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Recent advances and summarization of fault diagnosis techniques for proton exchange membrane fuel cell systems: A critical overview

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HIGHLIGHTS

- Four typical fault types with sub-classifications are summarized.
- Various fault diagnosis methods in five categories are thoroughly discussed.
- A comprehensive table summarizes and compares all diagnosis approaches.
- Thirteen other fault diagnosis techniques are systematically covered.
- Several constructive recommendations are given for future development.

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ABSTRACT

With soaring growth in the utilization of proton exchange membrane fuel cell (PEMFC) systems on various applications, researches on fault diagnosis techniques of PEMFC systems have gained widespread attention in the last few decades. Inspired by the ever-increasing demand for a reliable fault diagnosis, numerous diagnosis techniques have been proposed which aim to enhance system reliability and durability. Hence, this paper attempts to carry out an in-depth and comprehensive overview of various typical faults and state-of-the-art diagnosis methods of PEMFC systems, which are classified into five main categories, i.e., analytical model based, black-box model based, data driven based, statistical, and experiments testing. Furthermore, based on a thorough investigation of over 140 literatures, this paper not only systematically reviews various existing fault diagnosis approaches but further summarizes their performances with focus on their basic characteristics, such as main merits and drawbacks, practical applications, future developments, etc. Besides, an overall summary together with thirteen other advanced techniques is provided for a more comprehensive analysis with enriched strategies diversity. At last, six recommendations and perspectives for future researches are presented. In general, this paper is envisioned to offer insightful guidance to prompt related researchers/engineers to broaden the width of their researches.

1. Introduction

Ever-increasing global energy consumption [1,2], rapid depletion of traditional fossil fuels [3,4], and serious environmental deterioration [5,6] in recent years threaten the world's healthy functioning [7,8]. Hence, various renewable energy and clean production technologies [9,10] are envisaged as promising candidates for energy crisis management [11,12]. Among them, proton exchange membrane fuel cell (PEMFC) systems have achieved widespread attention and applications owing to their distinguished merits [13,14], such as zero-emission, easy installation and maintenance, high energy conversion efficiency, noiseless operation, etc. In general, PEMFC technologies play a crucial role in alleviating environmental pressure and reconstructing energy-consuming structure thanks to their outstanding environment-friendly characteristics [15].

PEMFC systems are widely utilized in a series of practical applications, e.g., stationary power station and transportation sector, which are complex integrations of chemical, electrical, mechanical, and thermal operation management [16,17]. However, the reliability and durability

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Nomenclature

ANN	Artificial neural network
ARR	Analytical redundancy relations
BiLSTM	Bidirectional long short-term memory
BN	Bayesian network
BoPs	Balance of plants
CPE	Constant-phase-element
CVA	Canonical variate analysis
CWT	Continuous wavelet transform
DBN	Deep belief network
DWT	Discrete wavelet transform
DS	Dempster-Shafer
EIS	Electrochemical impedance spectroscopy
ELM	Extreme learning machine
EMD	Empirical mode decomposition
FC	Fuel cell
FDA	Fisher discriminant analysis
FDD	Fault detection and diagnosis
FDI	Fault detection and isolation
FUIO	Fuzzy unknown input observer
HAS	High air stoichiometry
HNN	Hamming neural network
LME	Linear matrix equalities
LMI	Linear matrix inequalities
LPV	Linear parameter varying
NN	Neural network
OLDA	Orthogonal linear discriminant analysis
PCA	Principle component analysis
PEMFC	Proton exchange membrane fuel cell
RBF	Radial basis function
RC	Reservoir computing
RNN	Recurrent neural network
RVM	Relevance vector machine
SAGAFCM	Simulated annealing genetic algorithm fuzzy c-means clustering
SMOTE	Synthetic minority over-sampling technique
SoH	State-of-health
SVM	Support vector machine
t-SNE	t-distributed stochastic neighbour embedding
TS	Takagi-Sugeno
UIO	Unknown input observer
WT	Wavelet transform

of PEMFC systems during long-period operation are still the two most critical and thorny obstacles, which hinder their further applications and commercialization. Generally speaking, degradation or failures of systems can be easily triggered by many causes [18,19], e.g., bad water management, improper operation and so forth. To address the aforementioned problems, numerous fault detection and isolation (FDI), as well as fault detection and diagnosis (FDD) methodologies have been devised [20–22]. Particularly, fault diagnosis of PEMFC systems requires fast and simultaneous processing of high-nonlinear, multiple failure sources, and various model scale problems. Based on whether accurate modelling is required, various diagnosis techniques are often divided into two main categories: model-based methods and non-model based methods [23]. The former ones are usually based on analytical models with a deeper investigation on fuel cell (FC) systems' internal reaction process [24], which are also called residual-based methods [25]. Non-model based methods are mainly based on heuristic knowledge or signal processing techniques [26], which are envisaged as emerging trends for fault diagnosis compared against model-based methods [27].

In the past few decades, a large number of advanced PEMFC diagnosis approaches have been proposed [28,29]. Thus, this paper undertakes an overall statistic on these studies in 'PEMFC fault diagnosis' over the last decade (2010–August 2020), as demonstrated in Fig. 1. The data are collected from Web of Science, Scopus service of Elsevier, and Google Scholar, respectively.

