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Review

A review of control strategies for proton exchange membrane (PEM) fuel cells and water electrolysers: From automation to autonomy

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ABSTRACT

Proton exchange membrane (PEM) based electrochemical systems have the capability to operate in fuel cell (PEMFC) and water electrolyser (PEMWE) modes, enabling efficient hydrogen energy utilisation and green hydrogen production. In addition to the essential cell stacks, the system of PEMFC or PEMWE consists of four sub-systems for managing gas supply, power, thermal, and water, respectively. Due to the system's complexity, even a small fluctuation in a certain sub-system can result in an unexpected response, leading to a reduced performance and stability. To improve the system's robustness and responsiveness, considerable efforts have been dedicated to developing advanced control strategies. This paper comprehensively reviews various control strategies proposed in literature, revealing that traditional control methods are widely employed in PEMFC and PEMWE due to their simplicity, yet they suffer from limitations in accuracy. Conversely, advanced control methods offer high accuracy but are hindered by poor dynamic performance. This paper highlights the recent advancements in control strategies incorporating machine learning algorithms. Additionally, the paper provides a perspective on the future development of control strategies, suggesting that hybrid control methods should be used for future research to leverage the strength of both sides. Notably, it emphasises the role of artificial intelligence (AI) in advancing control strategies, demonstrating its significant potential in facilitating the transition from automation to autonomy.

1. Introduction

The contemporary fabric of civilisation is intricately woven with the foundational element of energy. Global primary energy consumption and its sources before the COVID19-induced slump, with a growth trend that has been evident and continued over the past three decades [1,2]. In addition, according to the International Energy Agency report, the total volume and growth trend of energy consumption have fully recovered in 2021 [3]. This trajectory is anticipated to persist until the year 2040, propelled by an expanding global population [2]. A dominant proportion, exceeding 80 % of the global energy requirements, is presently met by fossil fuel [4]. Despite the prevailing reliance on fossil fuels, a consciousness regarding their finite reserves and deleterious environmental implications has catalysed a concerted quest for clean energy alternatives. This search for reliable energy alternatives remains a critical priority in the quest to meet growing energy demands in an environmentally responsible manner. Fossil energy still dominates although the proportion of fossil energy is gradually declining, and its total volume continues to grow. Furthermore, although the proportion of sustainable energy is growing rapidly, compared with the huge global energy demand, its proportion is far lower than that of fossil energy [2]. While the commercialisation of renewable energy sources like solar and wind energy has been successful, their intermittent nature poses a challenge to their widespread application. Therefore, there is an urgent need to explore and develop energy solutions that can compensate for the shortcomings of solar and wind energy.

Hydrogen, recognised as an energy carrier with zero emissions, its energy density is several times higher than that of most traditional energy sources [5,6]. Its huge application potential has attracted global research interest. The predominant method for hydrogen production currently relies on reforming coal or natural gas [7], a process emits substantial greenhouse gases (GHG) and produces grey hydrogen of

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relatively low purity [7,8]. Alternative methods, e.g., photo-catalysis and fermentation, are beset by issues such as high costs and low efficiency [7]. In contrast, water electrolysis technology, utilising zero-emission renewable energy sources, stands out for its ability to efficiently produce high-purity green hydrogen [9]. This process only generates oxygen as a by-product, positioning it as a highly promising alternative. Within the domain of water electrolysis, various types of electrolysers have been developed, including Alkaline Water Electrolysers (AWE) and Proton Exchange Membrane Water Electrolysers (PEMWE). PEMWE, is distinguished by its capacity to produce hydrogen of exceptionally high purity (99.999 %) and its ability to operate at high current densities to circumvent the production of pollutants like carbonates [9,10], therefore considered one of the most promising technologies.

While hydrogen can function as an intermediate energy carrier for storing chemical energy from solar or wind power, finding an efficient approach capable of transforming hydrogen back into electrical power is also important. Fuel cells, as a highly promising alternative to conventional power generation methods, such as Coradia iLint (the world's first hydrogen powered passenger train), Carnot engine, offers a more efficient energy conversion process. Fuel cells directly transform the chemical energy stored in fuels into electrical energy. This direct conversion mechanism results in higher efficiency levels [11]. Moreover, fuel cells operate without significant emissions of gases or waste heat, and they do not require extensive cooling systems [12]. These characteristics make fuel cells environmentally friendly. Additionally, their compact and silent nature enhances their versatility [13], allowing their application in a broad spectrum of settings, from small-scale systems generating just a few watts to large-scale installations capable of producing several thousand megawatts [14]. Numerous varieties of fuel cells are currently under development, including Proton Exchange Membrane Fuel Cells (PEMFCs), Solid Oxide Fuel Cells (SOFCs), and Alkaline Fuel Cells (AFCs), among others. Of these, the PEMFC is particularly notable due to its distinctive advantages, such as a low operational temperature, high power density, and rapid start-up capabilities [14,15]. These characteristics make PEMFCs a widely utilised choice in the fuel cell domain. Its primary applications span across stationary and portable power generation as well as in the transportation sector.

Despite the considerable progress made in the development of PEMWE and PEMFC, several challenges persist in making them sufficiently competitive to supplant traditional energy sources on a large scale [14,16]. These challenges mainly lie in how to improve the cell performance as well as enhance the service life. To improve the PEMWE performance, it is important to develop dielectric membrane with high ionic conductivity and operation at low humidity, electrode materials with excellent corrosion resistance, etc. On the other hand, optimising the operating parameters, such as temperature, water flow rate, and air pressure is an effective way [17]. For example, elevating the temperature during the electrolysis process can enhance the electrochemical of catalysts and conductivity of the ionomer [18], thereby decreasing the power requirement. However, excessively high temperature may increase atmospheric saturation, leading to a large number of gas bubbles accumulating on the anode surface. When a fuel cell operates at a too high temperature, it affects gas management inside the cell, especially on the anode side. The solubility of gases, e.g., hydrogen, decreases at high temperatures, which means the gas is more easily released from the electrolyte, forming bubbles. As the temperature increases, the water vapour saturation in the atmosphere also increases, which may cause vapour condensation on the electrode surface and/or in the electrolyte, forming more bubbles. If these bubbles accumulate on the anode surface, they will block the path of hydrogen gas to the electrode surface, reduce the effective reaction area, and thus reduce the performance of the fuel cell. The formation and accumulation of bubbles may also lead to poor gas flow inside the fuel cell, further affecting the supply of fuel and oxygen, as well as the removal of generated water. This accumulation hampers the access of water to the electrode [19], consequently diminishing the rate of hydrogen production. For PEMFC, apart from the deterioration of various components over time [20], specific issues like the dehydration of the proton exchange membrane (PEM) and oxygen starvation on the cathode side can result in a decline in both the performance and durability of PEMFC [21,22]. Moreover, PEMFCs exhibit a more gradual response to fluctuations in load, a characteristic that can contribute to reduced durability. Such conditions not only reduce the performance of the system but also have the potential to inflict damage, thereby escalating into significant safety concerns. Addressing these issues necessitates enhanced efficiency and precision in the control of various system variables [23,24]. Additionally, the membrane electrode assemblies (MEA) integral to PEMWE and PEMFC are susceptible to issues like gas leakage and membrane rupture [25]. Consequently, a diverse array of control strategies for PEMWE and PEMFC has been the subject of extensive study. Each control strategy exhibits unique advantages and disadvantages, making them appropriate for specific application requirements.

The control strategies currently implemented in the realm of PEMWE and PEMFC fall into two distinct categories. The first encompasses traditional control strategies with proven track records, such as feed-forward control and proportional-integral-derivative (PID) control [26]. These strategies boast a lengthy history of application across various domains, evidencing their efficacy. Typically, they offer benefits like simplicity in design, cost-effectiveness, and swift response times. However, they may lack in precision or adaptability. The second category is advanced control strategies based on artificial intelligence (AI), including model predictive control (MPC) and AI-based control systems. These strategies significantly enhance control accuracy compared to their traditional counterparts, but often at the expense of more complex structures and slower response rates. Some studies have also explored the integration of both traditional and AI-based control methods. Those studies aim to synergies the respective strengths and mitigate the limitations of each category, thereby achieving a more balanced and effective control system for PEMWE and PEMFC applications.

The objectives of this review paper encompass the following aspects: 1). overviewing the principles of PEMFC and PEMWE associated with their operational issues in their systems; 2). delivering a comprehensive review of the current advancements in control strategies, that is dedicated to a thorough evaluation and comparison of different control strategies for PEMWE and PEMFC, includes extensively proven and advanced control methods; 3). introducing the principles and main application status of various control methods; 4). engaging in discussions and comparisons of various control strategies through case studies; and 5). providing valuable insights into the future development of control strategies, aiming to offer insights into the future development of these strategies.

2. PEMFC and PEMWE system

2.1. Structure and principles of PEMFCs and PEMWEs

The structure of a typical PEMFC is shown in the Fig. 1, which comprises of a MEA and bipolar plates (BPPs). The MEA can be divided into several layers include anode gas diffusion layer (AGDL), anode micro-porous layer (AMPL), anode catalyst layer (ACL), cathode gas diffusion layer (CGDL), cathode micro-porous layer (CMPL), cathode catalyst layer (CCL), and proton exchange membrane (PEM) between the anode and cathode. Notably, in some articles, MPL is considered as a part of GDL [27], or the entirety of GDL and MPL is treated as a single multi-layer gas diffusion medium (GDM) [28]. Additionally, MPLs are not included in some studies [29]. We consider MPL as a part of GDL in this paper. Each component serves a specific function: 1). BPPs can isolate reaction gases, introduce them into the fuel cell, collect current, and favour the heat and water. 2). PEM conducts protons and isolates electrons and avoid gas crossover, 3).CL is the core of PEMFC, it is the

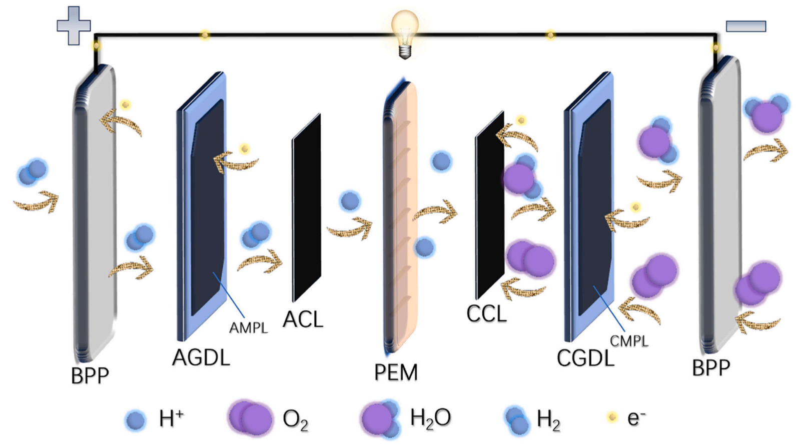

Fig. 1. Schematic and operational fundamentals of PEMFC.

location where the electrochemical reactions take place, 4). GDL is mainly used to transfer electrons, reactants, products and heat, it also provides mechanical support to the cell's structure. During the PEMFC operation, hydrogen is introduced at the anode, traversing the AGDL to undergo hydrogen oxidation reaction (HOR) at the ACL, producing protons (H^{+}) and electrons (e^{-}). Protons migrate through the PEM to the cathode, while electrons flow externally to the cathode. Concurrently, oxygen (or air) enters the cathode, reaching the CCL through the CGDL, participating in an oxidation–reduction reaction (ORR) with protons and electrons, resulting in the generation of water.

