comprehensively and systematically review the research on SOFC control. It summarizes the control strategies of SOFC and classifies them into eight categories of control approaches. It can be regarded as the latest one-stop manual for SOFC control. We also provide some prospects for future research in this field. The main contributions of this paper can be summarized as follows:

- Eight control strategies are included, and the control strategies of SOFC are classified and summarized;
- Three indices of complexity, robustness and accuracy are used to evaluate the performance of each control strategy;
- A comprehensive summary and comparison of these control strategies are provided.

The rest of the paper is organized as follows. Section 2 explains the review screening methods of this paper, while Sect. 3 provides the working principle of SOFC and the system composition of SOFC. Section 4 describes the various SOFC control strategies in detail, and Sect. 5 summarizes the characteristics of the different control strategies. Finally, Sect. 6 describes the challenges and perspectives.

2 Statistical analysis and evaluation indices

2.1 Review screening methods

Since the advent of SOFC, researchers have proposed a large number of controller designs. We present a comprehensive literature review of research on SOFC control, using three digital databases (ScienceDirect, Web of Science and Google Scholar), searching on terms such as SOFC, PID control, MPC and related control methods. The flow chart of the search filtering is shown in Fig. 1a, while the statistical data of relevant studies over the past ten years (from 2011 to Oct. 2021) are shown in Fig. 1b.

At present, the main research methods include literature research, investigation, qualitative analysis, quantitative analysis, and observation. In this paper, the control strategies of SOFC are summarized and analyzed using the literature research method, and the robustness, accuracy and complexity of various control strategies are evaluated.

2.2 Evaluation criteria

The complexity, accuracy and robustness of each control method are evaluated [47, 48], and the evaluation criteria of each controller are as follows.

Complexity: Complexity is mainly evaluated according to the principle, structure and composition of each controller. In addition, some elements can add additional complexity to the controller, e.g.: (a) Linear algebraic calculation; (b) Nonlinear algebraic calculation; (c) Integration or differentiation; (d) Discontinuous function or absolute calculation; (e) Matrix calculation. Note that among the above five elements, one additional element will be assigned to one additional *.

Accuracy: Accuracy is evaluated mainly by the overshoots of the outputs in the results presented in the corresponding papers. It can be divided into five grades: (a) above 20% (low, *); (b) 15% to 20% (lower, **); (c) 10% to

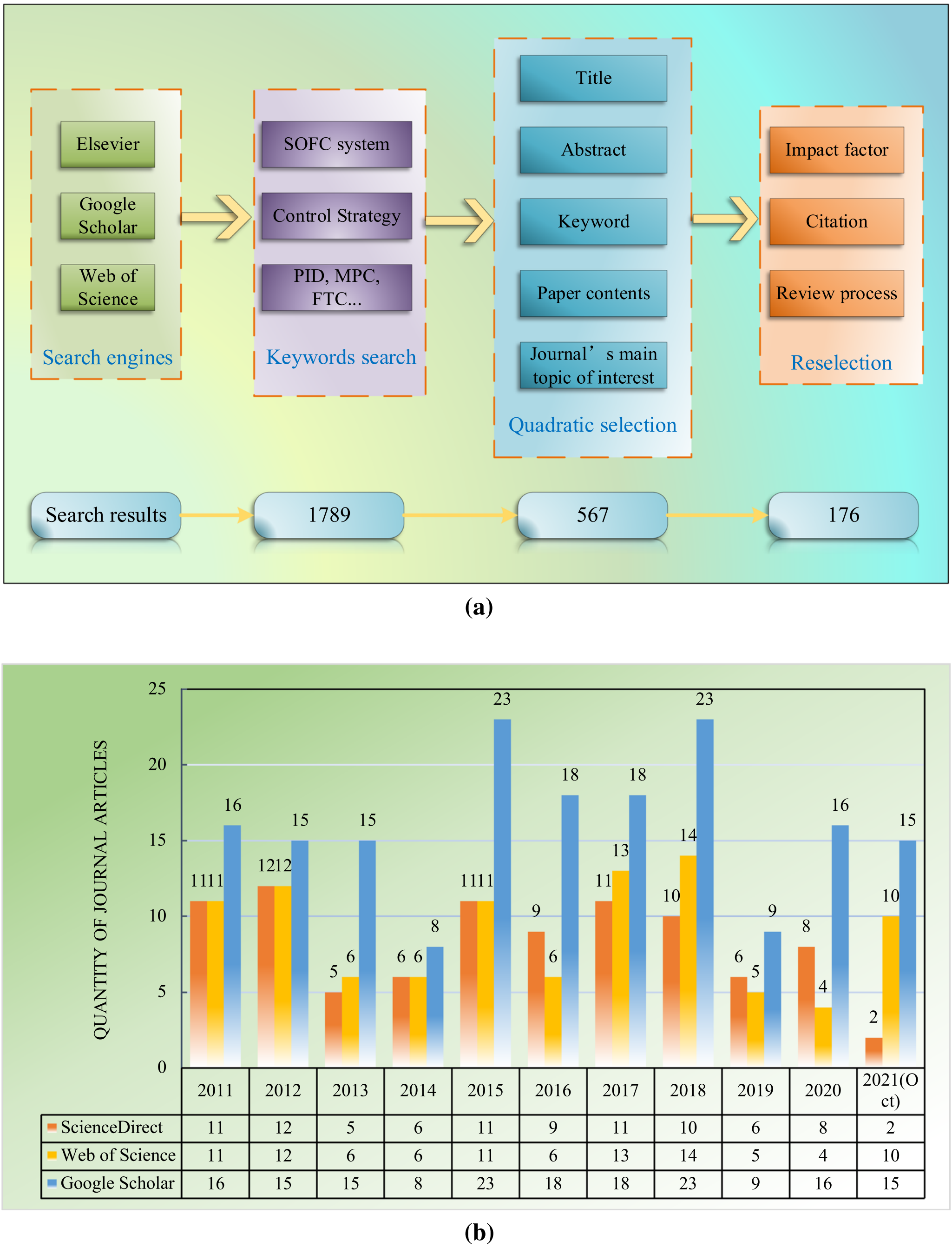

Fig. 1 Review screening method of related references in the last decade: (**a**) execution procedure and (**b**) research statistics

15% (general, ***); (d) 5% to 10% (higher, ****); and (e) Less than 5% (high, *****). It is worth noting that some previous research results have not been quantitatively analyzed, so the accuracy of these control methods can only be judged through simulation results.

Robustness: Robustness is mainly evaluated by the output deviation of simulations and experiments in previous studies. It is worth noting that some papers don't have quantitative analysis, so the robustness of the control method can only be evaluated vaguely through the characteristics and simulation results. It can also be divided into five levels: (a) Higher than 10% (weak, *); (b) 7.5% to 10% (Relatively weak, **); (c) 5% to 7.5% (general, ***); (d) 2.5% to 5% (Relatively strong, ****); (e) Less than 2.5% (strong, *****).

3 Operating principle and system structure of SOFC

3.1 Operating principle of SOFC

A FC is a device that converts chemical energy into electrical energy by electrochemical processes. An SOFC has a sandwich structure that is mainly composed of an anode, a cathode and an electrolytic layer [42]. An SOFC can use a variety of fuels, such as hydrogen, hydrocarbons and carbon monoxide, while air (or oxygen) is used as the oxidant [39]. Fuel flows in from the anode side, while oxygen flows in from the cathode side. During the reaction process, oxygen reacts with free electrons on the cathode side to produce oxygen ions and flows through the electrolytic layer to chemically react with the fuel on the anode side to produce electric energy [49, 50]. The operating principle of an SOFC with hydrogen as fuel is shown in Fig. 2. The main chemical reactions are:

Anode side:

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O \tag{1}$$

Cathode side:

$$\frac{1}{2}O_2 + 2e^- \rightarrow O^{2-} \tag{2}$$

When hydrogen is used as fuel, water is the only by-product, and the power generation process is almost zero-emission. Thus, hydrogen is a fuel with high electrical efficiency. In practical applications, it is difficult to apply hydrogen on a large scale because of the difficulties in its production, storage and transportation [49]. Thus, methane is commonly used as fuel for an SOFC. In the working process, methane is steam reformed in the reformer to generate H_2 and CO, and then the H_2 and CO participate in the reaction to generate electrical energy [51]. At the same time, to eliminate the demand for external reformers, FCs can internally reformat natural gas or other hydrocarbon fuels to extract the necessary hydrogen [24]. An SOFC is usually one of two types: self-supported and externally supported. There are many papers on SOFC geometry, but the mainstream research direction is plane and tubular geometries [52].

3.2 SOFC model

In the past decade, a lot of work has been done on on the physical model of an SOFC. A variety of accepted SOFC dynamic models, which are widely used in control research on SOFC, are shown in Fig. 3, while the parameters of the models are shown in Table 1. Here, $V_{\mathrm{d}\mathrm{c}}$ indicates the stack output voltage (V), P_{H_2}, P_{O_2} and $P_{\mathrm{H}_2\mathrm{O}}$ indicate the partial pressures of hydrogen, oxygen, and water (Pa), respectively [53]. The input hydrogen and oxygen flow rates are represented by $q_{\mathrm{H}_2}^{\mathrm{i}\mathrm{n}}$ and $q_{\mathrm{O}_2}^{\mathrm{i}\mathrm{n}}$, respectively. To ensure the safe and stable operation of an SOFC system, researchers mainly control the variables such as air/fuel flow rates, current and temperature to maintain the parameters such as system stack temperature, fuel utilization etc.

Using Nernst's equation and considering the resistance, concentration and activation losses (i.e., η_{ohmic}, η_{conc} and η_{act}), the stack output voltage can be expressed as:

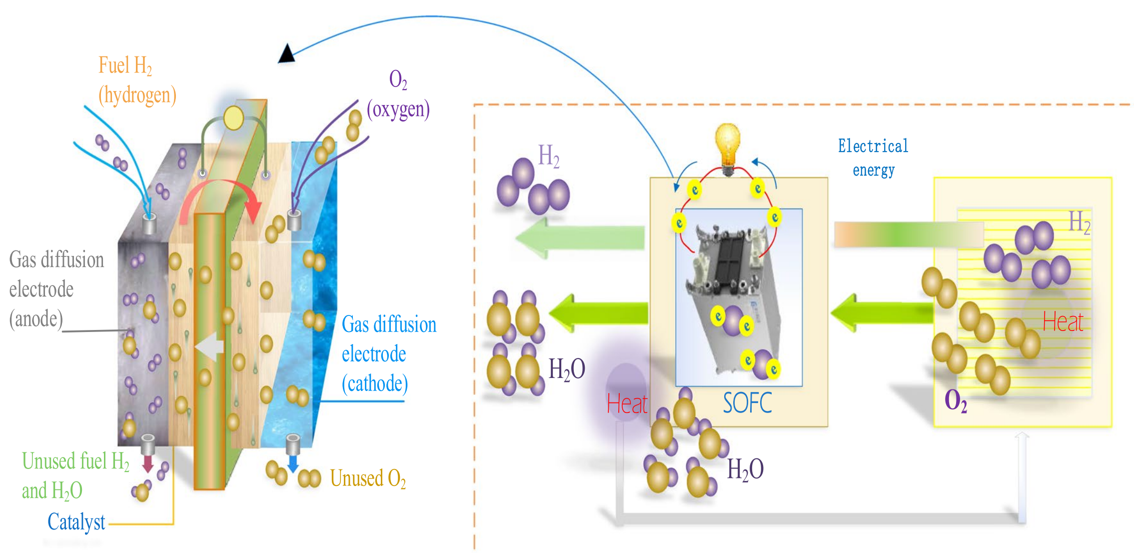

Fig. 2 SOFC operation mechanism

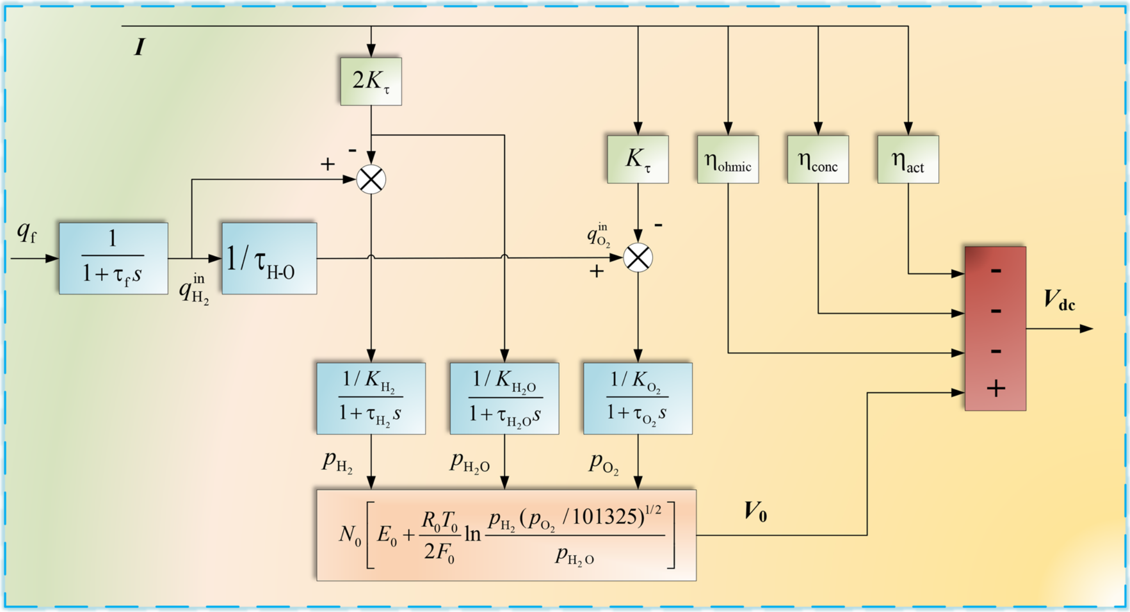

Fig. 3 Dynamic model of an SOFC

$$V_{dc} = V_0 - \eta_{act} - \eta_{ohmic} - \eta_{conc} \tag{3}$$

$$V_0 = N_0[E_0 + \frac{R_0 T_0}{2F_0} \ln \frac{P_{H_2}(P_{O_2}/101325)^{1/2}}{P_{H_2O}}] \tag{4}$$

where pressures are:

$$P_{H_2} = \frac{1/K_{H_2}}{1+\tau_{H_2}s}(\frac{1}{1+\tau_f s}q_f - 2K_r I) \tag{5}$$

$$P_{O_2} = \frac{1/K_{O_2}}{1+\tau_{O_2}s}(\frac{1/\tau_{H-O}}{1+\tau_f s}q_f - K_r I) \tag{6}$$

$$P_{H_2O} = \frac{1/K_{H_2O}}{1+\tau_{H_2O}s} 2K_r I \tag{7}$$

and the losses are:

$$\eta_{ohmic} = Ir \tag{8}$$

$$\eta_{act} = \partial + \beta \ln I \tag{9}$$

$$\eta_{conc} = -\frac{R_0 T_0}{2F_0}\ln(1 - \frac{I}{I_L}) \tag{10}$$

3.3 SOFC balance of plant

At the system level, an SOFC power system mainly includes an SOFC stack and corresponding balance of plant (BOP) subsystem. This has the functions of gas transmission, heat exchange and gas treatment, as shown in Fig. 4. A BOP subsystem can generally be divided into fuel-processing (FPS) and thermal management subsystems (TMS) [54].

3.3.1 Fuel-processing subsystem

An FPS is mainly composed of pre reformer, burner, mixer, etc. Its main task is to convert methane into hydrogen for the normal operation of an SOFC.

Reformer The preheated methane from the fuel heat exchanger and a separate stream of steam are fed into the reformer, where an endothermic reaction takes place between CH_4 and H_2O [55].