Until now, several reviews have also been published to summarize various PEMFC fault diagnosis strategies, however, there still exists some limitations or drawbacks that need to be further improved. Literature [30] undertook a review on voltage degradation of PEMFC related to water management issues, along with some corresponding prevention approaches. However, this work still exists some disadvantages and shortcomings, such as only one specific fault is investigated, insufficient methods diversity and systematic evaluations, and lacking detailed recommendations for future researches. Besides, an overview of different model-based approaches for PEMFC systems diagnosis was

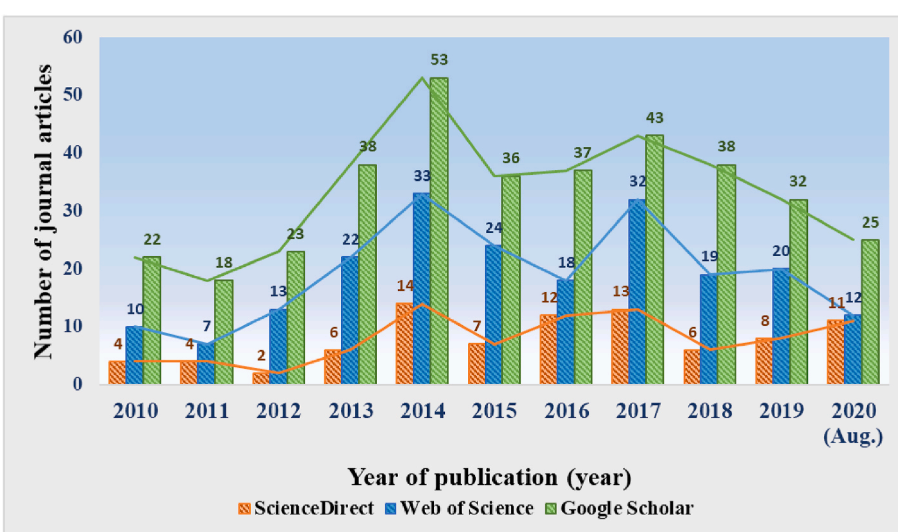

Fig. 1. Research statistics in PEMFC fault diagnosis.

proposed in literature [31], in which only seven general model-based approaches are addressed without uniformly comprehensive comparison. Meanwhile, literature [32] proposed an overall summarization on non-model based methodologies applied to PEMFC systems diagnosis, which divides these methods into five general groups. Nevertheless, some state-of-the-art technologies are not covered, and it also lacks systematic comparison and specific applications of various methods, along with perspectives for future researches. Moreover, a review on water fault diagnosis of PEMFC related with pressure drop was developed in Ref. [33], which comprehensively investigates the effect factors and estimation of pressure drop and six water fault diagnosis approaches, but lacks detailed comparison of different diagnosis approaches. Literature [34] provided a review on relevant studies on fault diagnosis methods for PEMFC systems, which aims to identify the root causes of these faults. However, such work lacks detailed descriptions and evaluations for methods in each subcategory, complete classifications, and many promising or state-of-the-art technologies. To remedy the aforementioned shortcomings in prior studies, this paper undertakes a more comprehensive review on various fault diagnosis methods more systematically and explicitly. All the fault diagnosis methods are classified into five main categories with sub-categories, i.e., analytical model based methods, black-box model based methods, data driven based methods, statistical methods, and experiments testing methods. Four main fault types with twelve detailed sub-classifications are systematically introduced. Particularly, various indicators are employed for a more systematic and reliable comparison of different methods, and detailed application conditions are also discussed along with the pros and cons of each subcategory. Besides, thirteen other advanced PEMFC diagnosis techniques are also comprehensively summarized. At last, six recommendations and perspectives for future researches are provided based on a thorough investigation of prior researches.

In general, compared with prior reviews, a more critical survey on PEMFC fault diagnosis methods is undertaken based on a thorough literature investigation, explicit classifications, systematic comparisons, detailed discussions, along multiple perspectives for future researches. In general, this paper can be envisaged as an insightful guidebook for future in-depth studies on PEMFC fault diagnosis.

2. Type of faults

Normal and healthy operation of PEMFC systems is critical to system warranty [35,36], which means any type of faults that occurs in PEMFC systems might result in undesirable safety hazards, thus energy conversion efficiency [37], power availability [38], and system reliability [39] might thereby be degraded. Particularly, a series of auxiliary devices in PEMFC systems, including compressors, humidifiers, sensors, controllers, and so forth are quite vulnerable to different faults [40,41], as demonstrated in Fig. 2.

Meanwhile, faults effects are not instantaneous due to the duration characteristic of faults setting, such that components of systems might suffer temporary or even permanent degradations and damages. Various faults occur in PEMFC systems are reported and discussed in literature [42–44], which contain cell flooding, membrane drying, high thermal gradient, local hot spots, fuel starvation, carbon corrosion, platinum oxidation, CO poisoning, degradations, cell reversal, etc. In addition, the causes of faults can be categorized into external or internal, and both can lead to an inevitable decrease in output power, efficiency, and reliability of PEMFC systems. In this section, four typical fault types of PEMFC systems are briefly introduced, and a comprehensive summary on various common faults is tabulated in Table 1.