The overall reaction and two half electrochemical reactions are listed as follows:

$$\text{Overall}: 2H_2 + O_2 \rightarrow 2H_2O \tag{1}$$

$$\text{HOR}: 2H_2 - 4e^{-} \rightarrow 4H^{+} \tag{2}$$

$$\text{ORR}: O_2 + 4H^{+} + 4e^{-} \rightarrow 2H_2O \tag{3}$$

The structure of PEMWE is same as that of PEMFC, while in PEMWE, the principles operation can be conceptualised as an inverse process of PEMFC. The structure of a typical PEMFC is shown in Fig. 2. In detail, liquid water is transported to the ACL via the AGDL. Subsequently, the hydrogen evolution reaction (HER) takes place, dissociating water into O_2, H^{+}, and e^{-}. The evolved oxygen is expelled at the anode, while the H^{+} traverse through the PEM to the cathode. Concurrently, e^{-} travel to the cathode via an external circuit. Upon reaching the cathode, the H^{+} and e^{-} recombine to generate hydrogen. The overall reaction and two half electrochemical reactions are listed as follows:

The overall reaction was as follows:

$$\text{Overall}: 2H_2O \rightarrow 2H_2 + O_2 \tag{4}$$

$$\text{OER}: 2H_2O \rightarrow O_2 + 4H^{+} + 4e^{-} \tag{5}$$

$$\text{HER}: 4H^{+} + 4e^{-} \rightarrow 2H_2 \tag{6}$$

2.2. PEMFC and PEMWE system integration

Beyond the fuel cell or electrolyser stacks, both PEMFC and PEMWE systems mainly composes of the other four subsystems, including gas management subsystems, water management systems, thermal management systems and power electronic subsystems, as shown in Fig. 3. The integration of various control systems of PEMFC and PEMWE stacks enables the simultaneous regulation of several key parameters to maintain the high-efficiency operation of the stacks. A general description of temperature control, pressure control, level control and velocity control are shown in Fig. 4. The role of each subsystem will be introduced as follows.

2.2.1. Gas management subsystems

In the gas management subsystem of a PEMFC system, the controlled introduction of reactants, namely hydrogen and air, to the PEMFC stack is of paramount importance. Hydrogen is supplied to the anode from a fuel processor, typically a natural gas or methanol steam reformer, or directly from a pressurised hydrogen tank [30]. The outlet pressure of

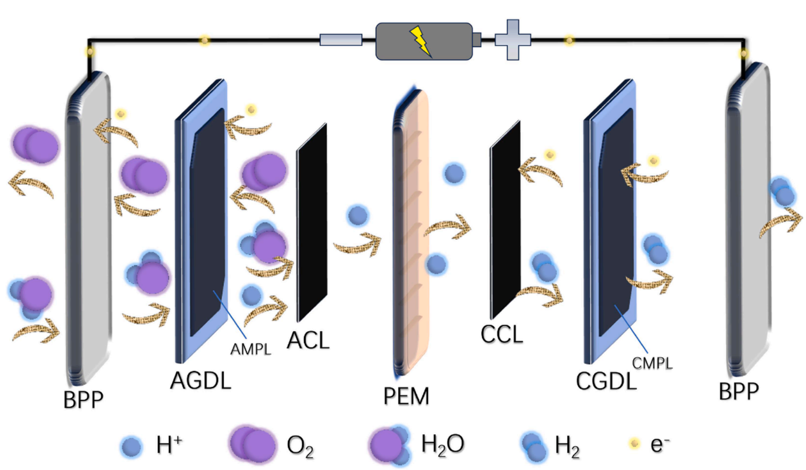

Fig. 2. Schematic and operational fundamentals of PEMWE.

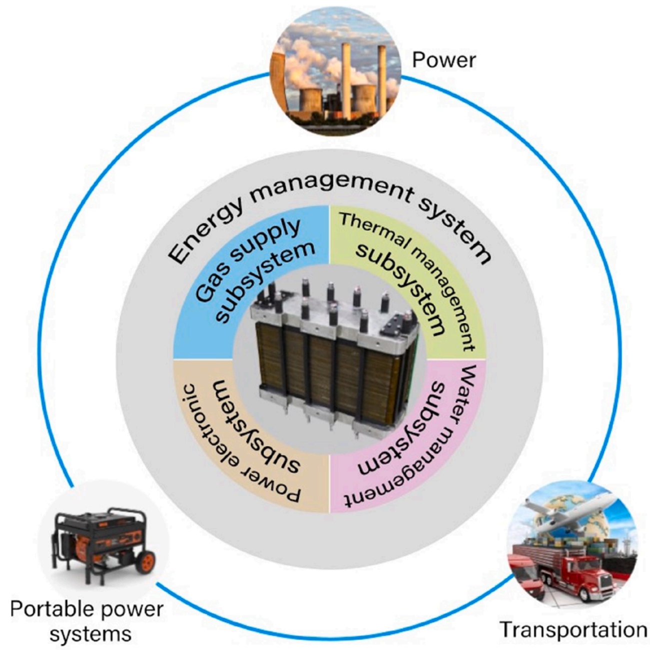

Fig. 3. PEMFC system integration.

the PEMFC stack is regulated through a backpressure regulator located at the stack outlet. In parallel, air or oxygen is introduced to the cathodes via either a blower or a compressed air tank, with the inlet air pressure carefully managed to achieve the prescribed air flow rate at the specified hydrogen-air/oxygen stoichiometric ratio. Fig. 5 shows a gas management subsystem of a PEMFC. Fig. 6 shows the effect of different control strategies on cathode oxygen delivery, measured by oxygen excess rate (OER) and output net power. A better control strategy can make the change of oxygen flow smoother to avoid oxygen deficiency and insufficient output power.

The determination of hydrogen pressure and flow rate at the PEMFC stack outlet, as well as the management of air supply inlet pressure and flow rate, presents a complex challenge [32]. Elevated pressures of both hydrogen and air enhance the kinetics of the electrochemical reactions, thereby elevating power density and stack efficiency [33]. However, this improvement is offset by a reduction in the net available power from the PEMFC system due to higher parasitic power requirements. It is crucial to strike a balance, as excessive cur- rent density resulting from inadequate power in the PEMFC stack can lead to detrimental voltage drops, potentially causing damage to the stack [34]. Moreover, the conventional practice of fixed fuel-air management, while adequate for supplying the rated power of the PEMFC system, faces limitations in adapting to variations in load demands, particularly in applications with frequent load changes such as automotive systems [35]. This inflexibility may lead to hydrogen starvation, posing a risk to the integrity of the fuel cell membrane and catalyst layer. Consequently, there is a pressing need for developing advanced control strategies to realise a more efficient hydrogen-air/oxygen supply management to enhance overall PEMFC system efficiency and optimise hydrogen utilisation [36].

Besides, in PEMWE, the gas management involves the segregation of concurrent produced hydrogen and oxygen for safety considerations, as well as for the subsequent storage and utilisation [37]. Ensuring the separation of hydrogen and oxygen is paramount to prevent any potential recombination or explosive hazards [38]. Similarly, managing the pressure within the PEMWE system is crucial to maintain operational stability and efficiency. Precise pressure control is essential not only to facilitate the optimal flow and reaction rates but also to prevent phase changes of water to vapour, especially under varying operational conditions. Maintaining a specific pressure threshold ensures that the liquid water is supplied continuously to the anode side, thereby ensuring an efficient and sustained electrolysis process. This intricate balance of gas purity and pressure control underscores the complex interplay of thermodynamics, fluid mechanics, and safety engineering in PEMWE systems, necessitating advanced materials and sophisticated control strategies for optimal performance and safety.

2.2.2. *Thermal management systems*

The electrochemical processes within PEMFCs yield a substantial portion of energy in the form of heat. Non-uniform temperature distributions can induce variations in electrochemical reaction rates and impact the evaporation and condensation of water in reactant gases. Elevated temperatures enhance PEMFC system performance by accelerating electrochemical reactions. However, excessive temperatures can lead to detrimental effects such as membrane dehydration, shrinkage, wrinkling, or rupture. The consequence of such occurrences includes an increase in the ohmic resistance of dry membranes, resulting in a lower output voltage. Damaged membranes may also cause the voltage to fall below the desired range, leading to electrode flooding and a subsequent decline in PEMFC performance and efficiency. In low-temperature environments, particularly those below freezing, water within the PEMFC can freeze, obstructing the gas channels and covering the catalyst sites, which leads to cold start failures [39]. Additionally, the formation of ice can inflict irreversible damage of MEA structure [40]. The principal aim of a thermal management subsystem is to uphold temperatures within the optimal operational range and regulate moisture levels within the stack and membrane [41]. Therefore, thermal management subsystem is important since its plays a pivotal role in ensuring the optimal operation of PEMFCs and extending their service life. An example of applying adaptive control is shown in Fig. 7. The red curve shows that the stack temperature changed at three different periods, while the blue dashed line is the temperature change after applying the thermal control subsystem, which changes smoothly with the maximum deviation of less than 1 K [42]. Developing effective control strategy for thermal management subsystem is imperative to uphold the integrity of the PEMFC stack material and sustain optimal electrochemical reactions. Such a control strategy should ensure a uniform temperature distribution throughout the stack, as emphasised in prior research [41,43]. Additionally, an optimised thermal management system has the potential not only to enhance overall PEMFC performance but also to reduce fuel consumption [44].