Reforming reaction:

$$CH_4 + H_2O \rightarrow CO + 3H_2 \tag{11}$$

Water-gas shift reaction:

$$CO + H_2O \rightleftharpoons CO_2 + H_2 \tag{12}$$

Burner In the burner, there is remaining fuel after the stack reaction is completely burned with air, and hot gas is then generated in the burner. At this stage, it is important to provide extra air to completely burn the remaining fuel. The molar flow rate after gas reaction in the burner can be obtained as [56]:

$$\dot{N}_{out} = \dot{N}_{in} + \sum R_i \tag{13}$$

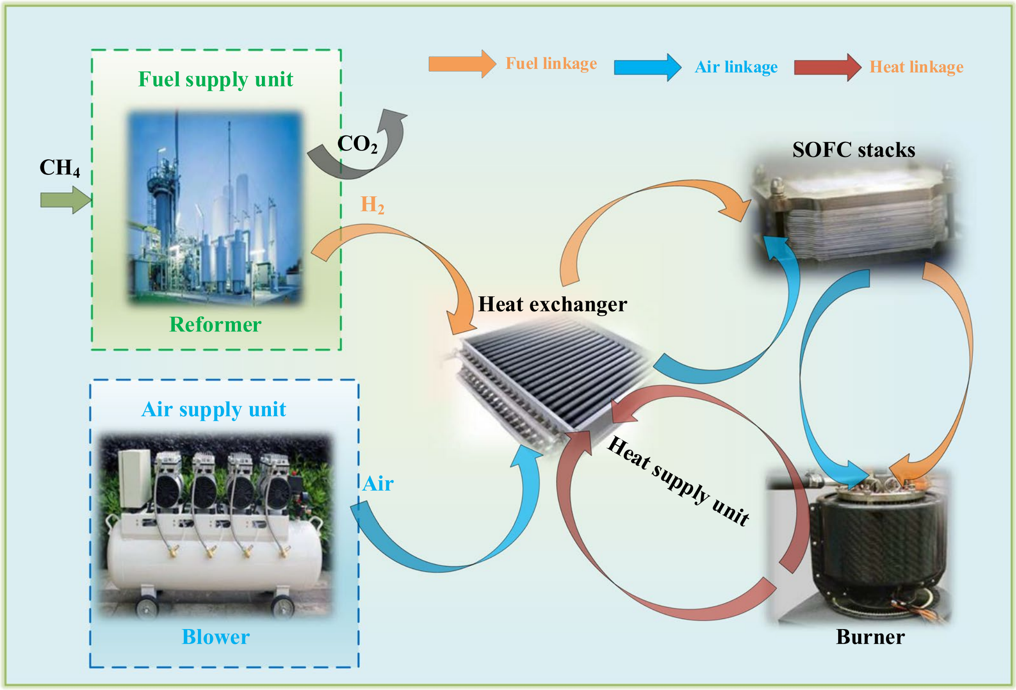

Fig. 4 Structure diagram of a typical SOFC system

Table 1 Parameters of the models of SOFC systems

Parameter	Value	Unit	Representation
T_0	1273	K	Absolute temperature
F_0	96485	C/mol	Faraday's constant
R_0	8.314	J/(mol·K)	Gas constant
E_0	1.18	V	Ideal standard potential
K_r	0.996×10^{-3}	Mol/(s·A)	Constant, $K_r = N_0/4F_0$
K_{H_2}	8.32×10^{-6}	Mol/(s·Pa)	Constant for hydrogen
K_{H_2O}	2.77×10^{-6}	Mol/(s·Pa)	Constant for water
τ_{H_2}	26.1	s	Response time of hydrogen
τ_{H_2O}	78.3	s	Response time of water
τ_{O_2}	2.91	s	Response time of oxygen
τ_{H-O}	1.145	–	Ratio of hydrogen to oxygen
r	0.126	–	Ohmic loss
τ_f	5	s	Lime constant
∂	0.05	–	Tafel constant
β	0.11	–	Tafel slope
I_L	800	A	Limiting current density

where $\dot{N}$ represents the molar flow rate, and R_i represents the electrochemical reaction rates of fluid *i*.

Mixer In the mixer, the gas coming from the bypass valve is mixed with the outlet cold gas of the heat exchanger [57].

3.3.2 Thermal management subsystem (TMS)

In the normal operation of an SOFC system, to achieve high overall operation efficiency, the temperatures of many key components need to be accurately controlled. Therefore, a TMS is very important for the stable operation of an SOFC, and is mainly used to maintain the temperatures of fuel and oxidant to achieve an effective chemical reaction. A TMS mainly includes heat exchanger, air compressor, etc. [53]. Generally speaking, an SOFC power generation system usually has two heat exchangers, which are used to preheat fuel and air, respectively. In order to reduce the temperature difference between the two at the stack inlet, the exhaust gas in the burner can be used to heat the fuel and air [58, 59]. Assuming that the heat exchanger is a counter-flow tube heat exchanger, part of the hot gas flow (waste gas) from the burner flows into the outer tube while the cold air flow (cold fuel and air) flows into the inner tube [55].

4 SOFC control

4.1 PID control

A PID controller is a linear combination of the proportion, integral and differential of the deviation and the functions of each correction link of the PID controller are:

(a) Proportional link: it reflects the deviation signal of the control system in proportion. After the deviation is generated, the controller acts immediately to reduce the deviation.
(b) Integration link: it is mainly used to eliminate static error and improve the error-free degree of the system. The strength of integration depends on the integration time constant.
(c) Differential link: it reflects the change rate of deviation signal and introduces an early correction signal into the system, so as to increase the speed of the system and reduce the adjustment time [60].

PID control is one of the earliest control strategies. It has a simple structure and high reliability and has been widely used in SOFC. PID controllers are of different types and can be divided into traditional [61–67], decentralized [40], fuzzy [68], adaptive [69], robust [70, 71] and intelligent [8]. Table 2 comprehensively summarizes the control variables and application scenarios of all PID control strategies and evaluates the control effect from three aspects: complexity, robustness and accuracy.

An SOFC is a multivariable, nonlinear and strongly coupled system [8, 63]. In order to pursue the best control effect, PID control is often combined with other control strategies. In reference [70], a multivariable robust PID control system is proposed for a kW SOFC system. The control strategy adopts a multi-loop feedforward/feedback control structure to solve complex dynamic problems, and has good robustness and dynamics for the change of operating point of the SOFC system within its working range. Reference [8] proposes a new intelligent proportional-integral adaptive sliding mode controller (IPI ASMC) with an anti-saturation compensator to deal with uncertainty and actuator saturation, and reduce the influence of current load disturbance, so as to effectively control the output voltage of the SOFC and enhance the dynamic performance of the system. The control system is mainly composed of three parts: the extended state observer (ESO) based on intelligent proportional-integral for estimating the unknown state, an adaptive sliding mode control (ASMC) for compensating the estimation error of unknown parameters, and an anti-saturation compensator based on inverse calculation for dealing with the saturation problem caused by input constraints. The architecture of the controller is shown in Fig. 5, where $y(t)$ represents the output voltage, V_{dc} represents the feedback output variable, $\widehat{\xi}(t)$ represents an unknown quantity, S represents the integral sliding surface, $u_a(t)$ represents the auxiliary input, $e_i(t)$ and $e(t)$ represent the integrator input and output tracking errors, respectively. $u_c(t)$ and $u_r(t)$ indicate the controlled variables before and after the saturation unit, respectively. In addition, the continuous development of intelligent optimization algorithms has seen them being applied in many research fields. In reference [72], the firefly algorithm is used to adjust the parameters of the fractional PID controller. After algorithm optimization, the anti-interference ability of the PID controller is enhanced, which improves the operation reliability of the SOFC.

As the most mature control method, PID control is widely used. Although the traditional PID control is reliable and simple, PID cannot meet the current control requirements because of the increased demand for accuracy in the system. To ensure control performance, PID control is constantly combined with other control methods. The performance of PID control combined with other control methods is shown in Table 3. A decentralized PID controller has the characteristics of fewer setting parameters and simple design and implementation. However, in a decentralized control structure, to ensure the stability of the system, the adjustment of the controller is relatively loose, which affects the working efficiency of the SOFC system. Adaptive PID control reduces the dependence on the model and enhances the robustness of the system. However, control accuracy and dynamic performance are reduced because of fuzzy signal processing. Robust PID control is more conducive to keeping the system running in a safe range, though the control accuracy of the system is reduced. The combination of intelligent and PID control improves the accuracy and robustness of the control system, but general intelligent control structure is complex and difficult to realize.

4.2 Adaptive control

APC generates the corresponding feedback control law according to the detected change in the performance

Table 2 Chronological summary of PID control

Control method		Control objective	Controller design	Parameters	Performance	Usage scenarios	Complexity	Robustness	Accuracy
Traditional PID	Aguiar [39]	1. Current density disturbance; 2. Air flow rate	N. P.	N. P.	Improve load tracking capabilit	A dynamic model	**	**	**
	Li [36]	1. Fuel flow rate; 2. Voltage	$K_P = -\frac{\cos(\psi - \theta_p)}{M_p}$ $K_I = -\frac{w_c' \sin(\psi - \theta_p)}{M_p}$	N. P.	Maintain output voltage; Maintain fuel utilization	A dynamic model	**	**	**
	Sorrentino [61]	1. Air or fuel rate	N. P.	N. P.	Effective temperature control	One-dimensional steady-state model of planar SOFC	**	**	**
	Chaisantikulwat [37]	1. Hydrogen concentration	The controller output: $u(s) = K_c(1 + \frac{1}{\tau_I s} + \tau_D s)e(s)$	$e(s)$: error; K_C: the controller gain; τ_I: integral time; τ_D: derivative time.	Maintain constant voltage	A dynamic model	**	***	**
	Hajimolana [62]	1. Temperature; 2. Pressure	The control system consists of two fully decentralized PI controllers.	N. P.	Improve anti-interference ability	A dynamic compartmental model	**	**	**
	Komatsu [51]	1. DC power output; 2. Cell operating temperature; 3. Fuel utilization factor; 4. Steam-to-carbon ratio.	N. P.	N. P.	Improve system operation efficiency	A dynamic model	***	**	**
	Cheng [63]	1. Air or fuel rate.	N. P.	N. P.	Strong anti-interference ability	A SOFC system model based on BP neural network	***	**	***
	Vreko [64]	1. Air or fuel rate; 2. Temperature	$u(t) = K_P(e(t) + \frac{1}{T_I}\int_0^t (e(\tau) - \frac{u(\tau) - u_r(\tau)}{K_P})d\tau)$ $u_r(t) = \begin{cases} u(t), automaticmode \\ u_m, manualmode \end{cases}$ $u_{lim}(t) = \begin{cases} u_{min}, if u(t) < u_{min} \\ u(t), if u_{min} \le u(t) \le u_{max} \\ u_{max}, if u(t) > u_{max} \end{cases}$	T_I: integral time constant; $e(t)$: control error; u_r: controller output.	Improve system robustness	Experimental model of 2.5 kW SOFC system	**	***	***
	Kupecki [65]	1. Air or fuel rate; 2. Current	Control strategy composed of 13 PID controllers.	N. P.	Maintain temperature; Increase stack power	Experimental model of 1kW SOFC system	***	**	***
	Singh [66]	N. P.	N. P.	N. P.	Reduce rise time and stabilization time	Experimental	**	***	**
	Zhang [67]	1. Air or fuel rate; 2. Current	N. P.	N. P.	Improve system efficiency and achieve fast tracking of output power	Experimental model of 5kW SOFC system	**	***	***

Table 2 (continued)

Control method		Control objective	Controller design	Parameters	Performance	Usage scenarios	Complexity	Robustness	Accuracy
Decentralized PID	Sendjaja [40]	1. Air or fuel rate	$K_c = \frac{1}{K_P}\frac{\tau_1}{\tau_c+\widetilde{\theta}};\ \tau_I = \min\left(\tau_1, 4\left(\tau_c + \widetilde{\theta}\right)\right);\ \tau_D = \tau_2$	K_c: controller gain; τ_I: integral time; τ_D: derivative time; τ_c: desired closed-loop time constant; $\widetilde{\theta} = \theta + T_s/2$ with T_s being the sampling time.	Improve load tracking capability	Benchmark nonlinear dynamic model of SOFC	**	***	**
Fuzzy PID	Marzooghi [68]	1. Voltage; 2. Current	Fuzzy PI controller with super capacitor is proposed.	N. P.	Improve performance under transient disturbances	Experimental model of 480-kW SOFC system	***	***	**
Adaptive PID	Xu [69]	1. Voltage	Adaptive constrained controller: $u(t) = \mathrm{Sat}\{(u(k-1) + \mathrm{Sat}\{(u_c(k) - u(k-1)), T\dot{q}_{fmin}, T\dot{q}_{fmax}\})\ \overline{q}_{fmin}, \overline{q}_{fmax}\}$	T: sampling time; $\mathrm{Sat}(a,b,c) = \begin{cases} b, a \le b \\ a, b < a < c \\ c, a \ge c \end{cases}$	Maintain fuel utilization	A dynamic model	***	***	***
Robust PID	Cao [70]	1. Air or fuel rate.	$u_{\dot{N}_{H_2}} = \frac{n\cdot\delta I_{st}}{2F\cdot r_{FU}}$ $u_{\dot{N}_{air},FF} = \frac{n\cdot\delta I_{st}\cdot AE_{SV,opt}}{4F\cdot X_{O_2}}$ $u_{\dot{N}_{air},by,FF} = \frac{n\cdot\delta I_{st}\cdot AE_{SV,opt}\cdot BP_{SV,opt}}{4F\cdot X_{O_2}}$	δI_{st}: stack current error; r_{FU}: control objective of fuel utilization (FU); $AE_{SV,opt}$ and $BP_{SV,opt}$: optimization at different stack Voltage operating points	Improve system reliability	Experimental model of kW SOFC system	***	****	***
	Cheng [71]	1. Air or fuel rate; 2. Temperature	$\Delta u = K_s \mathrm{sign}(T - T^{ref}) + K_P(T - T^{ref}) + K_I \int (T - T^{ref})dt + K_D \frac{d}{dt}(T - T^{ref})$ $K_s = \left(\frac{T - T^{ref}}{2}\right)^2$	Δu: control variables; T: controlled variables; T^{ref}: reference values of controlled variables; k_s: speed of the sliding mode control.	Ensure temperature safety; Maintain efficient operation	Experimental model of 5 kW cross-flow SOFC system	***	****	***
iPI-ASMC	Abbaker [8]	1. Voltage	Total output of controller: $u_c(t) = \frac{1}{\alpha}[\dot{y}_d(t) - \widehat{\xi}(t) - \xi_u + \lambda e(t) + \mu s + \eta(t)\varphi(s)]$	λ and μ: positive constant; $e(t)$: tracking error.	Improve dynamic respons	Experimental	****	****	****
PID based on Intelligent Algorithm	Zhang [72]	PID parameters	Fitness function: $J = \int_0^{t_s} \lvert e(t) \rvert dt$	t: time; t_s: integral upper limit time; $e(t)$: battery SOFC control error.	Improve operational reliability	A fractional PID parameter optimization model of SOC control	***	***	***

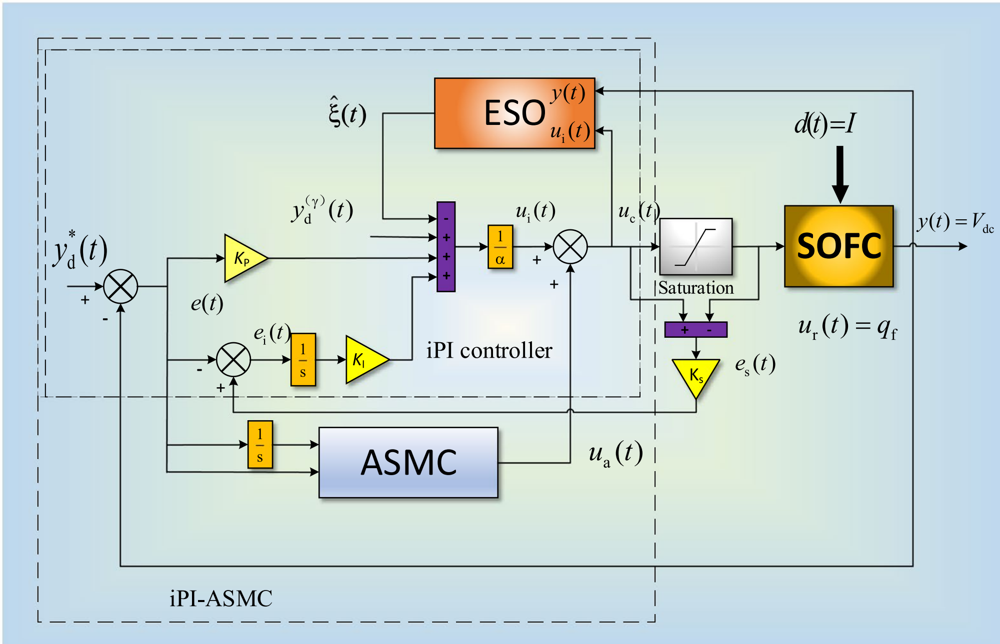

Fig. 5 IPI-ASMC control structure

Table 3 performance of PID control

Control methods		Traditional PID	Decentralized PID	Adaptive PID	Robust PID	Intelligent PID
Complexity	Low (*)	√				
	Lower (**)		√			
	General (***)				√	
	Higher (****)			√		
	High (*****)					√
Robustness	Weak (*)					
	Relatively weak (**)	√	√			
	General (***)			√		
	Relatively strong (****)					
	Strong (*****)				√	√
Accuracy	Low (*)					
	Lower (**)	√	√			
	General (***)			√	√	
	Higher (****)					
	High (*****)					√

index, to eliminate the change and achieve the desired control goal. APC can be divided into model reference adaptive control and self-tuning control systems.