2.1. Cell flooding

Water distribution in PEMFCs is extremely crucial that influences channel transmission stability and efficiency between membrane and electrodes, which is the basis to solve the problem of stable discharge performance and no-humidification operation [45]. Since any disturbances of water balance can lead to internal failures, including cell flooding or membrane drying which can affect the system's performance and reliability, water management is one of the most complex and crucial tasks during PEMFC systems operation. Flooding is one of the most common faults in PEMFC systems, especially for cathode due to its location on water production [46]. During the operation of PEMFC, the accumulation of large water droplets will hinder water transmission in the flow channel and cause water flooding. Besides, water coverage can result in catalyst active area decreasing, which will dramatically increase activation loss and concentration loss [47].

2.2. Membrane drying

On the contrary, drying faults might occur when the membrane cannot be sufficiently hydrated, which can lead to an increased resistivity to further increase heat production during PEMFC systems operation. If not handled timely, such condition can further deteriorate to reduce energy conversion efficiency and even cause membrane tearing, which can seriously affect output performance and residual service life [48]. Drying out faults are often caused by drying inlet gases with low humidity due to high temperature accelerates water evaporation.

2.3. FC poisoning

FC poisoning is a typical fault related to reactants supply that is mainly caused by various impurities [49], e.g., there might exist many

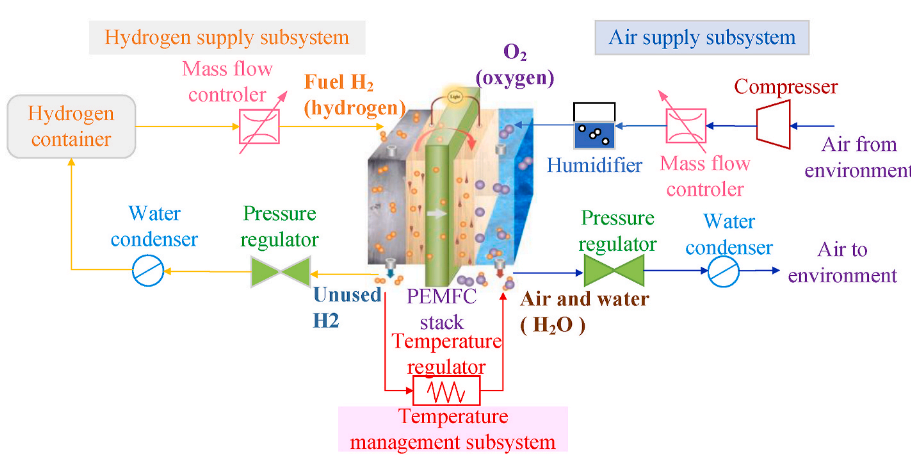

Fig. 2. Structure of PEMFC system.

Table 1
Summary on twelve typical faults of PEMFC system.

Type of faults		Causes	Effects	Recoverability	Severity
Fuel cell	Flooding	Higher current density, lower cell temperature, higher inlet humidity, lower stoichiometric flow, and inappropriate back pressure.	Performance losses and slow system degradation.	Reversible if treated in time.	**
	Drying	Opposite to the conditions lead to flooding.	Performance losses and pin-hole formation of the membrane.	Pin-hole formation cannot be reversed.	****
	FC poisoning	Low purity of intake reformate hydrogen.	Performance losses and then starvation.	Reversibility relies on exposure time, and inlet gas composition.	****
	Hydrogen starvation (local)	Non-uniform fuel distribution in the gas distribution layer	Air electrode damage, cell performance degradation, and current reversal	Reversible if treated in time.	***
	Hydrogen starvation (global)	H_2 supply is completely cut off	Water oxidation (the initial main reaction in an FC caused by fuel complete starvation at the anode) [42,54], carbon corrosion, and cell reversal caused by excessive fuel starvation	Cell reversal will cause irreversible damage to the FC.	*****
H_2 circuit	Fuel leakage	Faulty components, seal failures, stack misalignment, and lack of tightness.	Performance losses and flow rate decreases.	Reversibility relies on leaking time and leaking position.	**
	Fuel blocking	Faulty components and water management issues.	Performance degradation.	Reversible if treated in time.	***
Air compressor	Oxidant starvation	Sub-zero start-up, rapid load change, and water accumulation during long-term operation	Reversal of cell voltage might happen, and local hot spots at cathode air inlet might lead to membrane electrode assembly degradation.	It might cause irreversible damage to the FC if not treated in time.	****
	Electrical faults	Short circuit	Membrane and catalyst layer degradation.	Local irreversibility.	*****
	Air stoichiometry failures	Air feeding system failures.	Water management failures.	Reversible if treated in time.	***
	Controller faults	Controller breakdown.	Operation reliability and durability decline.	Reversibility relies on failed controller's role and damage extent.	****
Cooling system	Water cooling faults	Cooling system failures.	Flooding.	Reversible if treated in time.	**

Note.** *: low; **: medium-low; ***: medium; *: medium-high; *****: high.

different impurities in intake reformate hydrogen at the anode side, such as CO, CO_2, N_2, NH_3, H_2S, and hydrocarbons, which might significantly reduce the performance and service life of PEMFCs. For instance, the adsorption phenomenon of CO at the platinum anode catalyst surface can induce a catalyst deactivation, which can further result in a performance loss of PEMFCs [50]. Particularly, CO poisoning is mainly depending on inlet gas content, inlet flow rate, humidity, residence time, and temperature [51].

2.4. Air compressor failures

Air compressor failures consist of several sub-classifications, e.g., short-circuit electrical faults, mechanical faults, and hydraulic faults [17,52]. For instance, short-circuit circumstances can lead to high thermal gradient and local hot spots at the membrane [53], which will decrease operation efficiency or even cause irreversible degradations of PEMFC systems.