In PEMWE systems, the electrolytic dissociation of water is an intrinsically exothermic process, leading to the generation of significant heat. It is imperative for the thermal management system to efficiently dissipate this heat to maintain the operational temperature within an optimal range. This temperature regulation is crucial for ensuring the structural integrity and functional stability of the membrane, as well as the overall efficiency and longevity of the system. Excessively high or low temperatures can compromise the structural integrity and functional stability of polymer electrolyte membranes [45], which are key components of PEMWE systems. The membrane needs to operate within a specific temperature range to maintain its proton conductivity while maintaining its mechanical strength and chemical stability. Overheating can cause membrane dehydration, leading to reduced ionic conductivity and potential membrane failure. Second, temperature regulation affects the overall efficiency and longevity of the PEMWE system. High operating temperatures increase the rate of membrane and electrocatalyst degradation, causing system performance to degrade over time. Furthermore, optimal temperature conditions are crucial to achieve maximum electrolysis efficiency, as they influence the kinetics of the electrochemical reaction and the solubility of gases in the electrolyte. Concurrently, there is a growing interest in harnessing this thermal byproduct for enhancing system energy efficiency. One prevalent strategy involves the utilisation of the recovered thermal energy for preheating the feed water, thereby reducing the overall energy consumption of the system.

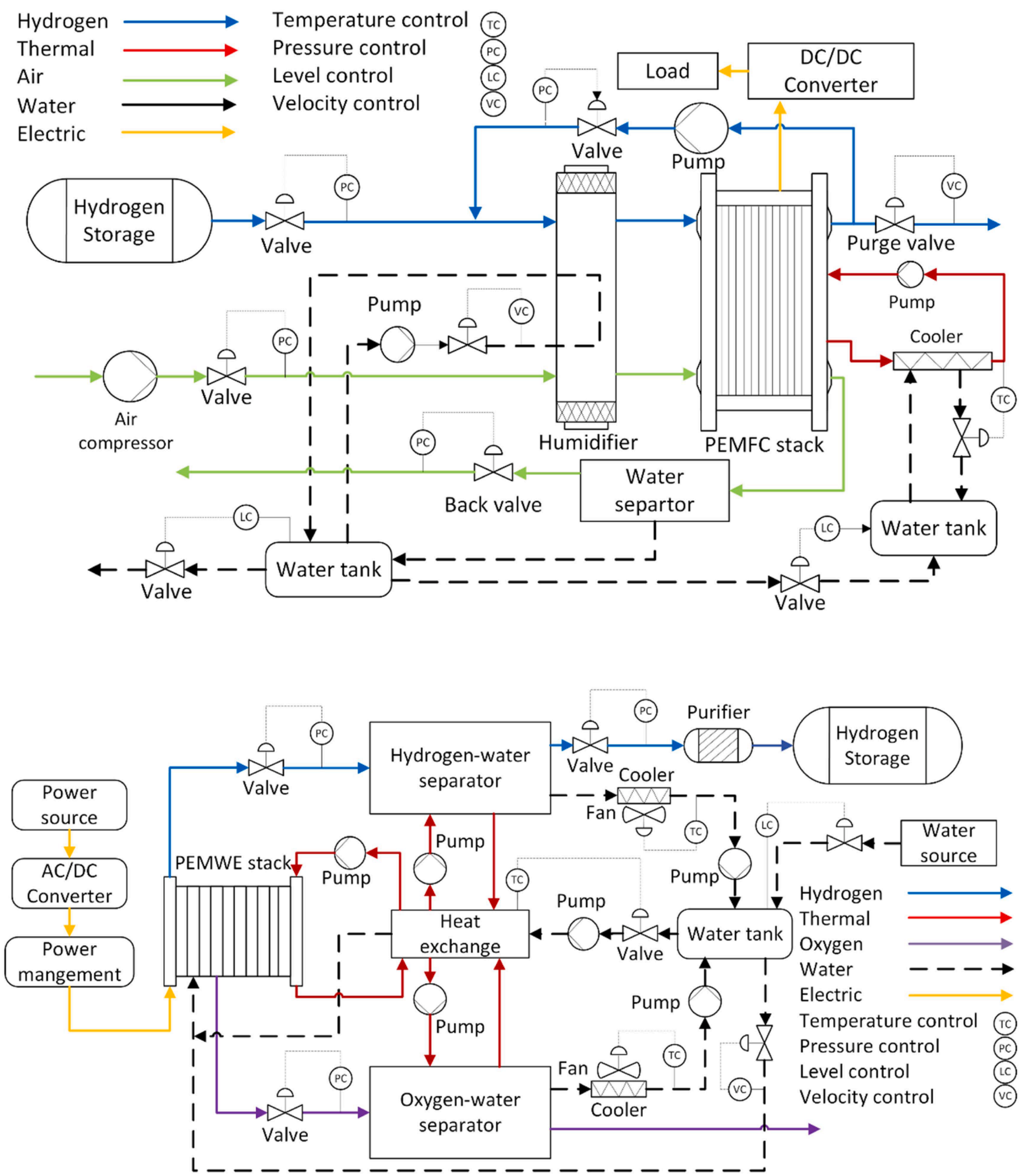

Fig. 4. Combined control systems of PEMFC (top) and PEMWE (down) stacks.

2.2.3. *Water management subsystem*

Water serves a pivotal role in facilitating the proton transport mechanism within the MEA in PEMFC and PEMWE. Sustaining an optimal level of moisture within the membrane is essential to ensure heightened membrane conductivity, enhance membrane stability, and preclude membrane desiccation. However, a delicate balance must be maintained to prevent excessive water accumulation, which can lead to issues such as flooding and resultant polarisation loss [46]. In addition, water management is typically coupled with gas and thermal managements. For example, water flooding tends to occur at lower air flow rates due to the diminished mass transfer rate of water into the air [47]. Similarly, lower temperatures contribute to increased flooding owing to the reduced rate of water evaporation [47]. Effective manipulation of the humidity levels of reactant gases can serve as a preventative measure against flooding [48]. Therefore, an efficient control in the water management system is essential not only to mitigate flooding issues but also to sustain optimal membrane humidity levels, thereby contributing to enhancing the performance of PEMFC or PEMWE.

In PEMFC system, water management systems assume a dual role, primarily oriented towards the optimisation of relative humidity, aiming to avoid flooding and preserve membrane hydration, inside the fuel cell stacks. Excessive humidity can cause water condensation, especially at the cathode side, leading to flooding that submerges the GDL and CL, hindering the transport of reactants, leading to mass transfer losses and reduced catalyst utilization [49]. However, insufficient water uptake at low humidity will cause membrane dehydration and reduce electrolysis rate, that accelerates membrane degradation and even cause membrane shedding [50,51]. These objectives are approached through two principal methodologies: external and internal humidification. Within external humidification systems, regulation of reactant gas humidity is achieved through the manipulation of both the humidification temperature and the duration of contact between reactant gases and water

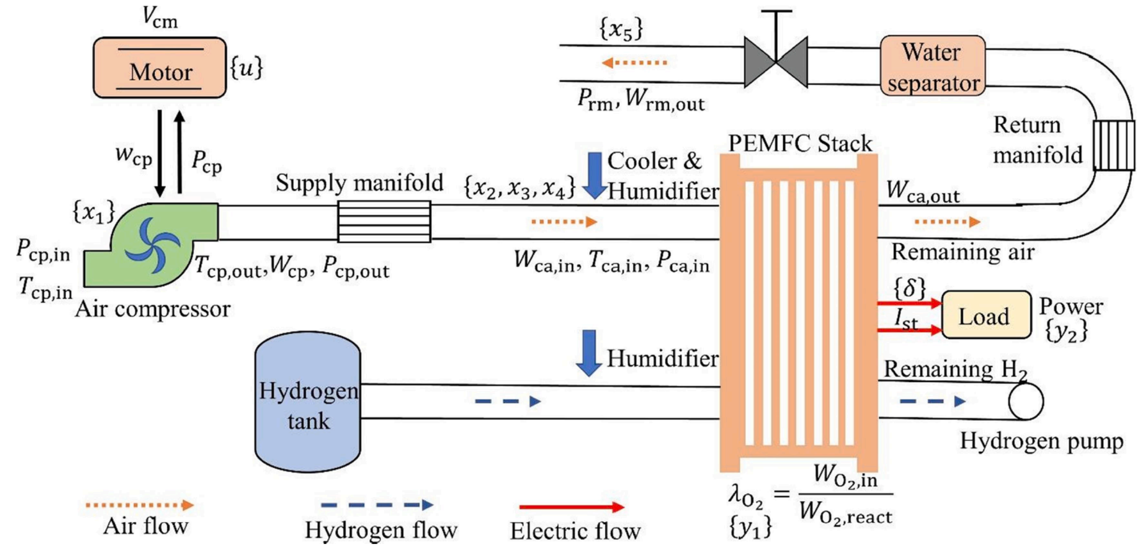

Fig. 5. PEMFC gas management subsystems [31].

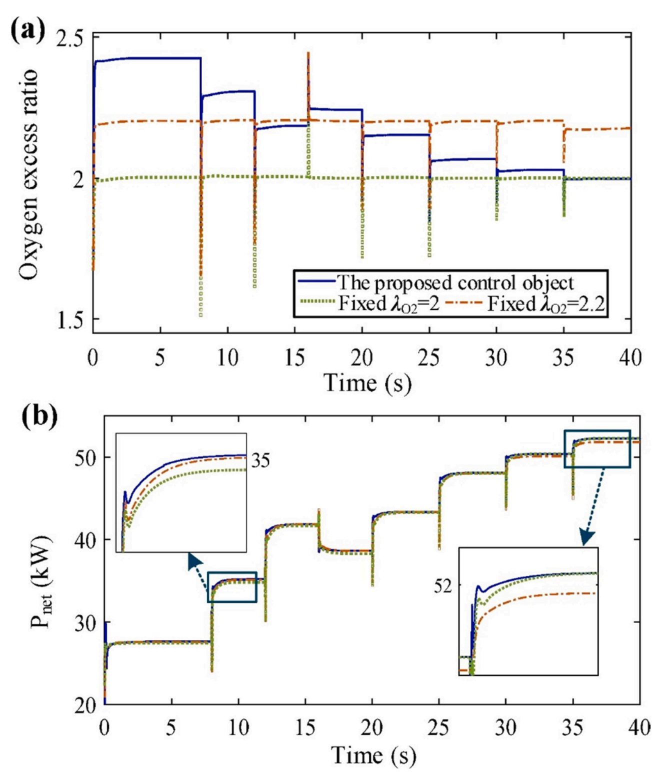

Fig. 6. Effects of different control strategies on OER and output net power changes[21].

within an external humidifier [52]. Conversely, internal humidification systems entail the direct introduction of water into the PEMFC. This intervention serves a dual purpose, namely the sustenance of membrane hydration and the maintenance of moisture content within the specified range [53]. Fig. 8 shows the voltage change in PEMFC before and after the application of water management system. The blue curve represents the voltage change without the management system; the green curve shows the change after the management system is employed. As shown in the figure, without the management system, the voltage experience abrupt changes with a higher degradation rate over time. On the contrary, the voltage is maintained at a relatively high level when the water management system is employed, which indicates an optimised water management and probably the mitigation of the degradation of vulnerable components, e.g., the membrane.