SOFC brings challenges to control because of its slow dynamics, complex nonlinearity and operational constraints. In reference [73], an SOFC control strategy based on APC is proposed. The main core of the control method is optimal utilization based on the safety range of the utilization factor, in which the hydrogen fuel flow rate is a controllable variable. The utilization factor value is used to determine the hydrogen fuel valve, while the air valve is adjusted according to the hydrogen fuel valve. This method can prevent the overuse and underuse of the SOFC system, and effectively improve the problem of the slow dynamics of the SOFC system. To solve the control problem of an

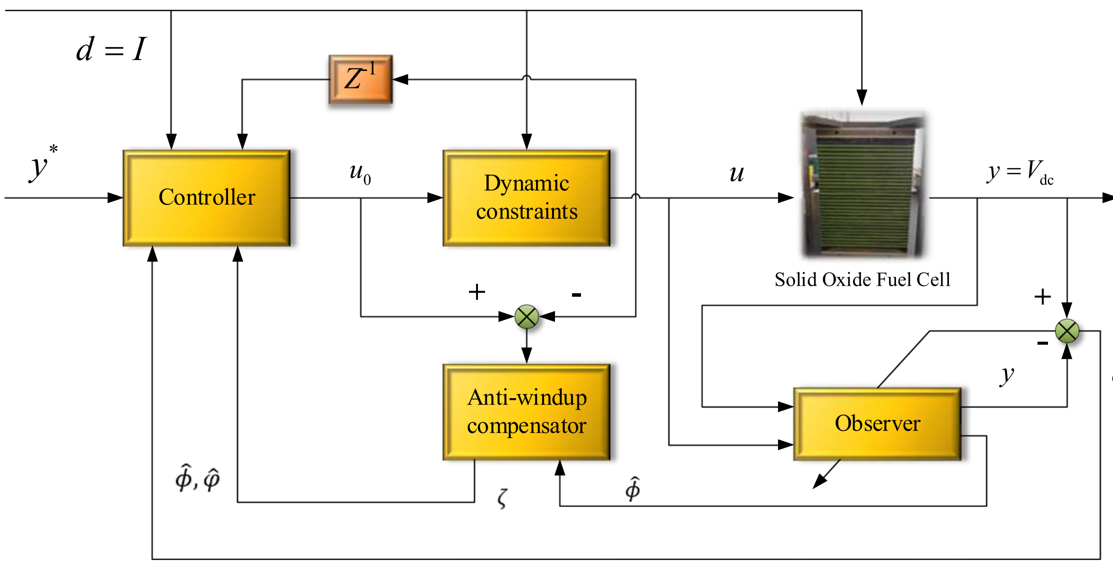

Fig. 6 Design flow chart of model-free APC strategy

SOFC system with I/O measurement data, an improved model-free APC strategy is proposed [74]. The design flow chart of the SOFC control system is shown in Fig. 6, where y^* is the reference trajectory, ζ is the compensation signal, I is the current load, ϕ is the sensitivity of SOFC output voltage V_{dc} to control input q_f, and φ is the sensitivity of V_{dc} to I. Further details can be found in reference [73]. In the design process of the controller, to maintain the fuel utilization within a safe range, a dynamic anti-saturation compensator is used to deal with the motion amplitude and rate saturation of the SOFC control input.

Adaptive control with low requirements for a model is very suitable for SOFC control because of difficulties in obtaining accurate models of an SOFC system. A self-tuning controller based on a neural network shows great potential in the control of highly nonlinear and uncertain systems. These show the great advantages of adaptive control. However, the fuzzy signal processing and computational burden of adaptive control can affect control accuracy and dynamic performance. This needs to be addressed.

4.3 Robust control

A 'robust' controller refers to the control that maintains the system stability and offers a certain dynamic performance quality when there is a certain degree of parameter uncertainty and a certain limit of unmodeled dynamics [75]. Robust control has always been a research hotspot in the control field, and typical robust control theories include H-infinity and sliding mode control (SMC) and structural variational theory [76, 77]. Reference [78] uses a robust regulator to solve the hypoxia problem of an SOFC system. To achieve the thermal management of an SOFC system and improve its performance, reference [79] designs a feedback controller based on the H-infinity principle. To reduce voltage oscillation and deviation and to keep the fuel utilization unchanged, an H-infinity control is designed in [80] based on the derived state-space representation of the SOFC. Two controller design schemes are proposed in [81], one being the robust nonlinear control strategy, and the other the standard H-infinity method. To ensure asymptotic stability, an interval-based SMC controller is proposed in [82] to carefully consider the estimation of uncertain parameters and bounded disturbances, while a robust SMC method is proposed in [83] to achieve the optimal operation of fuel and energy in an SOFC system. In addition, for SOFC systems with input constraints, a new model-free discrete-time SMC is proposed in [82] to adjust the output voltage under load disturbance. Table 4 summarizes and evaluates previous studies on robust controller strategies for an SOFC.

An optimal robust control strategy is proposed in [57]. It consists of three parts: an SOFC model with parameter uncertainty, a robust optimizer, and a robust controller. To ensure the safe operation of the system, two feedforward controllers and a robust high-order sliding mode controller are used to control fuel utilization, air excess coefficient and stack temperature. The control scheme is shown in Fig. 7. The input fuel rate, the inlet air flow rate and the opening ratio of the bypass value are employed as the manipulated variables, i.e., $u^T = [u_1\ u_2\ u_3] = [W_1\ W_7\ \delta]$. I is the stack current, F is Faraday's constant, N is

Table 4 Chronological summary of robust control

Control method		Control objective	Controller design	Parameters	Performance	Usage scenarios	Complexity	Robustness	Accuracy
Robust control	Sun [78]	1. Current.	N. P.	N. P.	The method is applied to the oxygen protection of FC	Experimental	**	**	**
H-infinity control	Fardadi [79]	1. Air or fuel flow rate; 2. Temperature	Controller based on Standard H infinity or L-2 gain method.	N. P.	Reduce the space temperature change under significant load disturbance	A physical based dynamic model of a single co-flow SOFC repeat cell	**	***	***
H-infinity control	Allag [81]	1. Current; 2. Voltage	Dynamic feedback law: $v(s) = -K_{\infty}(s)e(s)$ $e(t) = V_{uc,t} - V_{uc}$	K_{∞}: controller transfer function; $V_{uc,t} = S_t V_{max}$: target ultracapacitor voltage.	Improve load tracking capability; Prevent fuel shortage	Experimental	***	****	***
H-infinity control	Huo [80]	1. Air or fuel flow rate	N. P.	N. P.	Reduce voltage oscillation and deviation and keep fuel utilization unchanged	Experimental model of 100 kW cross-flow SOFC system	***	****	***
SMC	Dötschel [82]	1. Temperature	Corresponding variable-structure control law: $[v] := -\frac{a(\vartheta_{FC}(t),[p],[d])}{b(\vartheta_{FC}(t),[p],[d])}$ $\frac{\widetilde{\eta}\cdot \mathrm{sign}(\vartheta_{FC}(t)-\vartheta_{FC,d})}{b(\vartheta_{FC}(t),[p],[d])}$,	$v(t)$: control variable; $\vartheta_{FC,d}$: desired trajectory; [P]: interval parameter vector; d: point-valued disturbance; $\widetilde{\eta} > 0$.	Improve system stability	Experimental	**	***	**
	Rauh [83]	1. Air or fuel flow rate; 2. Temperature	Interval-based control law: $[v_{CG,d}] := \frac{-\widetilde{a}(x,[p],[d])+\xi_{1,d}^{(\delta)}-\sum_{r=0}^{\delta-2}\alpha_r\cdot\widetilde{\xi}_1^{(r+1)}-\widetilde{\eta}\cdot \mathrm{sign}\{s\}}{\widetilde{b}(x,[p])}$	[p] and [d]: interval parameters; $\xi_{1,d}^{(\delta)}$: time derivatives.	Improve system stability	Experimental	***	***	***
	Wu [57]	1. Air or fuel flow rate; 2. Air excess ratio; 3. Temperature	$\dot{\delta} = B^{-1}\left[-A + v_{ftc} + v_{sup}\right]$ $W_1 = 6.8 \times 10^{-4}\frac{I}{u_{f,ref}}$ $W_2 = 1.9 \times 10^{-3} I \lambda_{O_2,ref}$	δ: opening ratio of the bypass valve; W_1: inlet fuel flow; W_2: inlet air flow.	Ensure the safe operation of the system; Improve system operation efficiency	A SOFC model with parameter uncertainty	***	****	****
	Am [84]	1. Voltage	N.P.	N.P.	Strong dynamic performance	Experimental	***	****	***

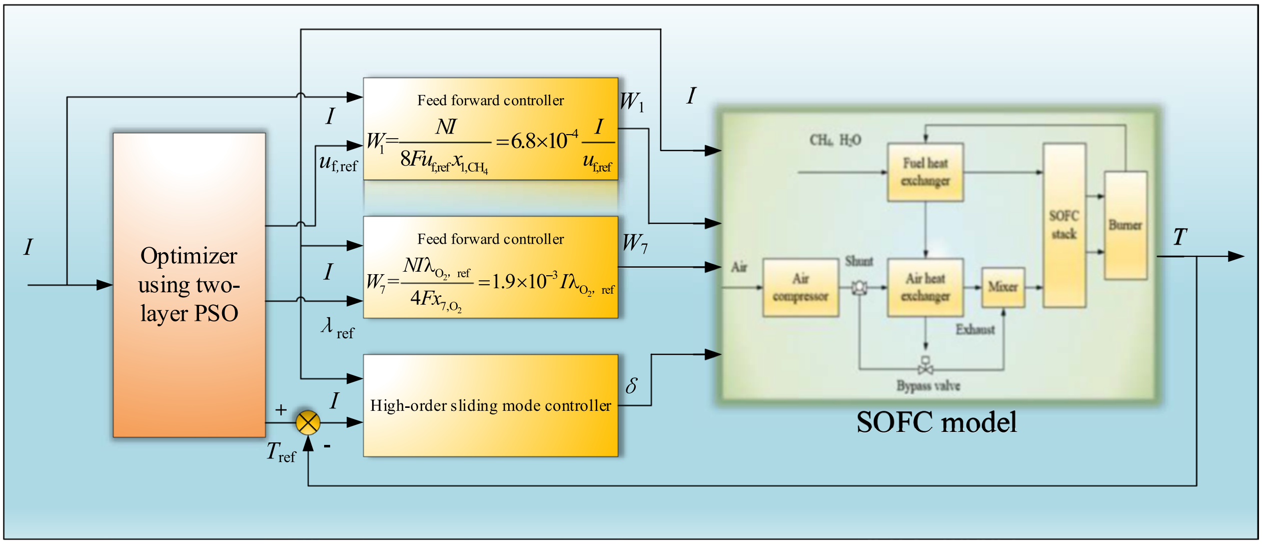

Fig. 7 The proposed optimal robust control scheme of the SOFC system

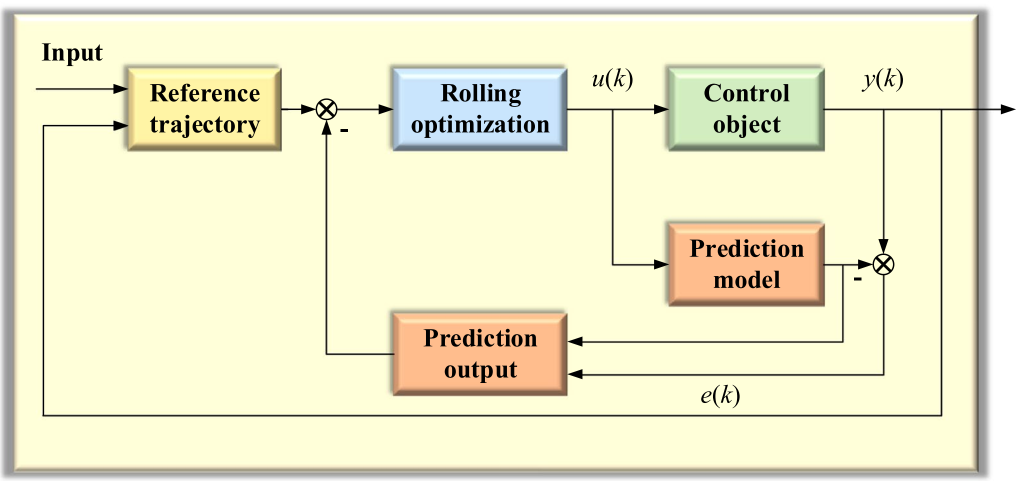

Fig. 8 Control flow chart of MPC

the number of cells, x_{7,O_2} and x_{1,CH_4} are mole fractions of oxygen and methane, respectively. The control strategy can effectively maintain the safe and efficient operation of the system.

Robust control is an effective method for solving the problems of control object and external disturbance uncertainty, and has attracted a lot of attention. SMC can effectively maintain the safe operation of an SOFC system because of its strong robustness and fast response. However, it is difficult to apply in practice because of the oscillation phenomenon of SMC. Although the robust control based on H-infinity theory can improve the anti-interference ability of an SOFC system, the controller structure is complex and the control accuracy is low.