3. Fault diagnosis methods

Until now, a large number of advanced techniques have been applied in PEMFC fault diagnosis, thus this section tends to comprehensively introduce and summarize these methods, which are classified into five categories, i.e., analytical model based, black-box model based, data driven based, statistical, and experiments testing, respectively.

3.1. Analytical model based methods

3.1.1. Parameter identification methods

Literature [55] devised a computing residuals based approach, in which critical diagnosis indicators are achieved by comparing measured inputs and outputs with analytical relationships [56]. Its main novelty is that it relies on the characterization of relative residual fault sensitivity instead of absolute sensitivity that is usually utilized in conventional model-based methods. The implementation of such method is accomplished in a modified FC simulator in the MATLAB/SIMULINK environment to diagnose two different fault scenarios, e.g., increase of compressor motor friction and compressor motor overheating. It is noteworthy that this method might be able to achieve diagnosis and isolation of all fault types in its proposed set compared against other well-established methods which utilize the binary signature matrix of analytical residuals and faults. The main challenge of future work of such method is the validation on more fault scenarios to testify if it can successfully diagnose and isolate more fault types in real-time.

In particular, impedance spectroscopy is another typical method that has been adopted in on-line applications. For instance, a constant phase element (CPE) based modified Randles-like equivalent circuit model was employed to better fit the data from the measured curve to measure impedance spectrum [57]. Based on the monitoring of such modified Randles-like equivalent circuit model's three resistances, an efficient and robust on-line state-of-health (SoH) monitoring of the PEMFC corresponding to the water content of the membrane electrode assembly can be realized. Based on this, the effects of drying and flooding faults on the model parameters are analyzed. In order to guarantee the stability and homogeneity of the FC under verification, the tests are carried out on a stack fed with air and pure hydrogen. The operation conditions of FC are monitored and controlled based on a Greenlight Power FCATS-L test station, and the impedance spectra are recorded with a Gamry FC350. The main challenge is to maintain the inconsistency caused by unavoidable instability to a "reasonable" level due to there exists no system that can always satisfy the stability demand in the theoretical sense.

In reference [58], an electrical equivalent model based fault diagnosis method that considered the main nonlinearities of the reaction process was proposed, which aims to act as a unifying technique to detect FC flooding, upon which gas dynamic and voltage prediction can be efficiently achieved. Based on the established global equivalent model, a model parameter identification approach is applied in two steps that firstly decouples the anode and cathode circuits, and then a nonlinear system with a varying resistance is treated. The main purpose of this work is to establish a general model that considers saturated conditions to study the liquid phase in diffusion layer and to further investigate its effect on circuit parameters. Besides, the performance of such method is verified on a 500 W 20-cell stack equipped with relevant testing facilities for model construction and validation, while the main challenge is how to further improve the diffusion resistance estimation technique. Basically, both flow resistance dynamics and cell voltage distribution will be integrated with parameter identification of electric circuit for a more desirable diagnosis performance.

Besides, literature [59] devised a novel total harmonic distortion (THD) analysis based diagnosis tool to realize PEMFC online health monitoring, in which a low-frequency signal is adopted in FC and the THD contained in the output signal is observed under various scenarios. As a result, a series of typical faults, e.g., drying, flooding, and hydrogen starvation are identified on-line based on the identification of various indicator frequencies for various aforementioned critical conditions. The commercial membrane-electrode assemblies of 25 cm^2 active area produced by Alfa Aesar, UK have been applied in both anode and cathode sides of the FC for validation. The main difficulties during the experiments are the complicated adjustment of corresponding parameters to simulate various critical fault conditions and the filtering of harmonics and noise signals.

Besides, distribution of relaxation times (DRT) has been applied to analyze electrochemical impedance spectroscopy (EIS) spectra of high-temperature PEMFC (HT-PEMFC) [60], which adopts DRT to the measured spectra, and polarization losses are separated based on their typical time constants. Prior knowledge about the physics of the studied system is not required for DRT based internal characteristics identification, which is beneficial for enhancing EIS spectra interpretation. In literature [61], DRT scheme has been utilized to analyze impedance data to further study the role of the anode in the polarization losses of HT-PEMFCs, in which various operation conditions of the anode are employed (e.g., humidification, CO impurities, etc.) to verify the influence on DRT spectrum. In particular, for the sake of better investigating the observed variations, a reference electrode has been applied to isolate the anode impedance from the cathode impedance. All the cell experiments are carried out in a single cell setup.

In reference [62], a resistive capacitive (C model) and resistive constant-phase-element (CPE) circuits based cell impedance model are employed for PEMFC fault diagnosis, modelling, and mitigation. The main advantage of the developed CPE model is that its better approximation of FC impedance, and C model can simultaneously realize an easy implementation due to its wide application in most simulation tools (e.g., MATLAB/Simulink or PSpice). Flooding and drying faults can be detected based on cell voltage and cell impedance response, in which the response of impedance under low frequency is applied to determine the causes of faults. Particularly, all the case studies are undertaken based on a single PEMFC fed with air and pure hydrogen, along with other corresponding FC testing equipment, during which the recording of *V–I* data under complete flooding scenario is a challenging but also a critical task. In general, based on the pulsing and higher water production at higher FC current, the voltage of FC can be effectively increased. Meanwhile, case study results demonstrate that the controlling of FC current and voltage operating points via converters successfully mitigates the fault.