In PEMWE systems, maintaining an optimal hydration level of the PEM is imperative to prevent performance degradation due to water undersaturation or flooding. Water undersaturation can lead to reduced proton conductivity, which in turn affects the overall electrochemical performance and efficiency [9].while flooding can obstruct gas diffusion pathways, both culminating in diminished system efficiency. Concurrently, efficient heat dissipation is predominantly facilitated through water flow, addressing the substantial thermal energy generated during electrolysis. Inadequate thermal management can escalate the temperature, potentially inflicting damage to the membrane and other critical components. The performance of PEMWE systems is significantly influenced by temperature. Higher temperatures can increase the vapour volume fraction in the gas mixture, affecting the overall system efficiency. Recent studies have highlighted the importance of multidimensional CFD simulations in understanding the complex interactions between heat transfer, fluid dynamics, and electrochemistry within PEMWE cells [55,56]. The PEMWE involves liquid water being circulated through the anode side, with electrolytic action causing the water molecules to split into oxygen and hydrogen gases. These gases then move through the membrane and accumulate on the cathode side. The compact and flexible nature of PEMWE, along with their ability to operate under varying electrical loads and high-pressure conditions, makes them attractive for hydrogen production. However, the efficient management of two-phase flow, ensuring adequate water supply at the reaction sites and effective removal of gases, is essential for improving current densities and overall performance. In addition, the air pockets generated during the reaction will reduce the effective reaction area of the catalyst, thereby reducing the reaction efficiency. Currently, some studies have improved this problem by increasing the water flow rate or adding a magnetic field [57].

Furthermore, a meticulously engineered water management system is essential for flushing out the produced gases, thereby mitigating the risk of cross-contamination between hydrogen and oxygen. This aspect is crucial for maintaining the purity and safety of the gases and for ensuring the structural integrity of the membrane. Adaptability to dynamic operational conditions is another critical requirement for water management systems in PEMWE [58]. Particularly when integrated with intermittent renewable energy sources, the system must exhibit resilience to fluctuating load demands and power inputs. This adaptability ensures stable operation, preventing performance lapses and premature degradation, thus extending the system's operational lifespan [58].

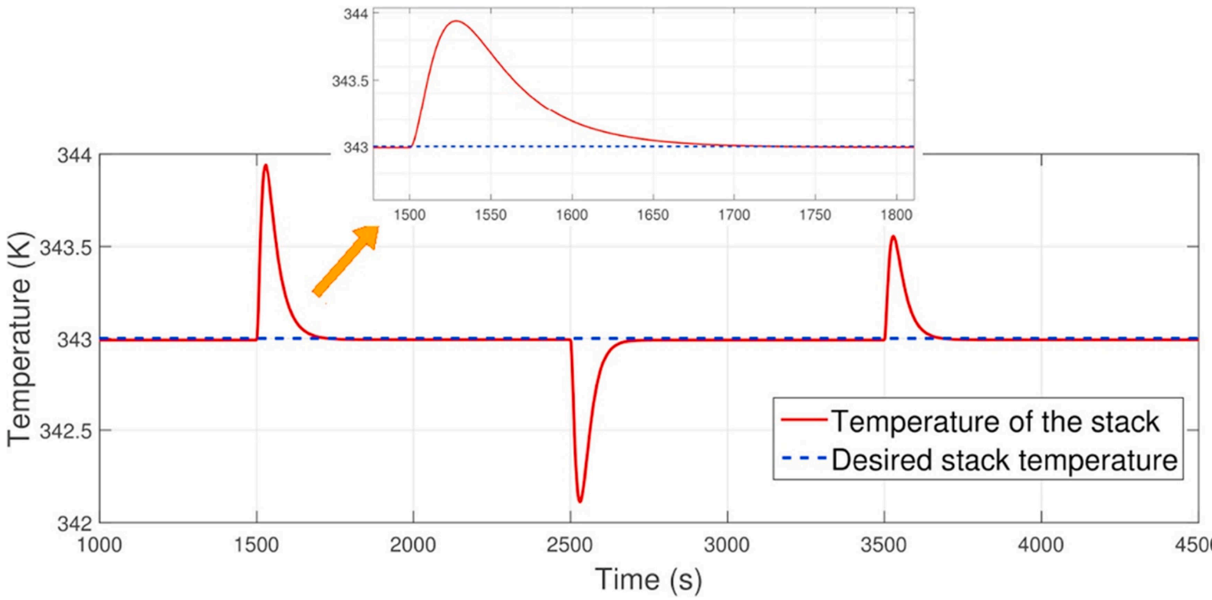

Fig. 7. Temperature changes before and after control system application in PEMFC [42].

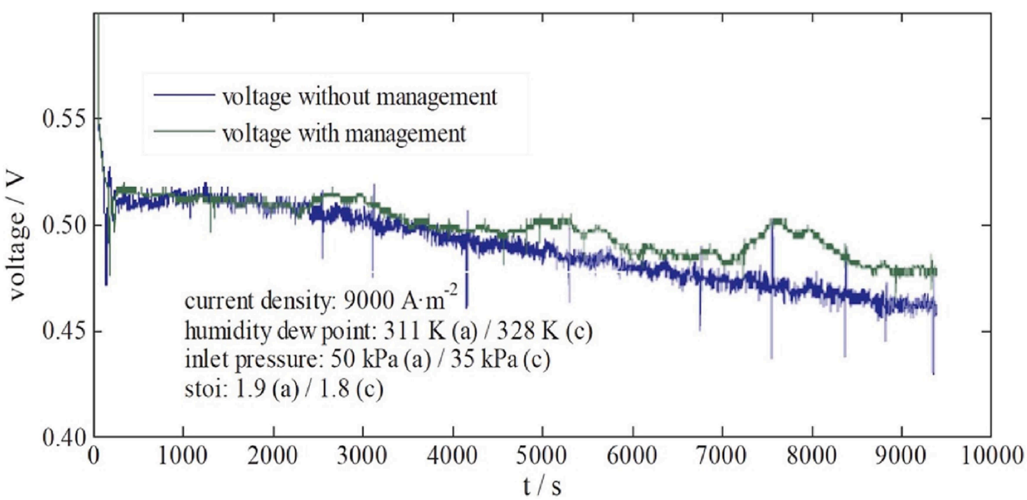

Fig. 8. Voltage changes before and after the application of water management system in PEMFC [54].

2.2.4. Power management subsystems

Power management subsystems, also known as the power electronic subsystems, are instrumental in governing the flow of electric power derived from potentially unstable sources. These subsystems utilise electronic power devices to process, filter, and efficiently deliver electricity. Key determinants in the choice of a particular power management subsystem include factors such as cost considerations, operational efficiency, the provision of electrical isolation to safeguard against overload, and the imperative for seamless and ripple-free operation [59]. The effects of two different control strategies on the PEMWE input power are compared in Fig. 9. When the power of the external power source changes, a more appropriate control system can make the change smoother to avoid sudden power changes that damage the equipment.

In the specific case of PEMFC stacks, the prevailing voltage levels in the market typically range from 25 to 50 V [61]. However, these voltages experience attenuation during periods of elevated current draw, especially under higher load demands, owing to various polarisation and ohmic losses. Consequently, the inherently unstable direct current (DC) power generated by PEMFC stacks necessitates control through a power management subsystem. Sufficient power from the PEMFC to the load hold be supplied via the power management subsystem, while concurrently regulating the electric power output to meet load demands regarding voltage, current, power quality, and transients. For different voltage control targets, different devices can be used. For example, to maintain voltage at fixed values either higher or lower than the stack operating voltage, voltage regulators, DC/DC converters, and chopper circuits are commonly employed. To either decrease the voltage, increase the voltage, or achieve a combination of both, various types of converters can be employed, such as the buck converter for voltage reduction, the boost converter for voltage increase, and the buck-boost converter for a combination of both operations [59].

Numerous control strategies have been implemented within the power management subsystems of PEMFC systems to enhance their overall performance. Voltage regulators, DC/DC converters, and chopper circuits are commonly employed to maintain voltage at fixed values either higher or lower than the stack operating voltage. The power management subsystem, often referred to as the power electronic subsystem, may involve the reduction of PEMFC voltage (buck converter), its augmentation (boost converter), or a combination of both (buck-boost converter) [62]. A simplified power electronic subsystem

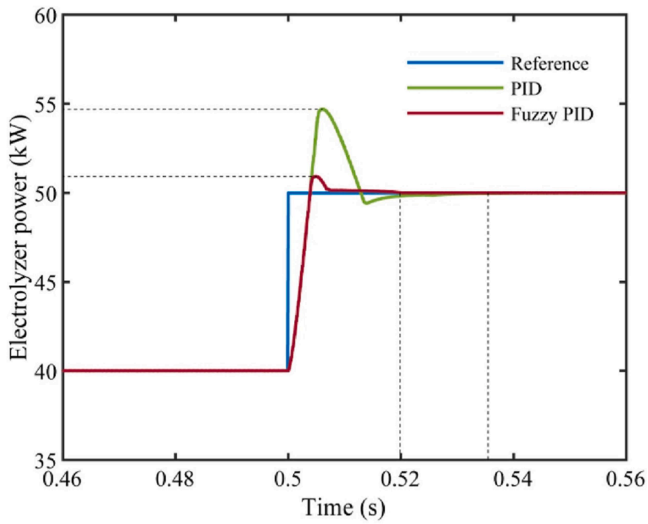

Fig. 9. Effects of different control strategies on input power changes in PEMWE [60].

comprises an adjustable external circuit for power output control, utilising components such as a rheostat, a metal-oxide-semiconductor field-effect transistor (MOSFET), or a DC/DC converter [63].

Given the prevalent need for alternating current (AC) in most consumer applications, power electronic subsystems are additionally equipped with inverters. These inverters serve to convert DC power generated by the PEMFC stack into AC, employing either a single-stage DC/AC inverter topology or a combination of a DC/DC converter in series with a DC/AC inverter for multistage conversion. A comprehensive summary of the control parameters, underlying rationales, and typical approaches to control implemented across various subsystems is provided in Table 1. A promising PEMFC subsystem design is shown in Fig. 10.

3. Methodologies and case study

Current scholarly discourse on control strategies for PEMFC and PEMWE encompasses a spectrum of methodologies, ranging from the enhancement of traditional control strategies to the exploration of advanced, innovative techniques. Traditional control strategies, such as PID control, have been extensively validated in practical applications, offering a proven track record of reliability and stability [26]. These methods have undergone rigorous technical verification, and ongoing research often focuses on refining these strategies to further enhance the performance and efficiency of PEMFC and PEMWE systems.