4.4 Model predictive control

MPC is a control algorithm in which a dynamic process model is used to predict and optimize system performance [85]. It is mainly composed of four parts: a prediction model, feedback correction, rolling optimization and reference trajectory. The prediction model predicts the output within a future period, the rolling optimization carries out online optimization in the finite time domain, and the feedback correction revises the prediction model

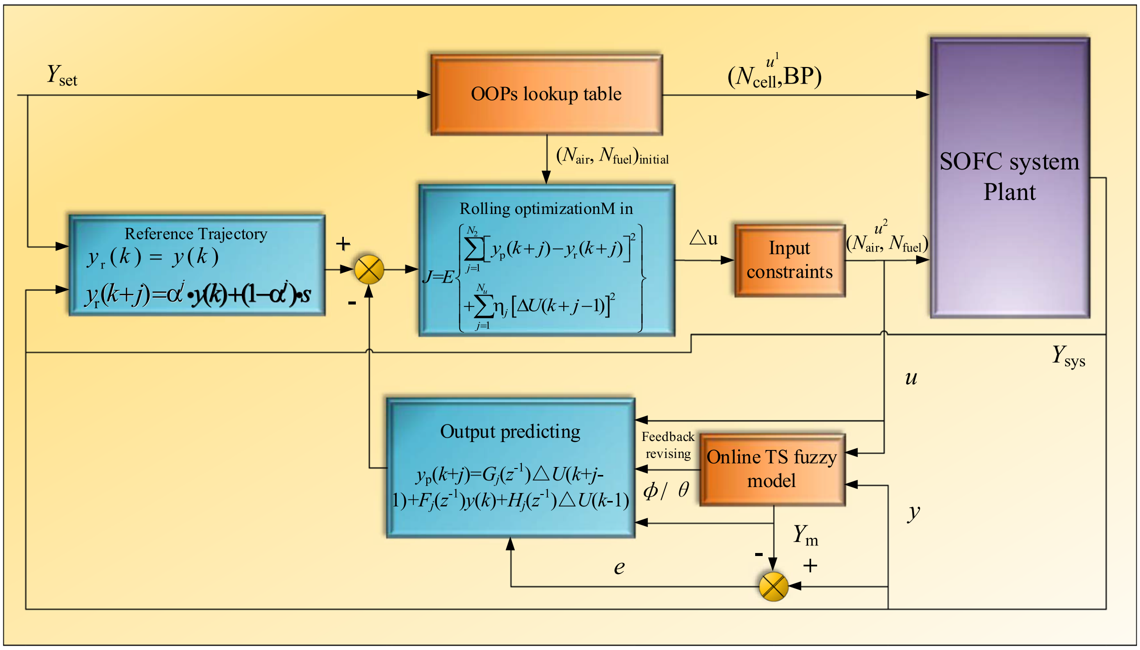

Fig. 9 SOFC system controller structure

and improves the prediction accuracy through prediction error feedback. During the whole action cycle, the model output error is used for feedback correction, and is compared with the reference trajectory. Rolling optimization is then carried out, and finally the control applied to the system at the current time is calculated. The flow chart of classical model predictive control is shown in Fig. 8. MPC not only has characteristics of strong robustness, good stability, and convenient modelling but is also suitable for dealing with the system control problem of large-scale multivariable object input [86]. Therefore, there has been a lot of MPC research on SOFC control, as summarized and evaluated in Table 5. It mainly includes traditional model predictive [87–92], data-driven predictive [86], nonlinear model predictive (NMPC) [93–97], generalized predictive (GPC) [98–102], constrained model predictive (CMPC) [53, 103], fuzzy MPC [14], and adaptive model predictive control (AMPC) [104].

In [100, 101], a thermoelectric decoupling method and thermoelectric cooperative control strategy of an SOFC system are proposed based on the transient analysis of the power switching process with optimal operating points (OOPs). The control strategy includes an OOPs-based feedforward controller for thermal management, and a GPC controller based on Takagi Sugeno (TS) fuzzy model for power tracking, fuel shortage prevention and input constraint processing. The schematic diagram of the proposed controller is shown in Fig. 9, where $G_j(z^{-1})\Delta U(k+j-1)$, $F_j(z^{-1})$ and $H_j(z^{-1})$ are calculated from the prospective control increment sequence, the known output sequence, and the known input increment sequence separately. $E\{*\}$ represents the expectation operator, η_j represents the control weighing sequence that limits the amplitude of the control sequence, N_2 represents the maximum cost horizon, N_u represents the control horizon, $\widehat{y}(k+j)$ represents the predictive system output and α is the smoothing factor.

The model of MPC is relatively easy to obtain and has good robustness and stability, but is difficult to put into practical use for complex dynamic problems. Because an SOFC system is a complex system with strong coupling and is multivariable, it is difficult to model. Therefore, if the system data can be obtained effectively, the data-driven predictive controller can have great potential. For complex systems with strong nonlinearity, it is difficult for linear MPC to obtain a satisfactory control effect. Therefore, NMPC is proposed to solve the control problem of complex systems. However, the calculation of NMPC is large, and it is difficult to obtain the model. In addition, GPC with good control performance is not suitable for a control system that needs a fast response because of the large number of calculations. To ensure the safe operation of anSOFC, a CMPC controller and fuzzy MPC controller has been designed to solve the problems of strong coupling and a multivariable system. However, the structure of the former is complex and time-consuming, while the control accuracy of the latter

Table 5 Chronological summary of MPC

Control method		Control objectives	Controller design	Parameters	Performance	Usage scenarios	Complexity	Robustness	Accuracy
MPC	Jurado [85]	1. Air or fuel flow rate	Cost function: $\min J(H_{p1}, H_{p2}, H_c, \lambda) = \sum_{j=H_{p1}}^{H_{p2}} (w(k+j) - \widehat{y}(k+j))^2 + \lambda \sum_{j=1}^{H_c} \Delta u^2(k+j-1)$	$\widehat{y}(k+j)$: predicted system output; $w(k+j)$: modified setpoint; H_{p1}: minimum costing horizon; H_{p2}: maximum costing or prediction horizon; H_c: control horizon; λ: move suppression coefficient.	Meet power demand	Multivariable fuzzy Hammerstein model of SOFC	**	**	**
	Sanandaji [87]	1. Air or fuel flow rate; 2. Voltage	N. P.	N. P.	Improve load tracking capability	Linear parameter variation model of SOFC system	**	***	**
	Kupilik [88]	1. Air or fuel flow rate	Objective function: $J = \text{minimize} x_{k,N}^{'} P_f x_{k,N} + \sum_{i=0}^{N-1} x_{k,i}^T Q x_{k,i} + u_{k,i}^T R u_{k,i} + \|Q_Y(y_{k,i} - y_{\text{ref},i})\|_2$	$y_{\text{ref},i}$: reference trajectory; P_f, Q, R and Q_Y: weighting matrix; $x_{k,N}$: state at time k.	Meet the change of load demand; Reduce carbon deposition	Experimental model of movable 1.5 kW SOFC system	***	***	***
	Horalek [89], [90]	1. Air or fuel flow rate	Multilinear MPC controller: $J(k) = \sum_{p=1}^{N} \sum_{j=1}^{n_y} (\lambda_j^y (y_{j,\text{ref}}(k+p\vert k) - y_j(k+p\vert k)))^2 + \sum_{p=0}^{N_u-1} \sum_{j=1}^{n_u} (\lambda_j^{\Delta u} \Delta u_j(k+p\vert k))^2$	y: controlled variable; y_{ref}: reference; Δu: increments of manipulated variables; p: Prediction horizon.	Stable output voltage	Nonlinear SOFC state model	***	***	**
	Miaomiao [91]	1. Current density	Performance index function: $J(U_N, x(0)) = \sum_{k=0}^{N-1} \left(x_k^{'} Q x_k + u_k^{'} R u_k \right) + x_N^{'} P x_N$	x: collection of the bounded parameter; Q: state weight; R: input weight; N: control domain.	Reduce computation and storage	Piece wise affine (PWA) model of SOFC	**	***	**
	Frenkel [92]	1. Power	Control law: $u_k = e_1^{\mathrm{T}} \cdot \widetilde{u}_k = e_1^{\mathrm{T}} (S_v \cdot \widetilde{y}_{\mathrm{d,k+1}} - \mathrm{k} \cdot \mathrm{x}_k)$	k: control gain.	N. P.	Experimental	**	***	**

Table 5 (continued)

Control method		Control objectives	Controller design	Parameters	Performance	Usage scenarios	Complexity	Robustness	Accuracy
Data-driven PC	Wang [86]	1. Air or fuel flow rate	Cost function: $\min J_k = \min\left(\widehat{y}_{k+1/L} - r_{k+1/L}\right)^T Q\left(\widehat{y}_{k+\frac{1}{L}} - r_{k+\frac{1}{L}}\right)$ $+\Delta u^T_{\frac{k}{M}} R_M \Delta u_{\frac{k}{M}} + u^T_{\frac{k}{M}} P_M u_{\frac{k}{M}}$	L: prediction horizon; M: control horizon; $\widehat{y}_{k+1/L}$: vector of prediction of future output; $r_{k+1/L}$: vector of future reference signals; Q, R_M and P_M: weighting matrices with block diagonal structure; $u_{k/M}$: vector of future manipulated signal.	Verify the effectiveness of data-driven predictive control algorithm	N. P.	**	**	***
NMPC	Huo [38]	1. Air or fuel flow rate; 2. Voltage	Cost function: $J = \sum_{j=1}^{H_p} \left[\widehat{V}_{dc}(k+j) - V_{dcr}(k+j)\right]^2$ $+\lambda \sum_{i=1}^{H_c} \left[N_f(k+i) - N_f(k+i-1)\right]^2$	$\widehat{V}_{dc}(k+j)$: predicted output voltage; H_c: control horizon; $N_f(k+i)$: manipulated variable; λ: weighting factor.	Stable output voltage	Hammerstein model of SOFC	**	**	**
	Zhang [93]	1. Air or fuel flow rate; 2. Current density	Cost function: $\Phi = \min\left\{\sum_{k=T}^{T+N_c} L(w_k, v_k) + \frac{1}{2}V\left(w_{T+N_c}\right)\right.$ $\left.+\sum_{k=T}^{T+N_c}\left(\frac{1}{2}\eta_{r,k} O_r \eta_{r,k}^T + O_r \eta_{r,k}\right)\right\}$	$V\left(w_{T+N_c}\right)$: penalty term; η: relaxation factor; Q_r: penalty matrix of regulator cost function.	SOFC under effective control constraints	Experimental	***	***	***
	Yang [94]	1. Temperature	Objective function: $J = \sum_{i=1}^{P} q_i [y(k+i) - y_m(k+i)]^2$ $+\sum_{j=1}^{M} r_j \Delta u^2(k+j-1)$	q_i and r_j: weight coefficient; P: prediction horizon; M: control horizon; $y(k+i)$: actual output; $y_m(k+i)$: model predictive output.	Effectively control temperature of SOFC stack	Improved TS fuzzy model of SOFC stack	**	***	**
	Murshed [95]	1. Voltage	Objective function: $\min J = \sum_{i=1}^{N}\left[\Vert\widehat{x}\left(k+\frac{i}{k}\right) - x_{ref}\Vert_Q^2\right.$ $+\Vert u\left(k+\frac{i}{k}\right) - u_{ref}\Vert_R^2 + \left.\Vert\Delta u\left(k+\frac{i}{k}\right)\Vert_S^2\right]$ $+W_{indirect}\left[\sum \dot{n}_{i,E} \int_{T_{ref}}^{T_{AE}} C_{p,i}(T)dT\right.$ $\left.+\dot{n}_{i,E} \frac{1-r}{r} \int_{T_{ref}}^{T_B} C_{p,i}(T)dT\right]$	Q, R, S and $W_{indirect}$: weighting matrices; T_{ref}: minimum temperature; T_{AE}, T_B: exit temperatures; $\dot{n}_{i,E}$: flow rate.	Improve the operation efficiency of the system	Experimental	***	***	***
	Bhattacharyya [96]	1. Air or fuel flow rate; 2. Voltage	Optimization formula: $\min\Vert W_1(\widehat{y} - \xi)\Vert_2 + \Vert W_2 u\Vert_2$	W_1: weighting matrix; W_2: move suppression matrix.	Meet the step change of load	Experimental	***	**	**

Table 5 (continued)

Control method		Control objectives	Controller design	Parameters	Performance	Usage scenarios	Complexity	Robustness	Accuracy
	Lee [97]	1. Air or fuel flow rate; 2. Voltage	Performance index: $J(k,k+1) \triangleq x(k\|k)^T ‡ x(k\|k)$ $+u(k\|k)^T \gamma u(k\|k) + V(k+1\|k)$	$V(k+1\|k)$: terminal cost; x: state vector; u: control input; $‡>0, \gamma>0$.	Improve load tracking capability	Sector bounded nonlinear model of SOFC system	**	***	**
	Wu [27]	1. Air or fuel flow rate	Control input: $u_k(i) = u_{k-1}(i) + K_P e_{k-1}(i)$ $+K_D \dot{e}_{k-1}(i) i = 1, \ldots, N_c$	N_c: control window; k: iteration index; $e_{k-1}(i)$: tracking error; $\dot{e}_{k-1}(i)$: error difference; K_P and K_D: learning gains.	Extend system life	Experimental model of SOFC system	****	***	****
	Awryńczuk [28]	1. Air or fuel flow rate	Cost function: $J(k) = \sum_{p=1}^{N} (V_{dc}^{sp}(k+p\|k) - \widehat{V}_{dc}(k+p\|k))^2$ $+\lambda \sum_{p=0}^{N_u-1} (\Delta q_f(k+p\|k))^2$	λ: weighting coefficient; $\widehat{V}_{dc}(k+p\|k)$: predicted values; $V_{dc}^{sp}(k+p\|k)$: set-point values; N_u: control horizon.	Meet fuel use restrictions; Good quality control	Continuous time model of SOFC system	***	****	****
GPC	Deng [98]	1. Current density	Cost function: $J = E\left\{\sum_{j=1}^{N} (\widehat{y}(k+j) - y_r(k+j))^2\right.$ $\left.+\sum_{j=1}^{M} \lambda(j)(\Delta u(k+j-1))^2\right\}$	$E\{\}$: expectation operator; N: maximum costing horizon; M: control horizon; $\lambda(j)$: control weighting sequence; $\widehat{y}(k+j)$: optimum ahead prediction; $y_r(k+j)$: future reference trajectory.	Improve load tracking capability; Extended stack life	Fractional order model of SOFC	***	***	**
	Jiang [99]	1. Air or fuel flow rate; 2. Temperature	Objective function: $J = E\left\{\sum_{j=1}^{N_2} [\widehat{y}(k+j) - y_r(k+j)]^2\right.$ $\left.+\sum_{j=1}^{N_u} \eta_j [\Delta U(k+j-1)]^2\right\}$	$E\{\}$: expectation operator; η_j: control weighting sequence which limits the amplitude of the control sequence; N_2: maximum costing horizon; N_u: control horizon; $\widehat{y}(k+j)$: predictive system output at the $(k+j)$ th instance; $y_r(k+j)$: reference value at the $(k+j)$ th instance.	Improve system response speed and stability; Improve anti-interference ability	TS fuzzy model of SOFC system	***	***	***

Table 5 (continued)