Besides, an EIS measurements based pattern-recognition-based diagnosis approach was proposed in Ref. [63], in which impedance modulus behavior at low and high frequency are observed. This method employs EIS measurements as the supporting database that requires no physical modelling of the FC system, upon which the faults can be automatically detected in the dataset and categorized into various types. The most critical step is to automatically produce a group of limited patterns, upon which one can realize fault diagnosis while reducing computation costs and information redundancy. It can effectively detect degradations of FC in three steps, i.e., (a) extracting measurable features, (b) merely relevant features are kept via correlation-based feature classification method, and (c) each observation is assigned to one pre-defined fault category. Its effectiveness is validated on evaluated on a PEMFC stack that consists of 20 cells under different operation conditions, which shows satisfactory identification accuracy though there still exists some misclassification between contiguous classes.

Literature [64] developed a fast EIS measurement system to more effectively decrease measurement cost and time for on-line fault diagnosis, in which the maximum length sequence disturbed current is integrated into PEMFCs based on a current pulse injection circuit. Meanwhile, EIS is achieved by continuous wavelet transform (WT) and maximum likelihood estimation, in which the continuous WT can enhance the EIS measurement efficiency. The current pulse injection circuit can also produce a low-cost, small-volume, and high-quality solution for disturbance injection, which can effectively validate its feasibility in commercial and engineering applications. The parameters extracted by the EIS act as the features for fault diagnosis, upon which a binary tree support vector machine classifier based multi-fault diagnosis approach is proposed to achieve accurate and fast fault diagnosis. Such EIS measurement based fault diagnosis strategy includes the on-line and the off-line stages, which is validated on a 3 kW PEMFC experimental platform to identify drying, flooding, and air starvation faults. The main challenge during on-line diagnosis is that the humidity of membrane is hard to obtain in real-time, which might cause missed diagnosis.

Besides, an impedance measurement was utilized to diagnose flooding and membrane drying in Ref. [65], which proves that low-frequency ripple current caused by faults can aggravate PEMFC degradation. Based on the average values of FC's extracted parameters that acquired based on the direct measuring of impedance curves of 12 single cells after hours of cycling under variable frequencies, it can be seen that the impedance magnitude of an FC injecting a low-frequency ripple current (100 Hz) increased compared against those injecting high-frequency ripple currents (1 kHz and 10 kHz). Based on such observation, additional impedance measurements are carried out directly to investigate flooding and drying faults involving a low-frequency ripple current. The experimental setup is composed of 12 individual cells to further verify its fault diagnosis ability for flooding and drying faults, during which the setting and maintenance of experimental test conditions are quite challenging and significant.

Furthermore, the dynamic EIS method was successfully implemented in corrosion detection [66], characterization of electrode materials [67], and direct methanol FC monitoring [68,69]. A dynamic EIS was applied in diagnosis and monitoring of PEMFC stack and individual cell operation [70], which can rapidly distinguish failure sources in a dynamical system. On this basis, impedance measurements are performed in galvanodynamic mode, which allows to simultaneously acquire impedances of individual FCs and the entire stack in a dynamical system to identify whether it is healthy or faulty. This method uses a multi-frequency perturbation signal. It consists of a number of elementary signals with different frequencies, amplitudes, and phase shifts. By using the superposition of sinusoidal stimulations, the theoretical total impedance acquisition time is reduced to the period of the component of the lowest frequency [70]. An experimental PEMFC stack consists of ten single cells was adopted for testing and controlling, upon which such method is verified to diagnose efficiency reduction of the FC stack, along with the identification of failure sources. Such.

Literature [71] combined current density distribution and EIS for load level and air feed conditions estimation, which can effectively utilize the merits of the two methods that can achieve improved and in-depth analysis for fault mechanisms with high sensitivity without any impact on FC's normal operation. In particular, based on the correlation of the analysis of the current density distribution within the active area under the FC level and EIS, fault diagnosis can be achieved without any influence of the adopted analytical approaches on the individual FC performance. This combined strategy is testified on a 10-cell liquid-cooled PEMFC stack under various load conditions for identification and isolation of cathodic flooding, air starvation, and FC dry-out faults. It is critical to maintain the rigorism of testing conditions, such as all the stack reactant supply pipes must be insulated heated, upon which the service life and efficiency of FCs can be enhanced during system operation. Moreover, a neural network (NN) technique based EIS modelling was proposed to analyze and diagnose PEMFC water management failures [72,73], in which NN has been adopted to establish an optimal PEMFC impedance model to assess the influence of relative humidity and FC impedance operating time. The implementation of such method is based on the Randles-like equivalent physical model with CPE, and an analytical approach called least squares method to extract the unknown parameters. The purpose of establishing a theoretical model is to realize predictive diagnosis of control system and water management. The devised optimum impedance model via ANN has high sensitivity for both internal resistors and biasing resistors, and it also can easily produce Nyquist diagram under various scenarios of humidity and operation time that is beneficial for stack's hydration status definition. In general, it can achieve flooding and drying fault diagnosis in a fast and simple way, which is verified by the time varies from (500–2500 s) at dehydrating and flooding conditions, respectively.

3.1.2. *Observer based methods*

Observer based methods are typical and common diagnosis methods for PEMFC systems, which are based on the combination of system characteristics and equivalent model.