Concurrently, there is a burgeoning interest in the development of more sophisticated control strategies that promise substantial improvements in system performance. These advanced methodologies, while still in the nascent stages of practical application, offer tantalising potential for the future of PEM technology. They encompass a variety of approaches, including MPC, adaptive control, neural networks, among others. These strategies are characterised by their ability to handle complex, nonlinear dynamics, manage multivariable systems with precision, and adapt to changing operational conditions. Despite the lack of extensive real-world application, the theoretical and simulated performance enhancements attributed to these advanced control strategies make them a compelling area of research. Their potential to significantly improve the efficiency, durability, and operational flexibility of PEMFC and PEMWE systems positions them at the forefront of innovation in renewable energy technologies.

3.1. *Control methods*

Although PEMFC and PEMWE are similar in structure and principle, their reaction processes and target products differ, leading to distinct control method requirements. PEMFCs primarily focus on the stability and efficiency of the system's output power, which is influenced by various parameters such as temperature, humidity, and air flow rate. To stably and accurately control these parameters necessitates a more complex control system, often involving a combination of multiple control methods. Additionally, fluctuations in load during PEMFC operation can impact performance, requiring the control system to possess high dynamic performance to swiftly respond to load changes. PEMWEs primarily emphasizse hydrogen production efficiency and energy consumption, largely relying on current and voltage control. Typically operating under relatively stable power conditions, the control system for PEMWEs is simpler, with advanced control strategies being primarily employed for optimization purposes.

3.1.1. *Extensively proven control methods*

The PID controller finds its historical origin in the incorporation within the feedback system of the steam engine by James Watt in the year 1769 [71]. The fundamentals of PID control are described in Fig. 11. The PID control principle involves three key components: proportional (P), integral (I), and derivative (D). The proportional part helps reduce the error by applying a correction that's proportional to the error. The integral part sums up past errors, aiding in eliminating residual steady-state errors. The derivative part predicts future errors, allowing the system to react pre-emptively. Together, these components adjust the output to bring the system to its desired state efficiently and effectively. Subsequently, during the 1950s, the PID controller witnessed widespread adoption in various industrial applications [71].

The advent of fuzzy logic controllers (FLCs) in industrial applications, initiated in the 1970s as highlighted by Mamdani [72], marked a transformative period in control systems engineering. FLCs are distinguished by their rapid responsiveness, simplified structural design, and an operational paradigm that eschews dependence on precise process models. Its fundamental structure is shown in the Fig. 12 and a possible FLC design is shown in Fig. 13.

Sliding mode control (SMC) is also an early developed control

Table 1
Subsystem detailed controlled information and typical control strategies.

Sub-system	Control parameter	Control methods	Improvement	References
Gas management subsystem	Gas flow rate, pressure	PID, FLC	Improve power density and efficiency, avoid excessive current density, transient response improved by about 80 %, overshoot improved by about 50 %	[64,65]
Thermal management systems	Stack temperature	FPID	Prevent membrane dehydration or damage, and ensure uniform electrochemical reaction rates, MEA temperature error reduced by 48 %	[66]
Water management subsystem	Water flow rate, humidity levels of reactant gases	MPC, RNN-MPC	Ensure optimal membrane conductivity, prevent membrane desiccation or flooding, maintain efficient proton transport, control accuracy improved by about 25 %, overshoot improved by about 15 %	[67,68]
Power management subsystem	Voltage, current	PID, AMPC	Ensure sufficient power supply to the load, hydrogen consumption reduced by 9.98 %	[69]

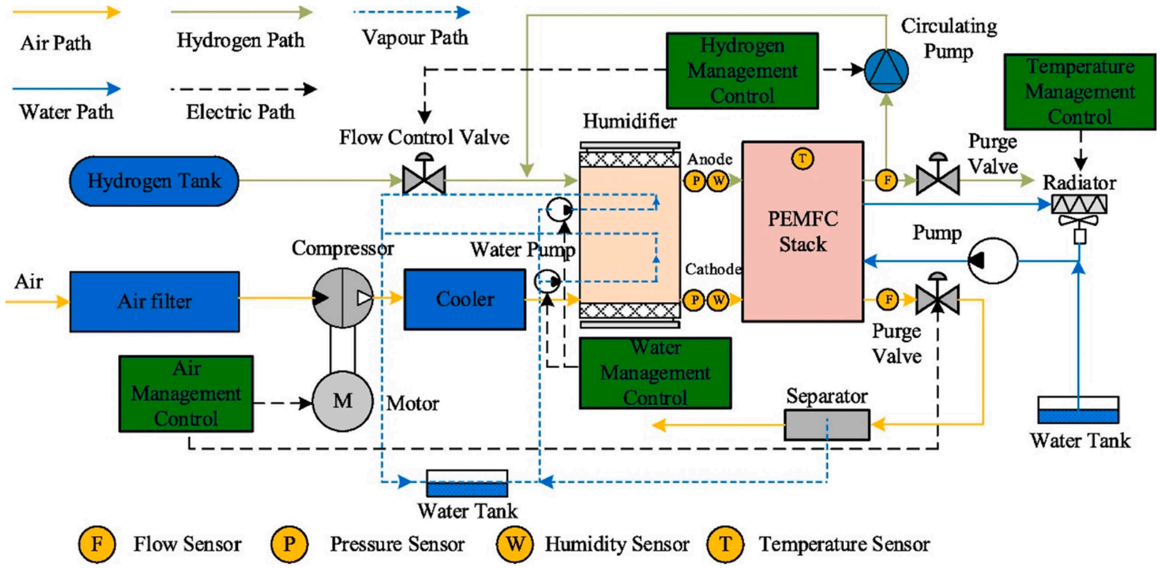

Fig. 10. A promising PEMFC subsystem design strategy [70].

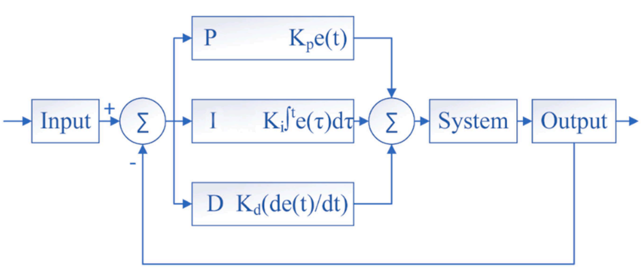

Fig. 11. Fundamental PID structure.

method. It was proposed in the 1950s, but it was not taken seriously until the 1970s [73]. SMC is insensitive to system parameter changes and external disturbances, so it does not need to build an accurate model of the controlled object [74]. And SMC can decouple complex systems into independent systems, thereby reducing the complexity of control system design. These characteristics of SMC make it widely used in various situations.

Adaptive control (APC) appeared in the 1950s with the purpose of developing reliable flight control systems. Like SMC, APC did not see rapid development until the 1970s [75]. APC monitors the error between the output and the expected value in real time and uses feedback mechanism to adjust the controller parameters to adapt to the uncertainty and changes of the system [76]. It is suitable for complex systems with unknown models or parameters that change over time. As widely used and technologically mature control methods, these methods are

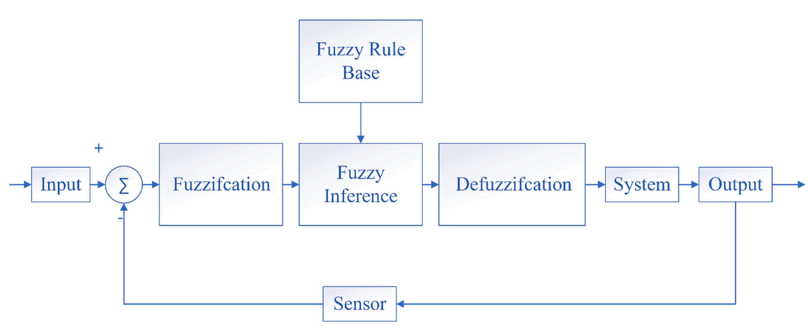

Fig. 12. Typical FLC structure.

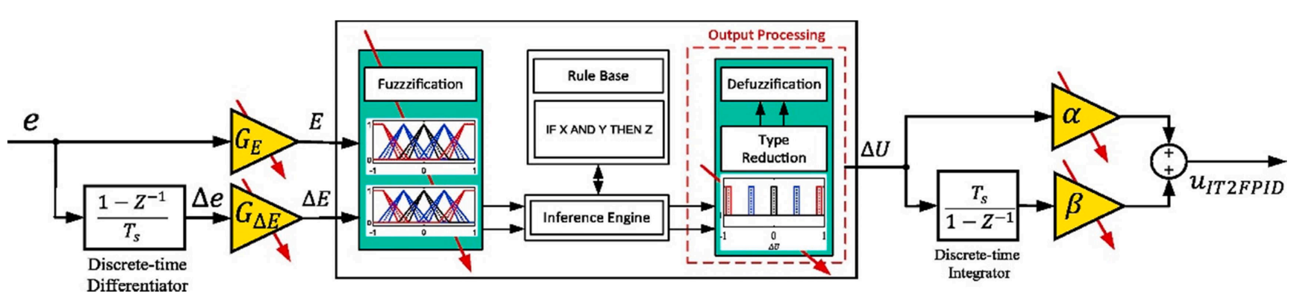

Fig. 13. FLC control system design [80].

constantly being improved in the process of continuous development.

There are also many excellent control methods developed based on them, such as the fractional-order PID controller (FOPID) developed based on PID. Compared with traditional PID, FOPID adds two parameters and therefore has greater design flexibility, but the design is more difficult [77]. FPID, which combines the characteristics of PID and FLC, can ensure control accuracy while not requiring an accurate process model [78]. Based on APC, robust APC (RAPC) with enhanced robust control [79].

3.1.2. More advanced control methods

The genesis of model predictive control (MPC) can be traced back to the 1980s [81], originating from the antecedent dynamic matrix control (DMC). Initially conceptualised as a response to the complex control demands of the chemical industry, MPC has evolved into a distinguished control strategy, renowned for its precision, robustness, and flexibility. The fundamental structure is shown in the Figs. 14 and 15 shows a design of an MPC for voltage and temperature control. MPC remains an advanced control strategy despite its development in the 1980s because it continuously evolves with advancements in computational power and algorithms. Especially with the rapid development of artificial intelligence and computer hardware in the past decade, the performance of MPC has been greatly improved [82]. The hallmark of MPC lies in its applicability to nonlinear and multifaceted systems, a capability derived from its fundamental reliance on accurate process models for prediction and optimisation.

Fault tolerant control (FTC) constitutes an area within control systems engineering that is geared towards enhancing system stability amid the occurrence of faults or disturbances. It is characterised by the integration of diverse control strategies with a primary emphasis on precision, minimal faults, and heightened adaptability. Compared with traditional control strategies, advanced control strategies are often based on AI and are also combined with traditional control during development.