Control method		Control objectives	Controller design	Parameters	Performance	Usage scenarios	Complexity	Robustness	Accuracy
	Pohjoranta [32]	1. Temperature	Objective function: $J(N_1, N_2, N_3) = \sum_{j=N_1}^{N_2} \Vert\widehat{y}(t+j\vert t) - w(t+j)\Vert_R^2$ $+ \sum_{j=1}^{N_3} \Vert u(t+j-1) - u(t+j-2)\Vert_Q^2$	$\widehat{y}(t+j\vert t)$: optimum j-step-ahead prediction of the output y; N_1, N_2: prediction horizon; N_3: control horizon; $w(t+j)$: set point trajectory; R and Q: positive definite weight matrices.	Extended service life	Simulink model of 10 kW SOFC system	***	***	***
	Jiang [100, 101]	1. Air or fuel flow rate	Objective function: $J = E\left\{\sum_{j=1}^{N_2} \left[\widehat{y}(k+j) - y_r(k+j)\right]^2 + \sum_{j=1}^{N_u} \eta_j \left[\Delta U(k+j-1)\right]^2\right\}$	$E\{\}$: expectation operator; η_j: control weighting sequence; N_2: maximum cost horizon; N_u: control horizon; $\widehat{y}(k+j)$: predictive system output; $y_r(k+j)$: reference value.	Improve load tracking capability; Extend system life	Simulink model of 5kW SOFC system	***	****	***
	Boubaker [102]	1. Air or fuel flow rate	N.P.	N.P.	Improve response speed	Dynamic model of SOFC system.	***	***	***
CMPC	Li [53]	1. Voltage	Performance index: $J(k) = \sum_{i=0}^{N-1} [\left(x\left(k+i+\frac{1}{k}\right) - \bar{x}\right)^T Q\left(x\left(k+i+\frac{1}{k}\right) - \bar{x}\right)$ $+ R\Delta q_f^2(k+i/k)] + \psi(x\left(k+N+\frac{1}{k}\right) - \bar{x})$	N: prediction horizon; $x\left(k+i+\frac{1}{k}\right)$: predicted state; $\bar{x}$: equilibrium value of the state vector; k: current time.	Successfully handle control and control motion constraints; Satisfactory closed-loop performance is obtained	Dynamic model of SOFC system	***	***	**
	Spivey [103]	1. Air or fuel flow rate; 2. Temperature; 3. Pressure	Objective function: $\min J = \frac{1}{2}(y - y_{ref})^T Q(y - y_{ref}) + \frac{1}{2}\Delta u^T R \Delta u + \frac{1}{2}\xi^T V \xi$	y: vector of controlled variables at all prediction time steps; y_{ref}: reference trajectory; Q, R and V: weight matrices; Δu: change in manipulated variables between each control time step; ξ: slack variables.	Extended service life	A dynamic, quasi-two-dimensional model for a high-temperature tubular SOFC combined with ejector and pre-reformer models	***	***	**

Table 5 (continued)

Control method		Control objectives	Controller design	Parameters	Performance	Usage scenarios	Complexity	Robustness	Accuracy
Fuzzy MPC	Wu [14]	1. Air or fuel flow rate	Preference index: $\min J = \Vert \frac{1}{2}(\lvert Y(k) - Y_{\mathrm{h}}(k)\rvert + \lvert Y(k) - Y_{\mathrm{l}}(k)\rvert$ $-\lvert Y_{\mathrm{h}}(k) - Y_{\mathrm{l}}(k)\rvert)\Vert_Q^2 + \Vert \Delta U(k)\Vert_R^2 + \Vert \Delta Y(k)\Vert_W^2$	$Y_{\mathrm{h}}(k)$: higher limit sequence; $Y_{\mathrm{l}}(k)$: lower limit sequence; $\Delta Y(k)$: increment of output prediction; Q, R and W: weight coefficient matrix	Stable output voltage; Stable fuel utilization	Fuzzy model with region tracking for SOFC system	***	***	***
AMPC	Liu [104]	1. Voltage	Objective function: $\min J(x(t), U(t), N_P, N_C)$ $s.t.\begin{cases} x(t+1) = Ax(t) + \mathrm{B_u}u(t) + \mathrm{B_d}d(t), \\ \left(t = t, t+1, \ldots, t+N_p-1\right); \\ y(t) = Cx(t); \\ \frac{2K_r I}{0.9} \le u(t) \le \frac{2K_r I}{0.7} \end{cases}$	N.P.	Improve output voltage tracking ability and dynamic performance	Dynamic model of SOFC system	***	****	***

Table 6 Performance of predictive control

Control methods		MPC	NMPC	Data-driven PC	GPC	CMPC	Fuzzy MPC
Complexity	Low (*)						
	Lower (**)						√
	Genera l(***)	√		√			
	Higher (****)		√		√		
	High (*****)					√	
Robustness	Weak (*)						
	Relatively weak (**)	√					
	Genera l(***)					√	
	Relatively strong (****)		√	√			√
	Strong (*****)				√		
Accuracy	Low (*)						
	Lower (**)						√
	General (***)	√		√			
	Higher (****)		√		√		
	High (*****)					√	

is poor. The evaluation of the above predictive control methods is shown in Table 6.

4.5 Fuzzy logic control

Fuzzy logic control (FLC) is a kind of nonlinear control, and belongs in the category of intelligent control. A typical FLC controller is mainly composed of the following parts: independent variable, fuzzification, rule base, fuzzy reasoning and defuzzification. FLC first determines the fuzzy rules according to experience and then blurs the real-time signals. The fuzzy signals are used as input, and the fuzzy reasoning is completed to obtain the outputs sent to the actuator. The structure diagram of a typical fuzzy reasoning system is shown in Fig. 10 [105].

FLC strategy can be used to control highly nonlinear, time-varying and poorly defined systems. FLC does not require an accurate mathematical model and has lower cost in controller design and implementation [106]. Therefore, FLC has attracted attention. In [106], a fuzzy logic controller is designed for an SOFC mathematical model. Reference [107] puts forward a nonlinear model of SOFC transient behavior, including an AC voltage control and active/reactive power control strategy for the DC/AC inverter, with a designed TS fuzzy controller for this purpose.

4.6 Fault-tolerant control

Fault-tolerant control (FTC) can work in both normal and faulty states. It is one of the feasible methods to ensure the operational safety and reliability of an SOFC system. Generally, FTC can be divided into active (AFTC) and passive fault-tolerant control (PFTC). PFTC is based on robust control technology and does not need any online fault information. The controller is designed according to the predicted fault to ensure that the system is not sensitive to a fault, so as to ensure the stability and performance of the system. In contrast, AFTC readjusts the parameters/structure of the controller through the online fault diagnosis signal. In the relevant literature, FLC, MPC and PID control are used to construct FTC to improve the service life and load tracking ability of the system. In Table 7, various FTC studies of SOFC systems are summarized and evaluated.

For the FTC of an SOFC system, references [109, 110] propose a structure of fault detection and FTC of a distributed power system to ensure safe and reliable operation. Reference [108] uses a fault-tolerant controller to control the system temperature within the allowable range and maintain high fuel utilization, while [112] designs a fault-tolerant controller based on predictive control to improve the life and performance of the system. In addition, reference [111] proposes an optimal fault-tolerant control strategy, which uses a PID control loop to achieve optimal operation. In [113], fault diagnosis is carried out using a Bayesian regularized neural network, and then four fuzzy controllers with different input signals are designed, consisting of system power, burner outlet temperature slope, system power and burner outlet temperature, and the system power and its differential term. The proposed FTC strategy is shown in Fig. 11, where P_{net} represents system power, f_{H2O} represents steam flow rate, ΔT_{stack} and T_{burner} represent stack temperature difference and burner outlet temperature, respectively.

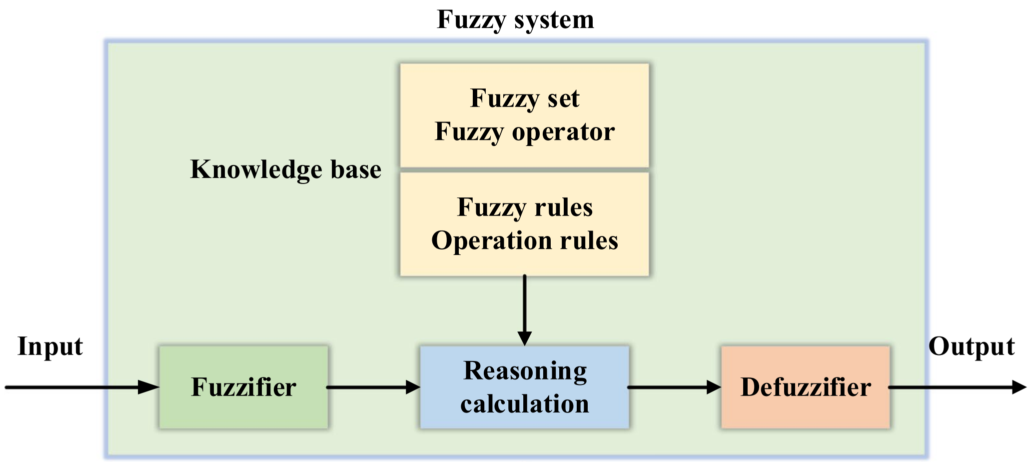

Fig. 10 Fuzzy system structure [105]

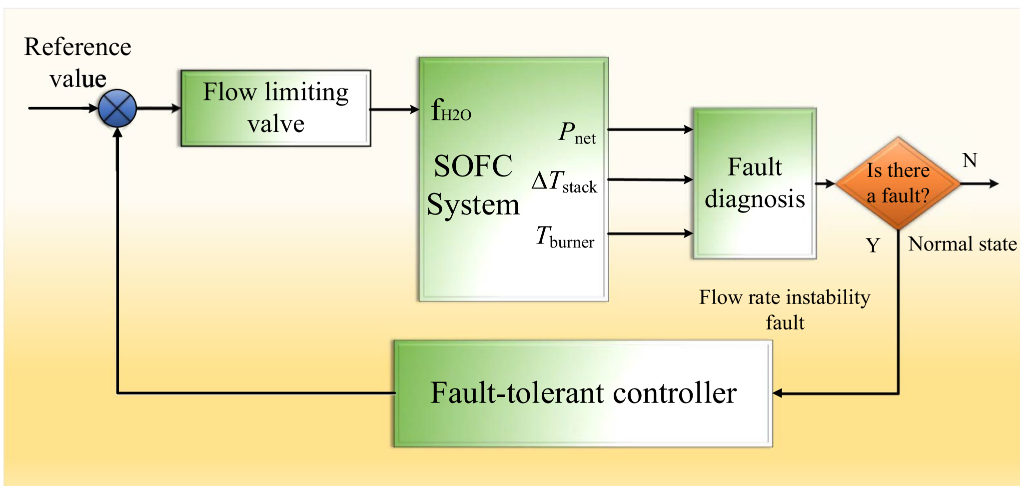

Fig. 11 FTC strategy scheme of the SOFC system

AFTC can quickly adjust the control parameters or structure according to the fault signal to achieve relatively high control accuracy. However, the structure of AFTC is complex and the cost is high. In contrast, PFTC is highly reliable and easy to implement, but it is difficult to realize an efficient operation of the SOFC system.

4.7 Intelligent control

Intelligent control is an effective control strategy for dynamic nonlinear systems. It mainly includes neural network control, fuzzy control and expert control. An expert control system is a programmed system with a large amount of expertise and experience. It applies artificial intelligence and computer technologies to reason and judges according to the knowledge and experience provided by one or more experts, and simulates the decision-making process of human experts. Neural network control refers to the application of neural network technology to identify the neural network model of complex nonlinear objects, that are difficult to accurately model, to be used as the system controller. Compared with other control strategies, intelligent control can effectively control complex systems which are nonlinear, fast time-varying and multivariable [114, 115]. Table 8 summarizes and evaluates the literature related to intelligent control in an SOFC.

References [116, 117] establish a dynamic model of a tubular SOFC and design an artificial neural network (ANN) predictive controller to achieve the thermal management of the SOFC. In [114], an adaptive constrained PID control strategy based on a radial basis function (RBF) neural network identification and

Table 7 Chronological summary of FTC

Control method		Control objectives	Controller design	Parameters	Performance	Usage scenarios	Complexity	Robustness	Accuracy
PFTC	Li [108]	1. Air or fuel flow rate; 2. Temperature.	Burner independent controller and fuel fault-tolerant controller.	N. P.	Ensure safe temperature; High level of fuel utilization maintained.	Experimental model of 5kW SOFC system.	***	***	***
AFTC	Sun [109, 110]	1. Air or fuel flow rate; 2. Temperature.	Observer based feedback controller.	N. P.	Improve system stability.	Experimental.	**	***	**
	Wu [111]	1. Power; 2. Air excess ratio; 2. Temperature.	Controller: $u = K_P(y - y_{ref}) + K_I \int (y - y_{ref})dt$ $+K_D \frac{d}{dt}(y - y_{ref})$	u: manipulated variables; y: controlled variables; K_P: proportional gains; K_I: integral gains; K_D: derivation gains; y_{ref}: reference value.	Achieve high efficiency and low unit cost.	Experimental.	***	****	***
	Wu [112]	1. Air or fuel flow rate.	Cost functions; $J_{1q}(k) = \frac{1}{2}\sum_{p=0}^{N_p}(T_r(k+p) - T_q(k+p))^2$ $+\frac{1}{2}\sum_{p=0}^{N_p}(V_r(k+p) - V_q(k+p))^2$ $+\frac{\lambda_1}{2}\sum_{p=0}^{N_p-1}(W_{fq}(k+p) - W_{fq}(k+p-1))^2$ $J_{2q}(k) = \frac{1}{2}\sum_{p=0}^{N_p}(T_r(k+p) - T_q(k+p))^2$ $+\frac{1}{2}\sum_{p=0}^{N_p}(V_r(k+p) - V_q(k+p))^2$ $+\frac{\lambda_2}{2}\sum_{p=0}^{N_p-1}(W_{aq}(k+p) - W_{aq}(k+p-1))^2$	λ_1 and λ_2: control weighting factors; V_r and T_r: reference trajectories; T_q and V_q: predicted values; N_p: prediction horizon.	Improve system operation efficiency; Extended service life.	Experimental.	***	***	****
	Xue [113]	1. Air or fuel flow rate; 2. Power.	Fuzzy controller with four different input signals.	N. P.	Solve the problem of combustion chamber temperature fluctuation.	A kW scale SOFC power generation system with reforming unit.	***	****	***

Table 8 Chronological summary of intelligent control

Control method		Control objective	Controller design	Parameters	Performance	Usage scenarios	Complexity	Robustness	Accuracy
NNPC	Haji-molana [116]	1. Temperature	$J(k,u(k)) = \sum_{L=M_1}^{M_2} (\alpha_r(k+L) - \alpha_m(k+L))^2$ $+\gamma \sum_{L=1}^{M_u} (u(k+L-1))^2$	$\alpha_r(k+L)$: j-step predictions of the process output; $\alpha_m(k+L)$: reference course; $u(k)$: control input; M_1 and M_2: costing scope; γ: weight of the control signal.	Effectively control the temperature of the cell-tube.	Dynamic model of tubular SOFC.	***	***	**
NNPC	Haji-molana [117]	1. Temperature	NNPC device adopts seven layer network, the hidden layer adopts sigmoid transfer function, and the output layer adopts linear transfer function.	N. P.	Improve transient response capability.	Dynamic model of tubular SOFC.	***	***	***
NNPID	Ji [114]	1. Air or fuel flow rate.	Controller: $u_c(k) = u(k-1) + K_P \cdot x_{c1}(k) + K_I \cdot x_{c2}(k)$ $+K_D \cdot x_{c3}(k) = u(k-1) + \sum_{l=1}^{3} K_l(k) x_{cl}(k)$	$K_l(k)$: parameters of adaptive neural network based PID controller;	Improve operational reliability and safety.	Experimental.	***	****	****
DHASL-MATD3	Li [118]	1. Air or fuel flow rate.	Target value: $y_t^1 = r(s_t, a_t) + \gamma \min_{i=1,2} Q_{\theta_i'}(s_{t+1}, \pi_{\phi_1}(s_{t+1}))$	N. P.	Effectively control the output voltage of SOFC system.	Experimental.	****	****	****
FOPID	Li [119]	1. Air or fuel flow rate.	Reward function:						
$r(t) = -\left[\mu_1 e^2(t) + \mu_2 \sum_{i=1}^{5} \lvert a_i(t-1) \rvert\right] + \chi$	N. P.	Maintain fuel utilization.	Experimental.	****	****	****			
TGSL-TD3PG	Li [120]	1. Air or fuel flow rate.	Target function of the algorithm: $F(t) = \int_0^{\infty} t(e(t))^2 dt$	$e(t)$: voltage error at time t.	Stable output voltage; Stable fuel utilization.	Experimental.	****	****	****