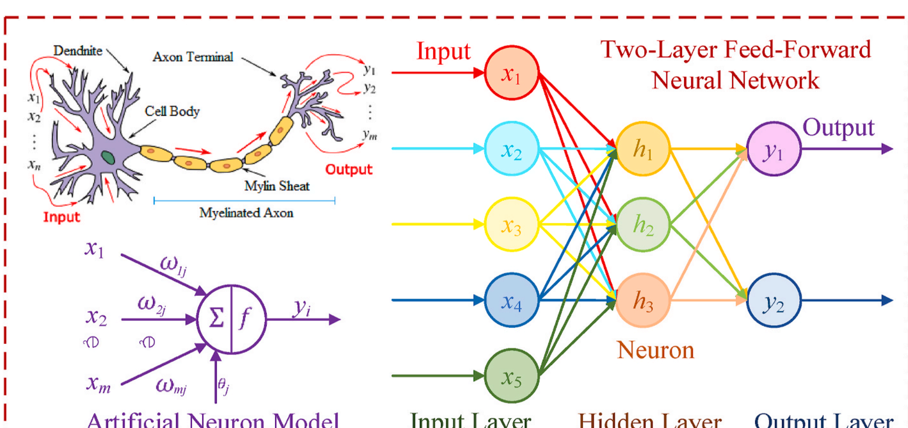

Fig. 3. The basic structure of a two-layer feed-forward neural network.

Due to linear parameter varying (LPV) models are constructed as similar as a linear time invariant (LTI) state space system, the design of various controlling and fault diagnosis strategies can be easily extended. Literature [74] proposed an LPV model based on the consideration of model parameter variation with the operating point, upon which an LPV observer is developed to dynamically estimate PEMFC system states. Such method has been verified under various typical fault circumstances, such as a leak of hydrogen under the model (Ballard, Nexa©) in the MATLAB/SIMULINK simulation environment. However, a major thorny challenge is that the dynamics contained in the complete LPV model are extremely different that causes numerical thorny during the observation, which might result in numerical difficulties during the implementation of observation.

Besides, A delayed LPV observer was proposed to effectively deal with unknown inputs and time delay in the output [75], in which an unknown input observer (UIO) for delayed LPV model is employed to investigate unknown inputs and time delay in outputs. The establishment of this varying time-delay LPV system is based on the descriptor technique with the measurement of mass flow oxygen is delayed. Then, an actuator fault identification method that considers the time delay related to the mass flow oxygen at the PEMFC anode is designed, and a PEMFC system is adopted to validate its performance on actuator faults. During the experiment, the setting and design of conservative time delay dependent conditions is a critical but challenging task, which can also be further optimized in future studies.

Besides, a novel robust fault diagnosis and fault tolerant control strategy has been developed in Ref. [76], in which an augmented robust observer is devised to simultaneously achieve internal states and component faults estimation under various scenarios. In general, the robustness of this strategy is achieved by considering the system disturbances and noises of measurement during the observer gain design. The design of this robust observer is transformed into solving a series of linear inequality matrices, in which various faults are regarded as additional state variables, and an augmented system can be established via the state augmentation to achieve fault reconstruction. In particular, a vehicle 75 kW fuel cell system is applied to verify the effectiveness of such observer for air management system faults diagnosis. The simulation results indicate the designed augmented robust observer can obtain accurate estimation of both the system status and faults under various scenarios. In addition, the oxygen stoichiometry is also estimated considering fault characteristics of the system for air supply fault tolerant control. In general, the design of the augmented system is the core content in researches.

Moreover, a robust fault diagnosis strategy called Takagi-Sugeno (TS) fuzzy unknown input observer (FUIO) was developed [77], which combines linear matrix equalities (LMEs) and linear matrix inequalities (LMIs) to effectively investigate stability conditions. A TS fuzzy model is firstly established to represent the PEMFC system, and then an FUIO and sensor fault identification approach is developed. Moreover, according to the characteristics and requirements of online fault estimation, the effect of faults is also compensated via stabilizing the closed-loop system. At last, this strategy is implemented on a PEMFC system that possesses return manifold pressure and hydrogen mass sensors fault to verify its effectiveness. The most challenging task in the research is to tackle the problem of TS FUIO based fuzzy fault tolerant control strategy for sensor faults estimation.

3.1.3. Parity space methods

Parity space methods are based on state space model via parity relations to generate residuals rather than an observer, which are characterized by subspace frameworks [78]. Such method was firstly developed in literature [79], in which a subspace estimation approach called linear canonical variate analysis (CVA) is utilized to model a non-linear PEMFC stack. It utilizes high dynamic data from operation to dynamically describe the PEMFC stack's input-output behaviors, in which two concepts, i.e., Kalman filter and inverse model are applied to demonstrate the principle of CVA used for diagnosis of non-measurable inputs. It can successfully diagnose all the failure modes of the oxygen stoichiometry, and the proper coordination between the Kalman filter and inverse model is the most crucial task.

Besides, an analytical redundancy-based approach was proposed in Ref. [80], which deconstructs model linearization into eight state equations. Analytical redundancy relations (ARR) are presented with practical experimental results, which validate its effectiveness. In general, such parity space approach is used to generate residual for linearized models to further provide faults signature, and it has been utilized to detect flooding, drying, and compressor over-voltage faults under MATLAB/SIMULINK environment. Furthermore, literature [81] linearized a non-linear model into eight state equations representation to achieve model simplification, upon which transient phenomena can be effectively described. Its basic implementation principle is quite similar to the literature [80], which can effectively identify flooding and drying faults.