3.2. PEMFC case study

In the study conducted by Swain et al. [84], a conventional PID control framework was formulated for the purpose of regulating pressure within PEMFC. The findings indicated consistent maintenance of pressure within a prescribed safe range (less than 3 atmospheres), and the overshoot is less than 5 %, coupled with expeditious responsiveness to pressure perturbations, it can return to stability within 1.5 s. However, the efficacy of control was compromised by diminished precision. Furthermore, the utilization of a simplified linear model for PEMFC introduced a measure of influence on the experimental outcomes. Another investigation, as presented by Damour et al. [85], endeavoured to enhance PID to control the gas flow rate by integrating artificial neural networks (ANN). This augmentation facilitated improved anti-interference capabilities and robustness, addressing inaccuracies inherent in the PEMFC model, the control error is only 0.1 % Notably, the proposed PID configuration exhibited notable computational efficiency. Nevertheless, the model in this study omitted consideration of error introduction. Tang et al. [86] pursued a hybrid approach by amalgamating PID with sliding mode control (SMC). The purpose is to control the gas flow rate by controlling the power supply system to adjust the compressor and other equipment in the air system. This synthesis yielded a 3.4 % reduction in overshoot compared to the conventional PID configuration, mitigating the impact of nonlinearity and temporal variations on control accuracy. Despite the achievement of enhanced robustness, an increase in system jitter was observed.

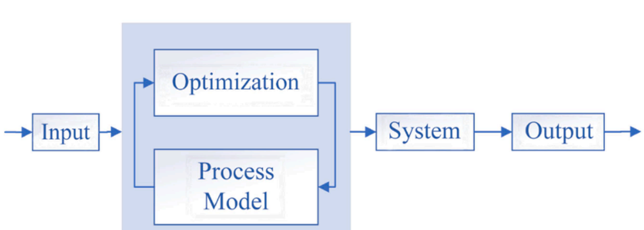

Fig. 14. Typical MPC structure.

Recent research has focused on employing PID control methodologies to ensure operational efficiency within optimal ranges [87], while adeptly responding to fluctuations in demand or supply conditions. This study intricately designs two distinct PID controllers tasked with the independent regulation of current and voltage parameters, respectively. A comprehensive comparative analysis is conducted between the stepwise tuning method and the phase margin method. The research findings elucidate that PID control, particularly when utilising the stepwise method, exhibits commendable reliability, robustness, and an adept system response (less than 0.3 s). This aligns with the controller's ability to maintain system stability and adaptability under varying operational conditions. However, a notable limitation surfaces with the application of the phase margin method, particularly in the context of current control, which underscores a restricted versatility inherent to the PID approach in this specific application.

Concurrently, Beirami et al. [88] conducted an investigation involving the synergistic integration of FLC and PID. Experimental results revealed the superior efficacy of this combined control strategy over individual implementations of FLC or PID. The fused FLC and PID strategy, referred to as FPID, demonstrated efficacy in mitigating PEMFC hypoxia issues, diminishing overshoot, and optimising the system for attaining maximum power. However, notwithstanding these advantages, the overall control precision of the system was deemed suboptimal. This composite approach, combining FLC and PID, has gained prominence and is indicative of a prevailing trajectory in contemporary research. In this study, the confluence of FLC and PID controls was delved by introducing an amalgamated control scheme known as FPID. The empirical evaluation of this hybrid methodology underscored its enhanced effectiveness compared to standalone FLC or PID systems. This FPID configuration notably addressed issues related to hypoxia in PEMFC, curtailed overshoot phenomena, and honed system optimisation for peak power output. The net system power is increased by 1 %. Despite these advancements, the integrated control system's precision remained an area for further enhancement. The fusion of FLC and PID epitomises a burgeoning trend in control system research, reflecting an evolutionary path toward more sophisticated and efficient configurations. Furthering this exploration, Baroud et al. [89] conducted a comparative study of FPID against traditional PID and FLC controllers. Improve system performance by improving oxygen excess ratio (OER). The response time is 0.06 s, which is a significant improvement compared to 0.15 s in previous studies. The findings from this inquiry underscored the significant enhancement in system performance attributable to FPID, albeit with a less pronounced augmentation in system robustness relative to performance gains.

Abouomar et al. [90] introduced an innovative approach by configuring FPID with ANN, aiming to harness the potential of adaptive and learning-based control strategies. This adaptation manifested comparable efficiency to other FPID strategies while offering marked improvements in system robustness. However, the limitations inherent to the ANN's design algorithm presented constraints affecting the FPID's overall performance efficacy. In a separate examination by Chen et al. [91], a FPID strategy specifically designed for pressure regulation was scrutinised. Despite the control precision being characterised as suboptimal, the strategy effectively mitigated pressure fluctuations across various load conditions, overshoot reduced by 5 % demonstrating the potential of FPID in managing dynamic and challenging operational scenarios. In the work undertaken by Benchouia et al. [92], the development and application of an adaptive fuzzy logic controller (AFLC) were meticulously scrutinised and its efficacy compared with the traditional PID control method. The research primarily focused on

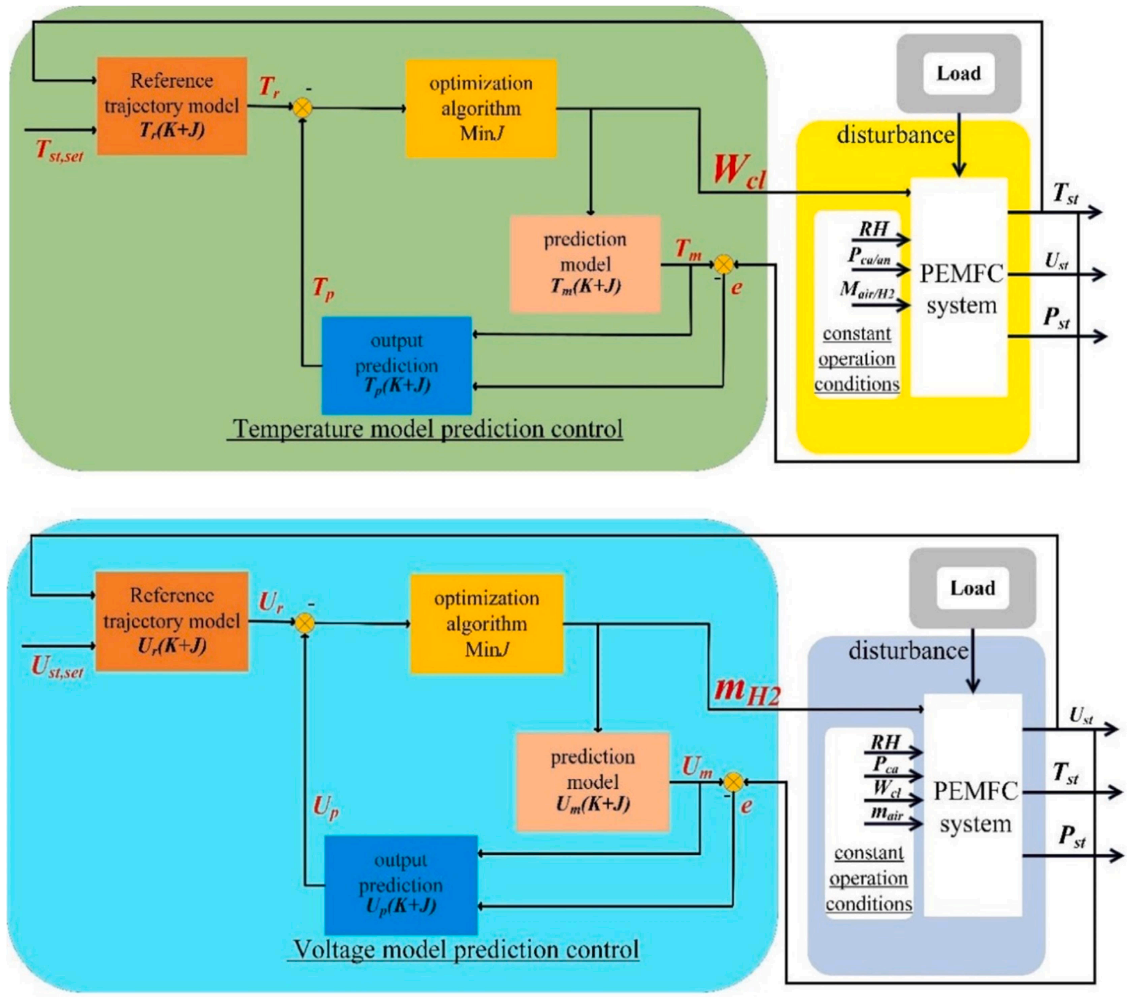

Fig. 15. MPC system for temperature (top) and voltage (down) control [83].

elucidating the comparative performance dynamics between these two control strategies, particularly in the context of system output power response. The study employed rigorous simulation techniques to evaluate the performance characteristics of the AFLC. The results from these simulations illuminated that the AFLC exhibited enhanced precision in managing the output power response of the system. This precision is attributed to the inherent adaptability and flexibility of the fuzzy logic controller, which allows for a more nuanced and responsive control mechanism compared to the more rigid structure of conventional PID controllers. Compared with PID, the steady-state time is reduced by about 10 %. The AFLC's ability to dynamically adjust control rules and membership functions based on real-time feedback provides a robust framework for managing complex systems where precision and adaptability are paramount. Consequently, this research highlights the potential of AFLC as a superior alternative to PID control in applications requiring sophisticated and precise control mechanisms.

In an innovative research endeavour, Li et al. [93] devised a synovial membrane controller (SMC) specifically tailored for voltage regulation. The empirical findings from this study underscore the SMC's underlying principle of simplicity and robustness. When benchmarked against the traditional PID control methodology, SMC exhibits superior performance metrics, notably in terms of reduced rise time, quicker stabilisation time, and minimised overshoot, thus enhancing overall control efficacy. However, the study also highlights a notable aspect of the SMC's operational dependency: its reliance on the precision of the process model. This dependency indicates that the controller's performance is contingent upon the accuracy and representativeness of the underlying model describing the system's dynamics. As such, the effectiveness of SMC in achieving optimal control is intrinsically linked to the quality and fidelity of the process model employed.

A study conducted by Huang et al. [42] used adaptive control (APC) to control system temperature and compared it with traditional PID. The research elucidated that APC exhibits a heightened degree of robustness compared to its traditional PID counterpart, particularly in terms of adapting to dynamic operational conditions and maintaining system stability. The overshoot was reduced by 57 % and response time was reduced by 60 %. This superiority is attributed to APC's capability to continuously adjust control parameters in response to real-time changes in system dynamics and environmental conditions. However, the study also illuminated the inherent complexities associated with the real-time application of APC. The need for incessant adaptation and the precision required in the estimation of system parameters contribute to the intricate nature of implementing APC. These challenges underscore the trade-off between achieving advanced control capabilities and the complexity of system design and operation.