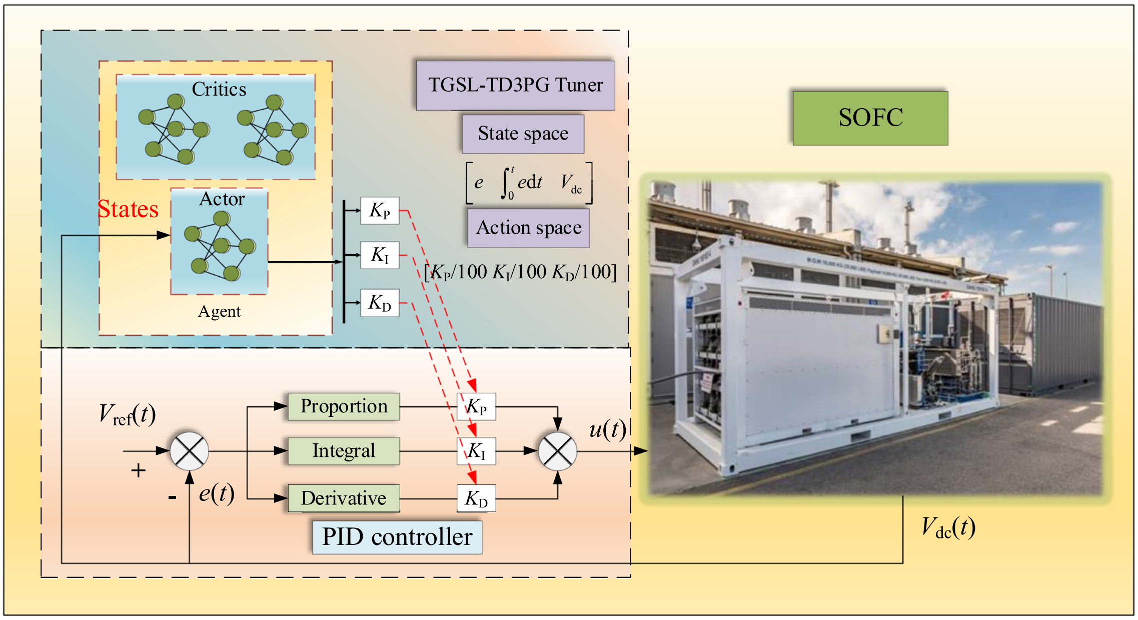

Fig. 12 Fuel control framework of the SOFC with the TGSL-TD3PG-tuned PID controller

dynamic anti-saturation backpropagation (BP) neural network is proposed. The control strategy can effectively control the fuel utilization and eliminate the divergence of parameter estimation and integrator saturation. To effectively control the output voltage of the SOFC, an SOFC output voltage data-driven controller based on multi-agent large-scale deep reinforcement learning is proposed in [118]. In reference [119], given the adaptability and model-free features of deep learning, an adaptive fractional order proportional integral derivative (FOPID) controller is proposed, and an intelligent algorithm is used as the tuner of the controller, so as to ensure that the fuel utilization of the SOFC is always maintained within a safe range. A data-driven adaptive PID controller is designed in [120], and its control framework is shown in Fig. 12. As shown, K_P, K_I and K_D are the proportional, integral and differential coefficients, respectively, while λ and μ represent the respective integral and differential orders. A new large-scale deep reinforcement learning algorithm is used to adaptively adjust the baseline parameters of the controller to improve the tracking ability of the SOFC output voltage. This is called a two-stage training strategy large-scale twin delayed deep determination policy gradient (TGSL-TD3PG). The data-driven adaptive PID controller has the advantages of being model-free, and having a simple structure. In addition, the algorithm adopts a two-stage large-scale training framework to improve the robustness and adaptability of the controller. The controller also benefits from the universality of PID control with good robustness. Compared with the traditional algorithm, although the setting time of TGSL-TD3PG algorithm is long, the adaptive ability of TGSL-TD3PG is strong. This can keep the fuel utilization within a safe range and provide satisfactory output voltage control performance. Therefore, the control strategy can effectively improve the load tracking ability and prevent violations.

Compared with traditional control, intelligent control has the ability of self-organization, being self-adaptive and self-learning, and can effectively control complex problems which have strong nonlinearity and coupling. However, the structure of intelligent control is often complex, with high requirements for the amount of data and being time-consuming. This leads to a difficulty in applying intelligent control in a practical SOFC system.

4.8 Observer-based control

The 'observer' mainly refers to an algorithm that combines the sensing signal with other information from the control system to generate the observation signal. The observer can thus be used to supplement or replace the sensors in the control system. In addition, the observer can also be used to improve system performance, reduce sampling delay etc. Some researchers have proposed observer-based SOFC control strategies [56, 121]. In [56], a time-delay control with an observer is introduced into the fuel supply system to improve the load tracking ability, while [121] proposes a composite nonlinear controller

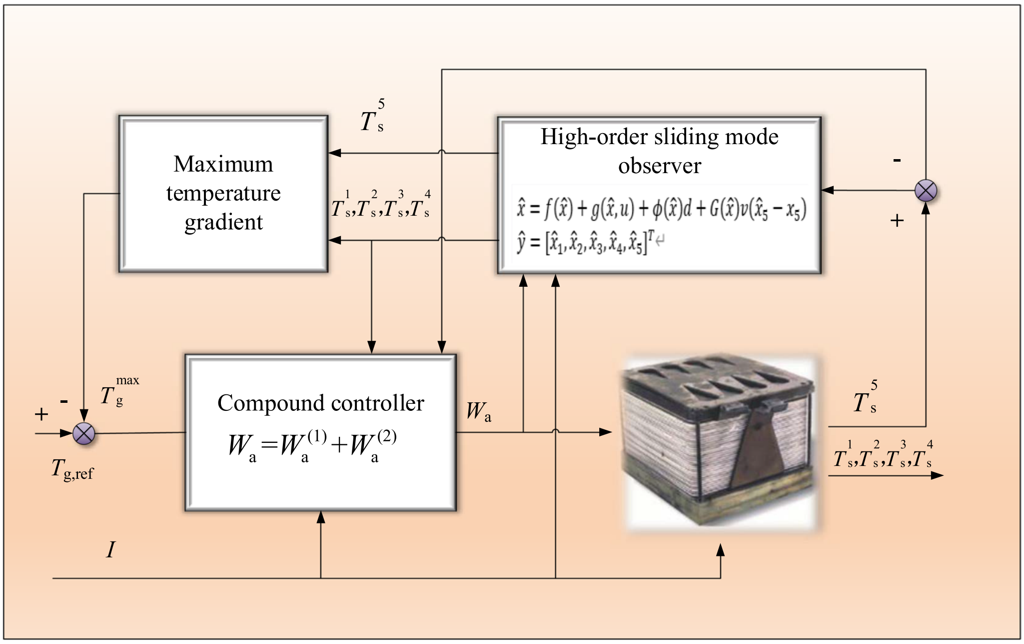

Fig. 13 Schematic diagram of SOFC control strategy based on high order sliding mode observer

based on a high-order sliding mode observer. This has fast tracking speed and small overshoot, and the temperature gradient can reach the expected value. The schematic diagram of the control strategy is shown in Fig. 13, where T_g^{max} is the maximum temperature gradient, $\widehat{x}$ and $\widehat{y}$ are the observed values of the state and output variables, respectively. $G(\widehat{x})$ is a decoupling matrix, while $W_a^{(1)}$ and $W_a^{(2)}$ are the control laws of the feedback linearization and the feedforward controllers, respectively.

Although the observer-based control method can effectively improve the performance of an SOFC system, it increases the complexity. In addition, the robustness of the observer is slightly worse than that when using sensors.

5 Summary and conclusion

To compare and analyze the control strategy of an SOFC system, this paper gives a comprehensive overview of SOFC control strategy. The control strategies are divided into eight categories: PID, APC, MPC, FLC, FTC, intelligent, and observer-based control. Each control strategy is analyzed and evaluated comprehensively. Figure 14 summarizes the advantages and disadvantages of the eight control strategies, and the main findings/conclusions are:

(1) The PID controller has the simplest structure associated with relatively high reliability, so is widely used for the SOFC in practice. However, its control accuracy is usually low and it cannot achieve a consistent control performance under large variations in operational conditions;
(2) APC does not need an accurate SOFC model and can maintain a satisfactory control performance with varying operational conditions and uncertainties. However, it usually has a fairly complex structure and high computational burden, and thus requires significant computation time;
(3) Robust control can effectively overcome various uncertainties of SOFC, e.g., uncertain parameters or unmodelled dynamics, such that strong robustness of the closed-loop system can be achieved. However, over-conservativeness is generally its inherent limitation and hence control optimality cannot be realized;
(4) MPC usually has a relatively high control accuracy, and can be easily combined with neural networks to further enhance its adaptiveness and response rate. However, its computational burden will grow dramatically in the face of strong nonlinearities;
(5) FLC simplifies the complexity of control system design without an accurate system model, and has great robustness and adaptability. However, FLC lacks generalizability and is difficult to apply to complex systems as the fuzzy rules may become significantly complicated;
(6) FTC is based on a specific fault detection feature which can generally achieve high control precision, safety and reliability. However, such a control

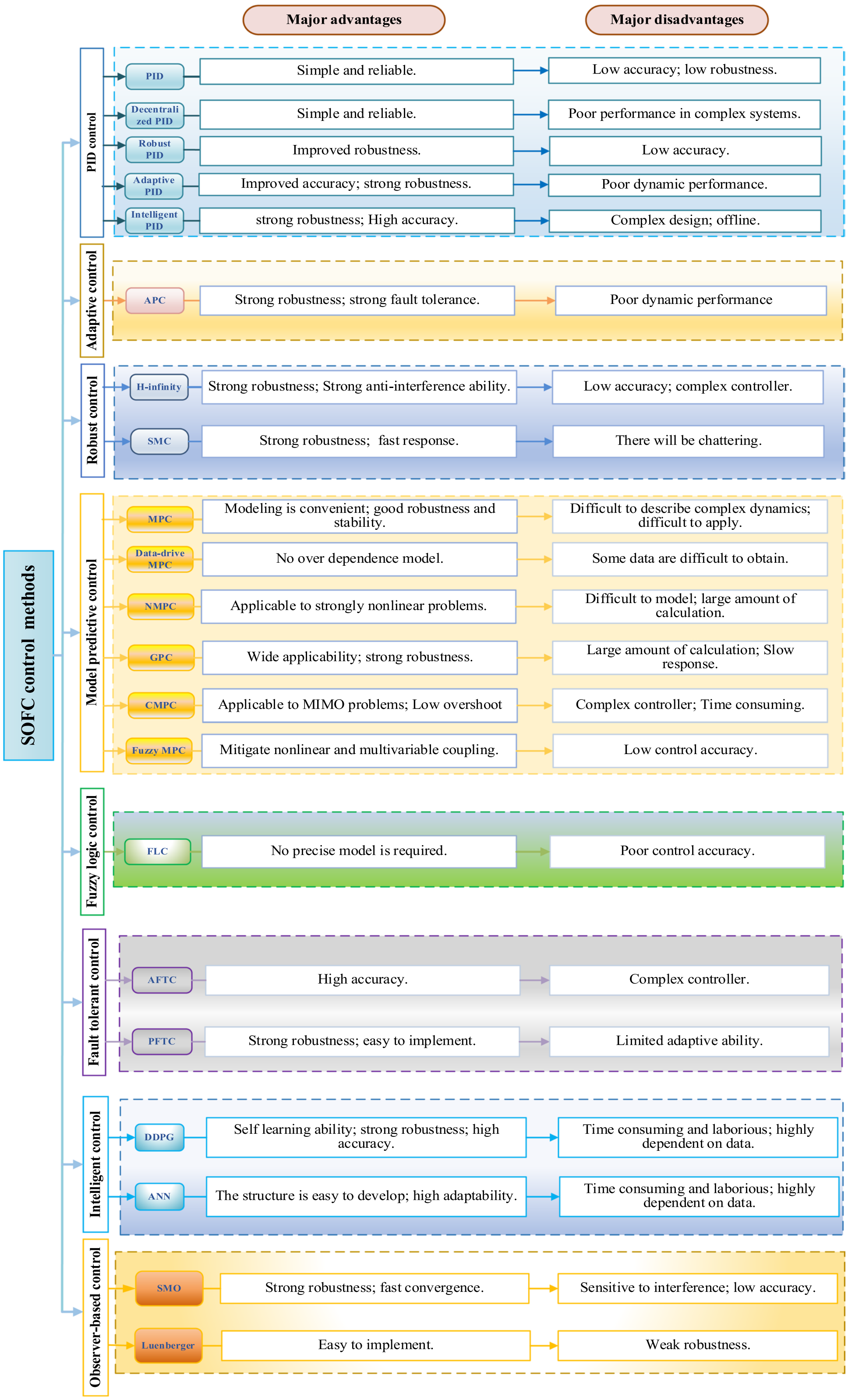

Fig. 14 Advantages and disadvantages of eight categories of control strategies

framework is largely case-oriented, which usually requires empirical information on the studied problem and thus the generalizability is often low;

(7) Intelligent control is mostly data-driven and does not require an accurate system model. It has satisfactory robustness and adaptability under different operating conditions and with various uncertainties. For example, simulation results of the TGSL-TD3PG algorithm demonstrate that the setting time of the output voltage is reduced by 45.2% while the magnitude of maximum voltage is reduced by 30%, together with zero constraint violation for fuel utilization. However, its practical implementation is difficult because of the requirement for a large amount of data and notable computation costs;

(8) An observer-based controller can rapidly estimate system states, uncertain parameters, unmodelled dynamics, as well as time-varying external disturbances, such that a consistent and robust control performance under the scenarios can be realized. However, the use of different types of observers inevitably increases the overall structural complexity, e.g., system order and computational burden, and it thus requires high-performance hardware and hinders its implementation in practice.

6 Challenges and perspectives

From this study, the main challenges of SOFC control can be summarized as follows:

(1) The measurement of variables/parameters is essential in various control strategies as SOFC control is highly complex, multivariable, and nonlinear. Therefore, advanced sensors must be employed which increases the overall costs;

(2) Most of the advanced control methods are complicated and difficult to apply in practical engineering;

(3) Because of the high temperature of an SOFC system during operation, then in order to ensure stable operation of the control system and the service life of its various components, the operating temperature of the corresponding SOFC control system hardware must be carefully controlled with effective heat sinks;

(4) SOFC control usually requires multiple control goals while most of the current controllers merely consider a few control targets. Hence, coordinated control of different control goals is a very challenging issue for the future.

In view of the development and advancement of SOFC, the following five suggestions/perspectives for SOFC control are proposed:

(1) Hybrid PV-SOFC system control design is worth studying, in which the required hydrogen of the SOFC system can be directly obtained by water electrification through the generated electricity from PV systems, such that the overall production costs can be reduced;

(2) Hybrid SOFC (or other FCs) and electric energy storage systems (EESSs) can enhance the reliability of energy supply. Advanced controller design for its energy management system (EMS) will be a very promising research direction;

(3) For the aforementioned controllers, their control gains/parameters can be optimally tuned by intelligent optimization algorithms to ensure control optimality and avoid the conventional time-consuming trial-and-error based parameter tuning procedure;

(4) Different types of controllers can be carefully incorporated to construct a hybrid control framework, such that the merits of each controller can be effectively combined or their inherent demerits can be partially/fully compensated for;

(5) Thus far, few hardware experiments or hardware-in-the-loop (HIL) tests have been undertaken to validate the effectiveness of advanced SOFC controllers. Hence, more experiments are encouraged.

Abbreviations

AC: Alternating current; AFC: Alkaline fuel cell; ANN: Artificial neural network; APC: Adaptive control; APU: Auxiliary power units; BOP: Balance of plant; BP: Backpropagation; CMPC: Constrained model predictive control; DC: Direct current; EESS: Electric energy storage system; EMS: Energy management system; FC: Fuel cell; FLC: Fuzzy logic control; FPS: Fuel-processing subsystem; FTC: Fault-tolerant control; GPC: Generalized predictive control; H_2: Hydrogen; HIL: Hardware-in-the-loop; IPI-ASMC: Intelligent proportional integral adaptive sliding mode control; MPC: Model predictive control; MIMO: Multiple input multiple outputs; NMPC: Nonlinear model predictive control; OOPs: Optimal operating points; PAFC: Phosphoric acid fuel cell; PEMFC: Proton exchange membrane fuel cell; PID: Proportional integral differential; RBF: Radial basis function; SMC: Slid mode control; SOFC: Solid oxide fuel cell; TDO: Time-delay control with observer; TMS: Thermal management subsystem; TS: Takagi Sugeno; UF: Utilization factor.