3.2. Black-box model based methods

3.2.1. Neural network methods

NN has been widely utilized for solving highly complex and non-linear pattern recognition or classification problem in the past decades, such that it can act as a powerful and efficient tool for fault diagnosis. A typical NN structure is demonstrated in Fig. 3.

In reference [82], an efficient static model and four experimental learning patterns are employed for the training process, which can be successfully carried out in a complete vehicle powertrain simulation. Besides, literature [83] employed an artificial NN (ANN) based training strategy to considerably increase experimental data scale for precise modelling. Such method has been successfully applied on a commercial NUVERA 5 kW PEMFC stack under the condition of physical variables relationship are unknown. The tuning of relative parameters and weights in ANNs is one the most challenging and time-consuming works.

Moreover, the Taguchi method has been combined with genetic ANN to distinguish various control factors in ANN model [84], in which the parameters of ANN are tuned by Taguchi method that has achieved high precision in output voltage estimation. The genetic ANN model can be trained and established based on the measured data from PEMFC performance test equipment to further acquire PEMFC's steady-state output voltage. Similarly, the most crucial task during the experiment is to determine the critical parameters in genetic ANN, such as its weights and biases. Furthermore, in Ref. [85], ANN based modelling was adopted to detect the variation of pressure drop to diagnose water management issues, which is characterized by easy implementation and satisfactory precision. It is mainly based on the analysis of two residuals produced by the comparison between the real operating condition of FC and the parameters determined via the NN under the normal operation condition to achieve fault classification. It has been validated on a 20-cell 1 kW PEMFC stack test bench, which can successfully diagnose drying out and flooding faults. It is critical to define threshold values based on reasonable and feasible rules.

Literature [86] developed an ANN ensemble method to enhance PEMFC system's stability and reliability, which has been verified by four common system failures, e.g., cooling system failures, fuel crossover, air delivery system faults, and hydrogen delivery system faults. Its implementation can be generally divided into three steps, i.e., (a) the dynamic model is established and tested based on MATLAB, (b) the mechanism of the aforementioned four faults is analyzed via the model and corresponding tests, and (c) the fault diagnosis ANN ensemble is established, and its framework design can be considered as the most important and challenging work.

Moreover, an independent radial basis function (RBF) network model based classification was employed for fault isolation [87,88], which can realize FC stack output prediction and various faults classification. It is implemented by classifying various features of different

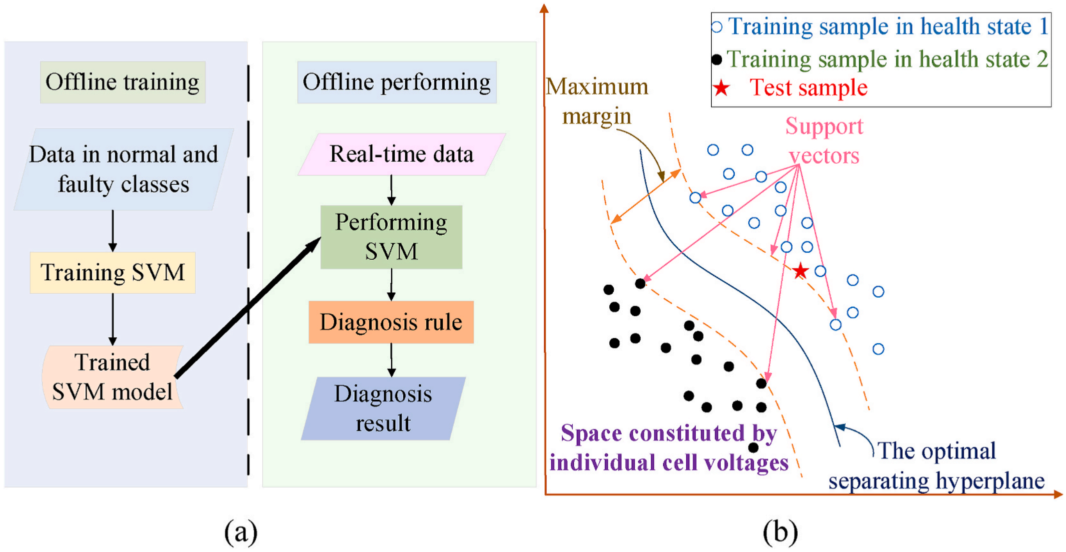

Fig. 4. SVM based method. (a) diagnosis flowchart and (b) operation principle.

faults based on model prediction error vector, upon which three general faults can be effectively diagnosed and isolated based on simulated benchmark model, e.g., actuator fault, air leakage in supply pipes, and sensors faults. Particularly, the design and establishment of neural network independent mode is the most challenging work. Furthermore, a novel modelling approach based fault diagnosis method was established by combining numerical simulation with ANN modelling principle [88]. Similar to literature [87], its main contribution is to utilize RBF model of independent mode for PEMFC output prediction, and an RBF classifier is applied to effectively diagnose the aforementioned three general faults under environmental variation.

Moreover, a fault diagnosis approach for PEMFC and DC/DC converter was devised in Ref. [89], which mainly depends on NN modelling and numerical simulation. Harmonic analysis is adopted to achieve fault classification based on the proposed sensitive model. Such method is validated on PEMFC models and interleaved DC/DC converter for drying and flooding faults diagnosis. Besides, ANN can be combined with pattern recognition techniques to realize fault classification. For instance, Hamming NN (HNN) based pattern recognition was employed for SoH monitoring of PEMFC [90], which can effectively reduce permanent internal damage risk. The representative patterns are constructed by the FC output voltage patterns of 20 PEMFCs and model parameters, and then HNN is utilized to identify the representative FCOV pattern.