In the study by Zhang et al. [94], the development of robust adaptive process control (RAPC) is meticulously examined as a solution to mitigate the effects of external disturbances, uncertain parameters, and the accuracy of process models on system stability. The empirical results delineated in the study accentuate the superior performance of RAPC in comparison to conventional PID control systems. Notably, RAPC demonstrates a more rapid convergence and reduced overshoot, indicating its efficacy in achieving desired control objectives more efficiently and effectively. Furthermore, the adaptability of RAPC is underscored as a significant advantage, particularly in scenarios where the system environment is subject to frequent or unpredictable changes. Despite these promising attributes, the study acknowledges the prevailing challenge of complexity associated with the practical application of APC. The intricacies involved in real-time adaptation, parameter estimation, and ensuring robust control in a dynamic and uncertain environment contribute to the complexity of implementing RAPC in industrial settings.

In a study conducted by Yin et al. [95], an innovative approach was explored where PID control was amalgamated with AI methodologies. This novel integration aimed to harness the robustness of PID control while leveraging the adaptive and learning capabilities of artificial intelligence to enhance control precision and responsiveness. Although this hybridisation resulted in a reduced overshoot, indicative of improved system stability, it concurrently manifested in extended time durations for the system to reach steady-state conditions (over than 1.5 s), along with an increase in overall system complexity. In light of these findings, the researchers advocate for the future investigation of neural network-PID configurations as a strategy to further refine and optimise control dynamics.

Complementarily, Ahmadi et al. [96] introduced a refined PID control strategy that incorporates particle swarm optimisation (PSO) to enhance the control system's accuracy and stability. The application of PSO in this context serves to optimise the tuning parameters of PID control, thereby achieving a more precise and jitter-free system response. The significant merit of this approach is the precise and dynamic adjustment of PID parameters, leading to an overall enhancement of system performance. However, the scope of this research was particularly focused on addressing the membrane water content in PEMFC, without extending the consideration to other critical operational parameters or system indicators. This limitation suggests the potential for expanding the research to encompass a broader array of performance metrics and operational conditions in future studies.

MPC was adeptly employed to regulate both the temperature and voltage within a PEMFC stack [68]. The research illuminated MPC's capacity to promptly respond to step load fluctuations, effectively stabilising the temperature and voltage parameters. Comparative analysis revealed that MPC outperforms other control strategies in terms of reduced overshoot and improved settling time, thereby demonstrating its superior dynamic performance and control precision. A distinct aspect of the study was the exemplary performance of MPC in controlling output voltage, particularly in minimizing overshoot, which is critical for maintaining the integrity and efficiency of PEMFC operations. This attribute underscores the adeptness of MPC in handling complex, multi-variable control scenarios with higher accuracy and responsiveness. Furthermore, the efficacy and applicability of MPC were corroborated through rigorous testing on an actual experimental platform. This practical validation signifies the feasibility and robustness of MPC as a control strategy, moving beyond theoretical simulations to demonstrate tangible benefits in real-world applications.

In the study by Chen et al. [83], the performances of PID, FPID and MPC, for controlling the temperature and voltage of the PEMFC stack, were compared. For voltage control, when the load of the stack changes (reflected as a current change in the experiment), the current step amplitude of the system controlled by MPC is smaller and returns to the steady state faster, which means that MPC superior to PID and FPID achieves better overshoot and settling time. With respect to temperature control, the flow of cooling water is used as a control variable. The system under MPC control has a faster response speed and a shorter stabilisation time. It is worth mentioning that the research results showed that MPC can reduce the temperature of the stack beyond, and the adjustment amount is controlled within 1.1 K. Good temperature control is the key to improving the performance and life of PEMFC. In addition, the study also compared the performance of MPC under different parameters. When the operating temperature changes, although MPC still performs better in controlling the voltage compared to other control strategies, excessive temperature will lead to higher overshoot. Wang et al. [31] conducted a study that couples PID and MPC to control the optimal oxygen excess rate (OER), in which the results of using MPC or PID alone and the performance of parallel and series algorithms were compared. In the series algorithm, the system uses double closed-loop control, where MPC is the outer loop and PID is the inner loop. In the parallel algorithm, the control weight distribution of PID and MPC are determined by adjusting the proportional and integral gains. Experimental results show that the parallel algorithm has better performance in controlling OER, output power and output voltage. MPC and PID parallel coupling control achieve better stability, anti-interference ability, and faster control speed. It should be noted that as the stack current increases, the difference in control performance of the stack voltage between different control algorithms decreases. The overshoot less than about 6 % and the control error less than 1 %. This study concluded that PID has fast response speed but large overshoot and poor robustness, while MPC can overcome the uncertainty of the system in practical applications and has stronger anti-interference ability. The coupling algorithm of MPC and PID is very effective in solving gas supply hysteresis. The other study also focus on OER control [97], developing an MPC based on long short-term memory (LSTM) neural network to model and control the system, and using the sparrow search algorithm (SSA) to update the hyperparameters of LSTM. The advantages of SSA's strong convergence and easy implementation make it easier for the model to obtain high-precision solutions, while LSTM has strong mapping capabilities for nonlinear functions. The results show that LSTM-SSA-MPC has satisfactory settling time (0.0002 s) and overshoot (0 %) and can improve the transient control performance of OER and net power.

One more related work focused on the response speed of the system [98]. The focal point was the enhancement of system response speed using MPC based on generalised predictive control (GPC). This study ventured into the realm of optimisation by employing offline computing strategies, aimed at expediting computational speed on hardware with constrained performance capabilities. The essence of this approach lies in pre-calculating complex predictive algorithms to facilitate quicker real-time execution. The empirical findings from the research are indicative of a significant reduction in the execution time of the control algorithm, notably falling below the system's sampling time and the system efficiency improved 3.46 %. This advancement addresses a prevalent critique of MPC pertaining to its computational latency, especially in scenarios demanding rapid control actions. By curtailing the execution time, the modified MPC approach enhances the system's responsiveness and real-time adaptability. Moreover, the study delineates that this accelerated version of MPC does not compromise system stability. On the contrary, it maintains, and in certain aspects improves the system's stability metrics, demonstrating that speed and stability are not mutually exclusive in advanced control strategies. In a pioneering study, Liu et al. [99] introduced an adaptive look-ahead model predictive control (ALA-MPC) designed to enhance the precision of temperature control, augment cooling efficiency, and optimise the energy utilisation efficiency of PEMFC systems. This innovative approach leverages a forward-looking sequence of load change information to proactively adjust control strategies, thereby aligning system operation with anticipated future states. The empirical findings from this investigation underscore the superior performance of ALA-MPC over conventional MPC. Specifically, ALA-MPC demonstrates significant advancements in both accuracy and energy conservation, control error reduced by 60 % and energy consumption reduced by 50 %, marking a substantial improvement in system control and efficiency. This enhancement is attributed to the adaptive nature of ALA-MPC, which integrates real-time data and predictive insights to optimise temperature regulation and energy usage dynamically. Furthermore, the practical applicability of ALA-MPC was rigorously validated through testing on an actual experimental platform. This step was crucial in demonstrating the viability of ALA-MPC for real-world applications, moving beyond theoretical and simulated environments. The successful deployment on a live platform indicates the readiness of ALA-MPC for integration into various industrial and technological settings, where precise temperature control and energy efficiency are critical.

A study proposes an MPC strategy utilising the least square support vector machine (LSSVM) to address the challenges in modelling and controlling PEMFC systems [68], which are characterised by their inherent nonlinearities and time-varying nature. The approach involves generating LSSVM models for various PEMFC performance outputs, simplifying the control algorithm's computational burden. The effectiveness of this strategy was demonstrated through simulations showing stable maintenance of oxygen excess ratio and stack voltage during abrupt stack current changes. This research highlights the potential of combining MPC with machine learning techniques to enhance PEMFC control. The other research focuses on an energy management strategy for PEMFC hybrid vehicles using adaptive model predictive control (AMPC) [100]. The study integrates PEMFC with a battery and supercapacitor to form a hybrid power system, developing a comprehensive dynamic model to account for the system's non-linearity and time-varying nature. AMPC is then applied to optimise power allocation within the system, with a particular focus on minimising hydrogen consumption. The effectiveness of the proposed strategy was validated under various operating conditions, the prediction accuracy increased by 9.75 % and hydrogen consumption decreased by 3.5 %, demonstrating improvements in the stability of PEMFC output and the safe operation of the fuel cell, battery, and supercapacitor.

The study of Sinha and Mondal [101] develops a FTC design based on a robust adaptive fault estimation observer (RAFEO) tailored for PEMFC with inherent time-delays. The pivotal component of this design, the robust adaptive fault estimation algorithm (RAFEA), is utilised to enhance the speed and accuracy of fault estimation, which is crucial for maintaining system efficiency and stability, especially in the presence of faults. A notable aspect of this approach is the use of the linear matrix inequality (LMI) technique, aimed at improving system efficiency. The design takes into account an actuator stuck fault scenario where faulty input signals are persistently obstructed, posing a significant challenge to system operation. Both the RAFEO and FTC algorithms are uniquely derived, considering the time-delay factors, which have not been previously incorporated in PEMFC studies. The inclusion of time-delays is a critical advancement as it reflects the real-world operational challenges and complexities of PEMFCSs. The validation of this advanced FTC design is demonstrated through simulation results, which confirm the efficacy of the proposed methods, particularly applied to the cathode pressure model of the PEMFCS. These results underscore the potential of this robust adaptive fault-tolerant approach in enhancing the operational efficiency and stability of PEMFCSs, even under faulty conditions and time-delayed responses. The pros and cons of all studied control strategies are summarised in Table 2.

3.3. PEMWE case study

Further experimental investigations reveal a pronounced excitation of the system response at certain specific frequencies. This phenomenon poses a risk of inducing oscillatory behaviour within the closed-loop system, highlighting a critical area for improvement in PID control application in PEMWE systems. The researchers advocate for the potential adoption of adaptive PID strategies in forthcoming studies to augment the system's versatility and address the highlighted limitations [102]. Moreover, the study posits that in small-scale PEMWE systems, current control might present a more effective control strategy compared to voltage control. This assertion stems from the direct correlation between the current and hydrogen production rate, suggesting a more efficient pathway for optimising hydrogen generation in smaller-scale systems. However, there is not enough research to confirm this conclusion for large-scale electrolysis systems. The research thus contributes valuable insights into the nuanced application of PID control

Table 2
Different control strategies.