Acknowledgements

This work was supported by National Natural Science Foundation of China (61963020); Key Program of National Natural Science Foundation of China (52037003); Major Special Project of Yunnan Province of China (202002AF080001); Curriculum ideological and political connotation construction project (2021KS037).

Author contributions

Summarize eight groups of solid oxide fuel cell system control strategies; Control complexity, robustness, and accuracy are summarized and evaluated; Present the advantages/disadvantages of all control methods; Five valuable and insightful perspectives are proposed for future research directions. All authors have read and approved the final version of the manuscript.

Funding

National Natural Science Foundation of China (61963020); Key Program of National Natural Science Foundation of China (52037003); Major Special Project of Yunnan Province of China (202002AF080001); Curriculum ideological and political connotation construction project (2021KS037).

Availability of data and materials

The datasets used or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author details

[1]Faculty of Electric Power Engineering, Kunming University of Science and Technology, Kunming 650500, China. [2]School of Management and Economics, Kunming University of Science and Technology, Kunming 650500, China. [3]Warwick Manufacturing Group, University of Warwick, Coventry CV4 7AL, UK. [4]China Southern Power Grid EHV Transmission Company, Dali, China.

Received: 21 January 2022 Accepted: 22 July 2022
Published online: 06 September 2022

References

1. Wang, J. B., Yang, B., Zeng, C. Y., Chen, Y. J., Yu, T., et al. (2021). Recent advances and summarization of fault diagnosis techniques for proton exchange membrane fuel cell systems: A critical overview. *Journal of Power Sources, 500*, 229932.
2. Yang, B., Wang, J. B., Yu, L., et al. (2020). A critical survey on proton exchange membrane fuel cell parameter estimation using meta-heuristic algorithms. *Journal of Cleaner Production, 265*, 121660.
3. Olujobi, O. J. (2020). The legal sustainability of energy substitution in Nigeria's electric power sector: Renewable energy as alternative. *Protection and Control of Modern Power Systems, 5*(4), 358–369.
4. Yang, B., Wang, J. B., Zhang, X. S., Yu, T., Yao, W., Shu, H. C., et al. (2020). Comprehensive overview of meta-heuristic algorithm applications on PV cell parameter identification. *Energy Conversion and Management, 208*, 112595.
5. Yang, B., Yu, T., Zhang, X. S., Li, H. F., Shu, H. C., Sang, Y. Y., & Jiang, L. (2019). Dynamic leader based collective intelligence for maximum power point tracking of PV systems affected by partial shading condition. *Energy Conversion and Management, 179*, 286–303.
6. Liu, J., Wen, J. Y., Yao, W., & Long, Y. (2016). Solution to short-term frequency response of wind farms by using energy storage systems. *IET Renewable Power Generation, 10*(5), 669–678.
7. Yao, W., Jiang, L., Wen, J. Y., Wu, Q. H., & Cheng, S. J. (2015). Wide-area damping controller for power system interarea oscillations: A networked predictive control approach. *IEEE Transactions on Control Systems Technology, 23*(1), 27–36.
8. Abbaker, A. M. O., Wang, H. P., & Tian, Y. (2019). Voltage control of solid oxide fuel cell power plant based on intelligent proportional integral-adaptive sliding mode control with anti-windup compensator. *Transactions of the Institute of Measurement and Control, 42*(1), 116–130.
9. Kumar, D. S., Savier, J. S., & Biju, S. S. (2020). Micro-synchrophasor based special protection scheme for distribution system automation in a smart city. *Protection and Control of Modern Power Systems, 5*(1), 97–110.
10. Murty, V. V. S. N., & Kumar, A. (2020). Multi-objective energy management in microgrids with hybrid energy sources and battery energy storage systems. *Protection and Control of Modern Power Systems, 5*(1), 1–20.
11. Tummala, A. S. L. V. (2020). A robust composite wide area control of a DFIG wind energy system for damping inter-area oscillations. *Protection and Control of Modern Power Systems, 5*(3), 260–269.
12. Yang, B., Jiang, L., Wang, L., Yao, W., & Wu, Q. H. (2016). Nonlinear maximum power point tracking control and model analysis of DFIG based wind turbine. *International Journal of Electrical Power & Energy Systems, 74*, 429–436.
13. Malik, V., Srivastava, S., Bhatnagar, M. K., & Vishnoi, M. (2021). Comparative study and analysis between solid oxide fuel cells (SOFC) and proton exchange membrane (PEM) fuel cell – A review. *Materials Today: Proceedings, 47*(10), 2270–2275.
14. Wu, L., Wu, X., Pan, L., Shen, J., Li, Y. G., & Zhang, J. L. (2019). Fuzzy model predictive control of solid oxide fuel cell with zone tracking. *IFAC-PapersOnLine, 52*(4), 210–215.
15. Yang, B., Zhong, L. E., Yu, T., Li, H. F., Zhang, X. S., Shu, H. C., Sang, Y. Y., & Jiang, L. (2019). Novel bio-inspired memetic salp swarm algorithm and application to MPPT for PV systems considering partial shading condition. *Journal of Cleaner Production, 215*, 1203–1222.
16. Yang, B., Zhang, X. S., Yu, T., Shu, H. C., & Fang, Z. H. (2017). Grouped grey wolf optimizer for maximum power point tracking of doubly-fed induction generator based wind turbine. *Energy Conversion and Management, 133*, 427–443.
17. Wang, Q., Yao, W., Fang, J. K., Ai, X. M., Wen, J. Y., Yang, X. B., Xie, H. L., & Huang, X. (2020). Dynamic modeling and small signal stability analysis of distributed photovoltaic grid-connected system with large scale of panel level DC optimizers. *Applied Energy, 259*, 114132.
18. Shen, Y., Yao, W., Wen, J. Y., He, H. B., & Jiang, L. (2019). Resilient wide-area damping control using GrHDP to tolerate communication failures. *IEEE Transactions on Smart Grid, 10*(3), 2547–2557.
19. Ferriday, T. B., & Middleton, P. H. (2021). Alkaline fuel cell technology-A review. *International Journal of Hydrogen Energy, 46*(35), 18489–18510.
20. Yang, B., Zhu, T. J., Zhang, X. S., Wang, J. B., Shu, H. C., Li, S. N., He, T. Y., Yang, L., & Yu, T. (2020). Design and implementation of battery/SMES hybrid energy storage systems used in electric vehicles: A nonlinear robust fractional-order control approach. *Energy, 191*, 116510.
21. Cheng, S., Zhao, G. J., Gao, M., et al. (2021). A new hybrid solar photovoltaic/phosphoric acid fuel cell and energy storage system; energy and exergy performance. *International Journal of Hydrogen Energy, 46*(11), 8048–8066.
22. Lin-Kwong-Chon, C., Grondin-Perez, B., Kadjo, J. J. A., et al. (2019). A review of adaptive neural control applied to proton exchange membrane fuel cell systems. *Annual Review in Control, 47*, 133–154.
23. Wee, J. H. (2014). Carbon dioxide emission reduction using molten carbonate fuel cell systems. *Renewable and Sustainable Energy Reviews, 32*, 178–191.
24. Stambouli, A. B., & Traversa, E. (2002). Solid oxide fuel cells (SOFCs): A review of an environmentally clean and efficient source of energy. *Renewable and Sustainable Energy Reviews, 6*(5), 433–455.
25. Vaishampayan, V., Vangari, A., Shah, J. (2014). Challenges and opportunities of affordable fuel cell for distributed generation. In *International Conference on Non Conventional Energy (ICONCE)*. 16–17 Jan, Kaliyani, India, https://doi.org/10.1109/ICONCE.2014.6808734.
26. Yang, B., Wang, J. B., Zhang, M. T., Shu, H. C., et al. (2020). A state-of-the-art survey of solid oxide fuel cell parameter identification: Modelling, methodology, and perspectives. *Energy Conversion and Management, 213*, 112856.
27. Wu, X. J., Xu, L. F., Wang, J. H., Yang, D. N., Zhang, M. T., & Li, X. (2020). Discharge performance recovery of a solid oxide fuel cell based on a prognostic-based control strategy. *Journal of Power Sources, 480*, 229102.
28. Awryńczuk, M. (2020). Constrained computationally efficient nonlinear predictive control of solid oxide fuel cell: Tuning, feasibility and performance. *ISA Transactions, 99*, 270–289.
29. Das, T., Roy, R., & Mandal, K. K. (2020). Impact of the penetration of distributed generation on optimal reactive power dispatch. *Protection and Control of Modern Power Systems, 5*(31), 332–357.

30. Huang, Z., Fang, B. L., & Deng, J. (2020). Multi-objective optimization strategy for distribution network considering V2G enabled electric vehicles in building integrated energy system. *Protection and Control of Modern Power Systems, 5*(1), 48–55.
31. Li, Z. R., Xu, J., Wang, K. Y., Wu, P., & Li, G. J. (2020). FPGA-based real-time simulation for EV station with multiple high-frequency chargers based on C-EMTP algorithm. *Protection and Control of Modern Power Systems, 5*(4), 283–293.
32. Pohjoranta, A., Halinen, M., Pennanen, J., & Kiviaho, J. (2015). Model predictive control of the solid oxide fuel cell stack temperature with models based on experimental data. *Journal of Power Sources, 277*, 239–250.
33. Deng, Z.H.; Li, X. (2007). The design for model and control of solid oxide fuel cell electrical characteristic. In *Chinese Control Conference (CHICC)*. 26–31 July, Zhangjiajie, China, https://doi.org/10.1109/CHICC.2006.4347521.
34. Bao, C., Wang, Y., Feng, D. L., Jiang, Z. Y., & Zhang, X. X. (2018). Macroscopic modeling of solid oxide fuel cell (SOFC) and model-based control of SOFC and gas turbine hybrid system. *Progress in Energy and Combustion Science, 66*, 83–140.
35. Wang, K., Hissel, D., Pera, M. C., et al. (2011). A review on solid oxide fuel cell models. *International Journal of Hydrogen Energy, 36*(12), 7212–7228.
36. Li, Y. H., Choi, S. S., & Rajakaruna, S. (2005). An analysis of the control and operation of a solid oxide fuel-cell power plant in an isolated system. *IEEE Transactions on Energy Conversion, 20*(2), 381–387.
37. Chaisantikulwat, A., Meadows, E. S., & Diaz-Goano, C. (2008). Dynamic modelling and control of planar anode-supported solid oxide fuel cell. *Computers & Chemical Engineering, 32*(10), 2365–2381.
38. Huo, H. B., Zhu, X. J., Hu, W. Q., Tu, H. Y., Li, J., & Yang, J. (2008). Nonlinear model predictive control of SOFC based on a Hammerstein model. *Journal of Power Sources, 185*(1), 338–344.
39. Aguiar, P., Adjiman, C. S., & Brandon, N. P. (2005). Anode-supported intermediate-temperature direct internal reforming solid oxide fuel cell: II. Model-based dynamic performance and control. *Journal of Power Sources, 147*(1–2), 136–147.
40. Sendjaja, A. Y., & Kariwala, V. (2011). Decentralized control of solid oxide fuel cells. *IEEE Transactions on Industrial Informatics, 7*(2), 163–170.
41. Spivey, B.J., Hedengren, J.D., Edgar, T.F. (2012). Constrained control and optimization of tubular solid oxide fuel cells for extending cell lifetime. In *American Control Conference (ACC)*, 27–29 June, Montreal, QC, Canada, https://doi.org/10.1109/ACC.2012.6315334.
42. Leung, M., Park, G., Radisavljevic-Gajic, V. (2013). Control of solid oxide fuel cells: An overview. In *Asian Control Conference (ASCC)*. 23–26, Istanbul, Turkey. https://doi.org/10.1109/ASCC.2013.6606314.
43. Chen, J., Yao, W., Zhang, C. K., Ren, Y., & Jiang, L. (2019). Design of robust MPPT controller for grid-connected PMSG-Based wind turbine via perturbation observation based nonlinear adaptive control. *Renewable Energy, 134*, 478–495.
44. Peng, J. X., Huang, J., Wu, X. L., Xu, Y. W., Chen, H. C., & Li, X. (2021). Solid oxide fuel cell (SOFC) performance evaluation, fault diagnosis and health control: A review. *Journal of Power Sources, 505*, 230058.
45. Schafer, F., Egger, S., Steiner, D., Carre, M., & Eichel, R. A. (2022). Control of oxygen-to-carbon ratio and fuel utilization with regard to solid oxide fuel cell systems with anode exhaust gas recirculation: A review. *Journal of Power Sources, 524*, 231077.
46. Yang, B., Zhang, M. T., Zhang, X. S., Wang, J. B., Shu, H. C., Li, S. N., He, T. Y., Yang, L., & Yu, T. (2020). Fast atom search optimization based MPPT design of centralized thermoelectric generation system under heterogeneous temperature difference. *Journal of Cleaner Production, 248*, 119301.
47. Yang, B., Li, J. L., Li, Y. L., et al. (2022). A critical survey of proton exchange membrane fuel cell system control: Summaries, advances, and perspectives. *International Journal of Hydrogen Energy, 47*, 9986–10020.
48. Dijoux, E., Steiner, N. Y., Benne, M., et al. (2017). A review of fault tolerant control strategies applied to proton exchange membrane fuel cell systems. *Journal of Power Sources, 359*, 119–133.
49. Singh, M., Zappa, D., & Comini, E. (2021). Solid oxide fuel cell: Decade of progress, future perspectives and challenges. *International Journal of Hydrogen Energy, 46*(54), 27643–27674.
50. Liu, S. M., Deng, Z. F., Xu, G. Z., Li, B. R., Song, P. X., & Wang, S. R. (2020). Industrialization status of solid oxide fuel cell (SOFC) in Europe. *Journal of Beijing University of science and technology, 42*(3), 278–288.
51. Komatsu, Y., Kimijima, S., & Szmyd, J. S. (2013). Numerical analysis on dynamic behavior of solid oxide fuel cell with power output control scheme. *Journal of Power Sources, 223*, 232–245.
52. Bhattacharyya, D., & Rengaswamy, R. (2009). A review of solid oxide fuel cell (SOFC) dynamic models. *Industrial & Engineering Chemistry Research, 48*(13), 6068–6086.
53. Li, Y. G., Shen, J., & Lu, J. H. (2011). Constrained model predictive control of a solid oxide fuel cell based on genetic optimization. *Journal of Power Sources, 196*(14), 5873–5880.
54. Mazumder, S. K., Acharya, K., Haynes, C. L., et al. (2004). Solid-oxide-fuel-cell performance and durability: Resolution of the effects of power-conditioning systems and application loads. *IEEE Transactions on Power Electronics, 19*(5), 1263–1278.
55. Murshed, A. K. M. M., Huang, B., & Nandakumar, K. (2007). Control relevant modeling of planer solid oxide fuel cell system. *Journal of Power Sources, 163*(2), 830–845.
56. Yang, J., Qin, S., Zhang, W. Y., Ding, T. F., Zhou, B., Li, X., & Jian, L. (2017). Improving the load-following capability of a solid oxide fuel cell system through the use of time delay control. *International Journal of Hydrogen Energy, 42*(2), 1221–1236.
57. Wu, X. J., & Gao, D. H. (2018). Optimal robust control strategy of a solid oxide fuel cell system. *Journal of Power Sources, 374*, 163–181.
58. Zhang, L., Li, X., Jiang, J. H., Li, S. H., Yang, J., & Li, J. (2015). Dynamic modeling and analysis of a 5-kW solid oxide fuel cell system from the perspectives of cooperative control of thermal safety and high efficiency. *International Journal of Hydrogen Energy, 40*(1), 456–476.
59. Xi, H.D., Varigonda, S., Jing, B.Y. (2010). Dynamic modeling of a solid oxide fuel cell system for control design. In *Proceeding of the 2010 American Control Conference (ACC)*. 30 June-2 July, Baltimore, MD, USA, https://doi.org/10.1109/ACC.2010.5531009.
60. Liu, J. K. (2011). *Matlab simulation of advanced PID control*. Electronic Industry Press.
61. Sorrentino, M., Pianese, C., & Guezennec, Y. G. (2008). A hierarchical modeling approach to the simulation and control of planar solid oxide fuel cells. *Journal of Power Sources, 180*(1), 380–392.
62. Hajimolana, S. A., & Soroush, M. (2009). Dynamics and control of a tubular solid-oxide fuel cell. *Industrial & Engineering Chemistry Research, 48*(13), 6112–6125.
63. Cheng, Y., Liu, D. Y., Zhang, L. T., Feng, X. D. (2008). Modeling and simulation analysis of solid oxide fuel cell system for marine equipment. In *Chinese Automation Congress (CAC)*, Xi'an, China, https://doi.org/10.1109/CAC.2018.8623226.
64. Vrecko, D., Nerat, M., et al. (2018). Feedforward-feedback control of a solid oxide fuel cell power system. *International Journal of Hydrogen Energy, 43*(12), 6352–6363.
65. Kupecki, J., Motylinski, K., Zurawska, A., Kosiorek, M., & Ajdys, L. (2019). Numerical analysis of an SOFC stack under loss of oxidant related fault conditions using a dynamic non-adiabatic model. *International Journal of Hydrogen Energy, 44*(38), 21148–21161.
66. Singh, S., Tayal, V. K.,Singh, H. P., Yadav, V. K. (2021). Performance Enhancement of solid oxide fuel cell by employing PI controller and PID controller with filter derivative. In: *2021 IEEE International Power and Renewable Energy Conference(IPRECON)*. 24–26 Sept., Kollam, India, https://doi.org/10.1109/IPRECON52453.2021.9640720.
67. Zhang, L., Xie, H.T., Wang, F., Xie, C., Liu, R.H., Tang, W.H., Zhou, W.B., Wang, G. Q. (2021). A multi-loop control strategy for 5 kW solid oxide fuel cell hybrid system. In *2021 China Automation Congress (CAC)*. 22–24 Oct, Beijing, China, 1109/CAC53003.2021.9727452.
68. Marzooghi, H., & Raoofat, M. (2012). Improving the performance of proton exchange membrane and solid oxide fuel cells under voltage flicker using Fuzzy-PI controller. *International Journal of Hydrogen Energy, 37*(9), 7796–7806.
69. Xu, D. Z.; Yan, W. X.; Ji, N. (2016). RBF neural network based adaptive constrained PID control of a solid oxide fuel cell. In *Chinese Control and Decision Conference (CCDC)*. 28–30 May, Yinchuan, China, https://doi.org/10.1109/CCDC.2016.7531681.

70. Cao, H. L., & Li, X. (2016). Thermal management-oriented multivariable robust control of a kW-scale solid oxide fuel cell stand-alone system. *Transactions on Energy Conversion, 31*(2), 1–10.
71. Cheng, H., Jing, S. W., Xu, Y. W., Deng, Z. H., Li, J., & Li, X. (2016). Control-oriented modeling analysis and optimization of planar solid oxide fuel cell system. *International Journal of Hydrogen Energy, 41*(47), 22285–22304.
72. Zhang, T., Li, H.L., Tu, X. W., Pang, H. Z.,Huang, Y. (2021). Optimization of SOC fractional PID control parameters for solid oxide battery based on improved firefly algorithm. In: *2021 3rd International Conference on Industrial Artificial Intelligence(IAI)*. 8–11 Nov, Shenyang, China, DOI: https://doi.org/10.1109/IAI53119.2021.9619450.
73. Nayeripour, M., & Hoseintabar, M. (2013). A new control strategy of solid oxide fuel cell based on coordination between hydrogen fuel flow rate and utilization factor. *Renewable and Sustainable Energy Reviews, 27*(27), 505–514.
74. Xu, D. Z., Jiang, B., & Liu, F. (2016). Improved data driven model free adaptive constrained control for a solid oxide fuel cell. *IET Control Theory & Applications, 10*(12), 1412–1419.
75. Sun, L. M., & Yang, B. (2020). Nonlinear robust fractional-order control of battery/SMES hybrid energy storage systems. *Power System Protection and Control, 48*(22), 76–83.
76. Yang, B., Yu, T., Shu, H. C., Zhang, Y. M., Chen, J., Sang, Y. Y., & Jiang, L. (2018). Passivity-based sliding-mode control design for optimal power extraction of a PMSG based variable speed wind turbine. *Renewable Energy, 119*, 577–589.
77. Yang, B., Yu, T., Shu, H. C., Dong, J., & Jiang, L. (2018). Robust sliding-mode control of wind energy conversion systems for optimal power extraction via nonlinear perturbation observers. *Applied Energy, 210*, 711–723.
78. Sun, J., & Kolmanovsky, I. (2005). Load governor for fuel cell oxygen starvation protection: A robust nonlinear reference governor approach. *Transactions on Control Systems Technology, 13*(6), 911–920.
79. Fardadi, M., Mueller, F., & Jabbari, F. (2010). Feedback control of solid oxide fuel cell spatial temperature variation. *Journal of Power Sources, 195*(13), 4222–4233.
80. Huo, H. B., Yang, H. D., Xu, K., Kuang, X. H., & Xu, J. X. (2021). Survey an H∞ robust control of the solid oxide fuel cell. *Mathematical Problems in Engineering, 2021*, 6693971.
81. Allag, T., & Das, T. (2012). Robust control of solid oxide fuel cell ultracapacitor hybrid system. *Transactions on Control Systems Technology, 20*(1), 1–10.
82. Dötschel, T., Rauh, A., Senkel, L., Aschemann, H. (2013). Experimental validation of interval-based sliding mode control for solid oxide fuel cell systems. In *European Control Conference (ECC)*, 17–19 July, Zurich, Switzerland, https://doi.org/10.23919/ECC.2013.6669534.
83. Rauh, A., Senkel, L., & Aschemann, H. (2015). Interval-based sliding mode control design for solid oxide fuel cells with state and actuator constraints. *Transactions on Industrial Electronics, 62*(8), 5208–5217.
84. Am, O. A., Wang, H. P., & Tian, Y. (2022). Enhanced model-free discrete-time adaptive terminal sliding-mode control for SOFC power plant with input constraints. *Arabian Journal for Science and Engineering, 47*, 2851–2864.
85. Jurado, F. (2006). Predictive control of solid oxide fuel cells using fuzzy Hammerstein models. *Journal of Power Sources, 158*(1), 245–253.
86. Wang, X. R., Huang, B., & Chen, T. W. (2007). Data-driven predictive control for solid oxide fuel cells. *Journal of Process Control, 17*(2), 103–114.
87. Sanandaji, B. M., Vincent, T. L., Colclasure, A. M., & Kee, R. J. (2011). Modeling and control of tubular solid-oxide fuel cell systems: II. Nonlinear model reduction and model predictive control. *Journal of Power Sources, 196*(1), 208–217.
88. Kupilik, M. J., & Vincent, T. L. (2013). Control of a solid oxide fuel cell system with sensitivity to carbon formation. *Journal of Power Sources, 222*, 267–276.
89. Horalek, R., Hlava, J. (2015). Multilinear model predictive control of solid oxide fuel cell output voltage. In *Electronics, Control, Measurement, Signals & Their Application to Mechatronics (ECMSM)*, 22–24 June, Liberec, Czech Republic, https://doi.org/10.1109/ECMSM.2015.7208702.
90. Horalek, R., Hlava, J. (2015). Multiple model predictive control of grid connected solid oxide fuel cell for extending cell life time. In *Mediterranean Conference on Control and Automation (MED)*. 16–19 June, Torremolinos, Spain, https://doi.org/10.1109/MED.2015.7158768.
91. Miaomiao, H., Zhou, B.Z. (2017). The multi-parameter programming control of solid oxide fuel cell. In *International Conference on Information Science and Control Engineering (ICISCE)*, 21-23 July, Changsha, China, pp. 1278-1281.
92. Frenkel, W., Kersten, J., Aschemann, H.,Rauh, A. (2021). Model predictive control as an industrially applicable approach for power control of solid oxide fuel cells. In *2021 25th International Conference on Methods and Models in Automation and Robotics (MMAR)*. 23–26 Aug, Miedzyzdroje, Poland, https://doi.org/10.1109/MMAR49549.2021.9528484.
93. Zhang, X. W., Chan, S. H., Ho, U. K., Li, J., Li, G. J., & Feng, Z. P. (2008). Nonlinear model predictive control based on the moving horizon state estimation for the solid oxide fuel cell. *International Journal of Hydrogen Energy, 33*(9), 2355–2366.
94. Yang, J., Li, X., Mou, H. G., & Jian, L. (2009). Predictive control of solid oxide fuel cell based on an improved Takagi-Sugeno fuzzy model. *Journal of Power Sources, 193*(2), 699–705.
95. Murshed, A. K. M. M., Huang, B., & Nandakumar, K. (2010). Estimation and control of solid oxide fuel cell system. *Computers & Chemical Engineering, 34*(1), 96–111.
96. Bhattacharyya, D., & Rengaswamy, R. (2010). System identification and nonlinear model predictive control of a solid oxide fuel cell. *Industrial & Engineering Chemistry Research, 49*(10), 4800–4808.
97. Lee, S. M., Kwon, O. M., & Park, J. H. (2012). Predictive control for sector bounded nonlinear model and its application to solid oxide fuel cell systems. *Applied Mathematics & Computation, 218*(18), 9296–9304.
98. Deng, Z. H., Gao, H. L., Li, X., Jiang, J. H., Yang, J., & Qin, Y. (2010). Generalized predictive control for fractional order dynamic model of solid oxide fuel cell output power. *Journal of Power Sources, 195*(24), 8097–8103.
99. Jiang, J. H., Li, X., Deng, Z. H., Yang, J., Zhang, Y. H., & Li, J. (2012). Thermal management of an independent steam reformer for a solid oxide fuel cell with constrained generalized predictive control. *International Journal of Hydrogen Energy, 37*(17), 12317–12331.
100. Jiang, J. H.; Li, X.; Li, J. (2016). The high efficiency cooperative control of power and temperature of a stand-alone solid oxide fuel cell system with an air bypass valve. In *Chinese Automation Congress (CAC)*, 27–29 Nov, WuHan, China, https://doi.org/10.1109/CAC.2015.7382680.
101. Jiang, J. H., Shen, T., Deng, Z. H., Fu, X. W., Li, J., & Li, X. (2018). High efficiency thermoelectric cooperative control of a stand-alone solid oxide fuel cell system with an air bypass valve. *Energy, 152*, 13–26.
102. Boubaker, B., Houari, K., Ahmed, B. (2021). Solid oxide fuel cell power management based on a predictive controller. In: *2020 6th International Symposium on New and Renewable Energy (SIENR)*, 13–14 Oct, Ghadaia, Algeria, https://doi.org/10.1109/SIENR50924.2021.9631888.
103. Spivey, B. J., & Edgar, T. F. (2012). Dynamic modeling, simulation, and MIMO predictive control of a tubular solid oxide fuel cell. *Journal of Process Control, 22*(8), 1502–1520.
104. Liu, Y. L., Chau, T. K., Zhang, X. N., Hu, Y. J. (2021). A novel adaptive model predictive control strategy of solid oxide fuel cell in power systems. In: *2021 31st Australasian Universities Power Engineering Conference (AUPEC)*, 26–30 Sept., Perth, Australia. https://doi.org/10.1109/AUPEC52110.2021.9597737.
105. Zhang, G. L. (2002). *Fuzzy control and its application in MATLAB*. [M]. Xi'an Jiaotong University.
106. Corcau, J. I., Dinca, L., Grigorie, T. L. (2011). Fuzzy logic controller development for a solid oxide fuel cell system. In *International Symposium on Computational Intelligence & Informatics (CINTI)*, 21–22 Nov, Budapest, Hungary, https://doi.org/10.1109/CINTI.2011.6108487.
107. Bhuyan, K.C.; Mahapatra, K. An intelligent control of solid oxide fuel cell voltage. In: International Conference on Power and Energy Systems (ICPES), 22–24 Dec., **2011**, Chennai, India, pp. 1–6, DOI: https://doi.org/10.1109/ICPES.2011.6156613.
108. Li, S. H., Gong, L., Yang, Y. P. (2017). Fault tolerant control of an anode offgas recycle based SOFC system. In *American Control Conference (ACC)*, 24–26 May, Seattle, WA, USA, https://doi.org/10.23919/ACC.2017.7963587.
109. Sun, Y. L., Ghantasala, S., El-Farra, N. H. (2010). Monitoring and fault-tolerant control of distributed power generation: Application to solid

oxide fuel cells. In *American Control Conference ACC*, 30 June-2 July, Baltimore, MD, USA, https://doi.org/10.1109/ACC.2010.5531012.
110. Sun, Y. L.; El-Farra, N. H. (2011). Robust fault detection and reconfigurable control of distributed energy generation systems. In *American Control Conference (ACC)*, 29 June-1 July, San Francisco, CA, USA, https://doi.org/10.1109/ACC.2011.5991316.
111. Wu, X. J., & Gao, D. H. (2017). Optimal fault-tolerant control strategy of a solid oxide fuel cell system. *Journal of Power Sources, 364*, 163–181.
112. Wu, X. J., & Gao, D. H. (2017). Fault tolerance control of SOFC systems based on nonlinear model predictive control. *International Journal of Hydrogen Energy, 42*(4), 2288–2308.
113. Xue, T., Wu, X. L., Zhao, D. Q., et al. (2019). Fault-tolerant control for steam fluctuation in SOFC system with reforming units. *International journal of hydrogen energy, 44*(41), 23360–23376.
114. Ji, N., Xu, D. Z., & Liu, F. (2016). A novel adaptive neural network constrained control for solid oxide fuel cells via dynamic anti-windup. *Neurocomputing, 214*, 134–142.
115. Xi, L., Yu, T., Yang, B., Zhang, X. S., & Qiu, X. Y. (2016). A wolf pack hunting strategy based virtual tribes control for automatic generation control of smart grid. *Applied Energy, 178*, 198–211.
116. Hajimolana, S. A., Hussain, M. A., Daud, W., et al. (2012). Neural network predictive control of a SOFC fuelled with ammonia. *International Journal of Electrochemical Science, 7*(4), 3737–3749.
117. Hajimolana, S. A., Tonekabonimoghadam, S. M., Hussain, M. A., Chakrabarti, M. H., Jayakumar, N. S., & Hashim, M. A. (2013). Thermal stress management of a solid oxide fuel cell using neural network predictive control. *Energy, 62*(30), 320–329.
118. Li, J. W., Yu, T., & Yang, B. (2021). A data-driven output voltage control of solid oxide fuel cell using multi-agent deep reinforcement learning. *Applied Energy, 304*(505), 117541.
119. Li, J. W., & Yu, T. (2021). Optimal adaptive control for solid oxide fuel cell with operating constraints via large-scale deep reinforcement learning. *Control Engineering Practice, 2021*(117), 104951.
120. Li, J. W., & Yu, T. (2021). A novel data-driven controller for solid oxide fuel cell via deep reinforcement learning. *Applied Energy, 2021*(321), 128929.
121. Wu, X. J., Yang, D. N., Wang, J. H., & Li, X. (2019). Temperature gradient control of a solid oxide fuel cell stack. *Journal of Power Sources, 414*, 345–353.