Categories	Controller	Controlled parameters	Application	References
Traditional	PID	Pressure	Control pressure range, overshoot less than 5 %	[84]
	ANN-PID	Gas Flow rate	Improve computing efficiency, 0.1 % control error	[85]
	SMC-PID	Gas Flow rate	Improve control accuracy, overshoot reduced by 3.4 %	[86]
	ADP-PID	Current, Voltage	High reliability and robustness, response time less than 0.3s	[87]
	FOPID	Current	Reduce overshoot (less than 1 %) and short settling time (less than 3 s)	[103]
	FPID	Flow rate	Alleviate hypoxia problems, reduce pressure fluctuations, improve hydrogen production and overall performance, system net power increased by 1 %	[88]
	ANN-FPID	OER	Improved robustness	[90]
	SSC	Wate and gas flow rate, Current, Voltage	Improve efficiency and hydrogen production, electrolysis efficiency increased by 3.9 %	[105]
	SMC	Voltage	Faster response and less overshoot	[93]
	APC	Temperature	High robustness, overshoot reduced by 57 %, response time reduced by 60 %	[42]
	RAPC	Gas Flow rate	Faster convergence and smaller overshoot	[94]
Advanced	AI-PID	OER	Improved control accuracy,	[95]
	PSO-PID	The boost converter duty cycle	Precisely and dynamically adjust parameters	[96]
	MPC	Voltage, Temperature	Reduce overshoot, improve response speed	[68,84, 87]
	MPC-PID	OER	Better stability and robustness, faster control speed, overshoot less than 6 % and control error less than 1 %	[31]
	LSTM-SSA-MPC	OER	Improve the transient control performance of OER and net power, 0 % overshoot and 0.0002 s settling time	[97]
	ALA-MPC	Temperature	Improved accuracy and response time, control error reduced by 60 % and the energy consumption reduced by 50 %	[99]
	AMPC	Current, Voltage	Optimise power distribution, prediction accuracy	[100]

(continued on next page)

Table 2 (*continued*)

Categories	Controller	Controlled parameters	Application	References
			improved by 9.75 % and hydrogen demand reduced by 3.5 %	
	FTC	Gas flow rate	Improve calculation speed and accuracy	[101]

in PEMWE systems, paving the way for future advancements in adaptive control strategies and optimized operational management.

Khokhar et al. [103] believe that fractional-order controllers show good robustness in the industrial field, so they proposed a fractional-order PID controller (FOPID) for PEMFC voltage stabilizing modules. In the study, they found that FOPID has excellent transient response. Experimental results show that the system controlled by FOPID has small overshoot (less than 1 %) and short stabilization time (less than 3 s), and the researchers believe that this controller can be easily applied to more complex control problems.

In a focused investigation [104], a FPID controller was applied to regulate the temperature within a PEMWE system. This approach entailed dynamically modulating the input water temperature to enhance hydrogen production. By aligning the operational temperature to a pre-determined instantaneous reference value via the FPID mechanism, a marked elevation in hydrogen production efficiency was observed, hydrogen production increased by 56 %. However, the study elucidates that while implementing FPID enhances efficiency, it necessitates a comprehensive consideration of the physical constraints inherent to the PEMWE system, particularly to avert the evaporation of water. This requirement adds a layer of complexity to the system's design and operational framework, demanding intricate control strategies and safety measures to maintain system integrity and prevent thermal overshoot. Furthermore, the research posits the potential integration of neural network algorithms as a future enhancement to the FPID control scheme [104]. Such integration aims to imbue the system with adaptive capabilities, allowing for real-time adjustments based on fluctuating environmental conditions and system states. The neural networks, with their capability to learn and predict complex patterns, could significantly refine the control strategy, offering a more robust, efficient, and intelligent temperature management system. This proposition aligns with the continuous pursuit of optimizing PEMWE systems for higher efficiency and reliability in sustainable hydrogen production.

Recent research has proposed a self-sustaining control strategy (SSC) specifically designed for PEMWE devices. This method aims to maintain the temperature of the internal operating environment by controlling the flow rates of gas and water as well as the current and voltage., thereby improving electrolysis efficiency and hydrogen production. The system electrolysis efficiency increased by 3.9 %. The strategy involves constructing an electrothermal-coupling dynamic model based on energy-substance balance and electrochemical reaction characteristics. By dynamically adjusting the required electrical energy and water molar flow rate, the model ensures the temperature of the cathode and the anode is maintained near an optimal level [105].

4. Conclusions

In this comprehensive review of control methodologies for PEMFC and PEMWE, we delve into a nuanced discussion of some primary control strategies as illuminated by current research, elucidating both their merits and existing challenges.

In traditional control approaches, PID is a widespread implementation in PEMFC and PEMWE owing to its minimal complexity. Nevertheless, the inherent limitation lies in its comparatively lower control accuracy. Despite challenges with control variable imprecision and response times, research is currently integrating AI to enhance PID performance and adaptability. FLC offers the advantages of timely response and a straightforward structure. Valued for its fast response and simplicity, it can be easily integrated with PID control without complex models. Current research focuses on combining FLC with AI and PID. On the contrary, APC is featured by its timely response, and the high accuracy. However, the dynamic performance of APC is poor, and the control accuracy depends on data and jitter signals. SMC is very robust but relies on a large amount of data. Some methods may achieve overly conservative performance, resulting in lower accuracy. PID controllers are extensively employed in practical applications due to their uncomplicated design and heightened reliability, thereby bolstering the stability and efficiency of PEMFC and PEMWE systems. However, their application is constrained by inherent inaccuracies stemming from control variable offsets and sluggish response rates. FLC finds widespread use in regulating OER and hydrogen flow rates, facilitated by its straightforward structure amenable to practical implementation, but the construction of pertinent logic rules poses a challenge, and optimality cannot be assured.

With respect to advanced control approaches, MPC undergoes extensive scholarly exploration, often in tandem with neural networks. While offering advantages, MPC is characterised by time-consuming computations, and its control accuracy is intricately tied to the accuracy of the model employed. Present research trajectories predominantly centre on the refinement of process model accuracy, reflecting a concerted effort to enhance the efficacy and precision of MPC in diverse applications. Intricately intertwined with ANN models and AI algorithms, substantially augments control accuracy, and accelerates tracking speed. Nonetheless, the complexity of its structure entails prolonged training times. FTC primarily constitute multiple controllers and amalgamates their respective advantages, e.g., PID and SMC controllers. Nevertheless, FTC's efficacy is contingent on specific use cases, requiring intricate pre-preparations. Present scholarly investigations predominantly concentrate on amalgamating active and passive FTC methodologies. FTC adopts a fault monitoring approach to pre-design or select a suitable controller for PEMFC based on identified issues, thereby constructing a case-specific scenario to enhance overall control accuracy and effectiveness. However, it demands significant computational resources and intricate preparatory measures. The increasing incorporation of AI control strategies within the domain of PEMFC and PEMWE regulation underscores a pivotal shift toward precision in control systems. The notable accuracy and efficiency of AI-based methodologies necessitate a concerted effort towards harmonising these advanced techniques with established conventional control strategies. This integrative approach is aimed at optimising the comprehensive control architecture of PEMFC and PEMWE systems. Contemporary research endeavours predominantly converge on strategies aimed at amalgamating FLC with both AI and PID methodologies. This line of inquiry represents a concerted effort to address and ameliorate the prevailing limitations associated with FLC, thereby fostering its enhanced performance and applicability within diverse operational domains.

Most studies on control parameters focus on flow rate, current, and voltage etc., while temperature receives less attention due to its complex control challenges, such as relaxation phenomena that delay adjustments. Consequently, this requires more advanced predictive capabilities from control systems. Addressing precise temperature control will be a crucial focus for future research.

Hybrid control strategies, as evidenced in a myriad of contemporary studies, stand at the forefront of this innovative trajectory. These strategies posit a foundational assurance through traditional and reliable control mechanisms while concurrently employing more sophisticated technologies to elevate the overall performance of the system. The synthesis of robust, time-tested control methods with the adaptive, predictive capabilities of artificial intelligence presents a balanced paradigm, ensuring systemic stability and enhanced performance.

5. Perspective

Future research is thus directed towards not merely the adoption but the refinement of these hybrid strategies. Leveraging the strengths of traditional control methods as a stable backbone, coupled with the dynamic enhancement afforded by AI, offers a promising pathway. This approach ensures that the overall stability and reliability of the system are not compromised, while the performance is meticulously optimised, avoiding excessively conservative outcomes. The evolution of control strategies in the PEMFC and PEMWE field reflects a broader movement towards intelligent, adaptive systems capable of meeting the rigorous demands of modern energy technologies. The integration of AI with conventional controls encapsulates this evolution, promising more efficient, responsive, and reliable fuel cell systems. This endeavour continues to drive the research frontier, advancing the operational efficacy of PEMFC and PEMWE in a rapidly evolving energy landscape. It is important for future research to adopt and refine these hybrid strategies. Traditional control methods are used as the basis to ensure system security, and advanced control strategies are used to improve system performance.

On the premise that the system can meet performance requirements, autonomous systems will also be the target of future control systems. Compared with traditional automation systems, autonomous systems can sense the environment and make complex decisions based on changes in the environment. Autonomy focuses on the independence and adaptability of a system to handle unanticipated situations. Compared with traditional control systems, it can handle content beyond preset instructions or programmes without human intervention.

With the advancement of AI technology and improvements in hardware performance, highly autonomous intelligent control systems are becoming a reality. Autonomous technology will promote the development of PEMFC and PEMWE systems to a higher level of integration and modularisation, allowing individual subsystems to coordinate with other subsystems more autonomously. Their flexibility will also be greatly improved, allowing them to adapt to different sizes and needs.

Based on this, future control systems should include sensors with excellent performance to provide large amounts of data. The system also can analyse and process data and retrograde. Various machine learning algorithms will be applied in this part to extract useful insights from the data. Characteristics provide the basis for system decisions. The controller will also be combined with machine learning to learn the best strategy through the interaction between the control system and the environment to optimise long-term goals, especially for systems, e.g., PEMFC and PEMWE, whose models are complex and difficult to accurately calculate the process. After the control system learns the best decision, AI will also be used to predict the future state of the controlled system to optimise control performance. For example, adaptive algorithms or MPC can adjust control parameters according to environmental changes and own performance. The control system should also include autonomous fault diagnosis and repair functions to identify abnormal behaviour of the system or predict potential faults and develop decision-making logic on its own to allow the system to recover on its own or take measures to minimise the impact of faults on the system.

CRediT authorship contribution statement

Jiahao Mao: Writing – original draft, Investigation, Data curation. **Zheng Li:** Writing – original draft, Investigation, Formal analysis. **Jin Xuan:** Supervision, Resources, Funding acquisition. **Xinli Du:** Writing – review & editing, Formal analysis. **Meng Ni:** Writing – review & editing, Formal analysis. **Lei Xing:** Writing – review & editing, Supervision, Investigation, Conceptualization.

Declaration of competing interest

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.

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