3.2.2. Fuzzy logic methods

Fuzzy logic can diagnose system SoH rapidly compared with pure mathematical methods, without specific tests. In Ref. [91], a diagnosis strategy based on fuzzy clustering nature was devised to detect PEMFC systems' durability performance deviation, which can effectively present explanations and relevant solutions for these degradations. Both steady-state condition and practical transportation applications are employed to validate its performance. It is worth noting that the thorniest obstacle during the researches is that efficient FC stack models that consider durability is not available.

Besides, in order to achieve higher diagnosis accuracy and efficiency, a powerful double-fuzzy diagnosis approach has been proposed for online application to monitor water behaviors in the PEMFC stack, which is based on the combination of non-model diagnosis strategy and stack EIS spectra [92]. The double-fuzzy diagnosis approach simultaneously combines fuzzy clustering and fuzzy logic to exploit diagnostic rules automatically, in which a fuzzy clustering approach for forming data clusters and a fuzzy logic method for decision-making based on the clustering results. Such method can significantly enhance interpretability and computational efficiency. It can successfully diagnose the flooding/drying faults inside the FC stack. Literature [93] developed a novel hybrid diagnostic technique that combined simulated annealing genetic algorithm fuzzy c-means clustering (SAGAFCM) and deep belief network (DBN) combined with synthetic minority over-sampling technique (SMOTE), which can accurately estimate four different operation states with reducing the influence of unbalanced data.

The operating data produced via the tram are clustered by SAGAFCM scheme, upon which the useful data are chosen as fault diagnosis samples that contain the samples for training and testing. Nevertheless, it is worth noting that the fault samples are basically unbalanced data, hence, in order to decrease the impact of unbalanced data on fault diagnosis precision, SMOTE is then applied to generate a new training sample by supplementing the data of small sample. Moreover, the newly generated training samples are employed to train DBN to determine the specific characteristics of the fault diagnosis model. In general, such scheme is implemented in the following three steps, i.e., (a) diagnostic variables and original data selection, (b) data pre-processing, and (c) fault diagnosis. Such strategy has been utilized to diagnose three different faults, which are high deionized water inlet temperature fault, hydrogen leakage fault, and low air pressure fault, with a precision of 99.97% for the training sample and 100% for the test sample. At last, various fuzzy logic methods are tabulated in for a systematic comparison.

3.2.3. Machine learning methods

Support vector machine (SVM) is an efficient classifier based on its remarkable superiorities, such as strong ability to avoid local optimum [94], and its basic characteristics for fault diagnosis are shown in Fig. 4.

For instance, PEMFC modelling has been achieved by SVM in Ref. [95], which can predict system dynamic behavior accurately under various operation scenarios. Besides, SVM has also been utilized for fault diagnosis of PEMFC systems [96], which is combined with designed diagnosis rules for FDI, upon which a highly-compacted embedded system is established for performance monitoring while individual cell voltage is regarded as the diagnosis variable. Apart from the classification strategy, the diagnosis results are acquired via a diagnosis rule based on the raw classification results. Besides, an embedded system of the System in Package (SiP) type is devised to realize accurate monitoring of the individual cell voltage and execution of the diagnosis method. Then, the diagnosis method combined with the SiP and validated online on a 64-cell PEMFC experimental platform, which can successfully identify and isolate four common faults that are generated deliberately in real-time, e.g., low/high pressure fault, drying fault, and low air stoichiometry fault. The monitoring and analysis of voltage signals is one of the most challenging and crucial tasks for determining the health states of FCs.

Moreover, SVM was integrated into the fluidic model to achieve water management failures identification [97], in which the fluidic model is utilized for health states identification of FC stacks. The fluidic model is usually considered as a method to investigate the fluidic condition in air channels, which is critical to data labeling task. Based on the utilization of fluidic models, raw measured data can be labeled with three different labels that can denote the normal/abnormal states. Then, the labeled data act as training data for the SVM classifier. During the diagnosis process, individual cell voltages are designed as the original variables due to their high sensitivity to faults and relatively low costs compared with fluidic measurements.

On-line diagnosis can also be achieved via the combination of trained fisher discriminant analysis (FDA) and SVM models, in which FDA is employed to decrease the dimension of cell-voltage vectors and select meaningful features for the SVM classifier to achieve the final fault diagnosis. The proposed approach is validated based on the experimental measured data of a 20-cell PEMFC stack to diagnose drying and flooding faults.

Furthermore, a data-based strategy called spherical-shaped multiple-class SVM (SSM-SVM) was proposed to realize fault classification according to various health states in literature [98], in which FDA is applied to identify the features from individual cell voltages. Such diagnosis method can detect the data from a potential novel cluster without supplemental procedures. During the off-line training phase, the models of FDA and SSM-SVM both can be effectively trained on the basis of the training database (established via historical samples of cell voltages) that distributes in various classes. During the on-line execution phase, the real-time samples (cell voltages) are processed based on the trained FDA model, upon which the features can be extracted from raw data. Afterward, SSM-SVM is adopted to achieve features classification to various health states, and a 5-kW PEMFC testbench is utilized to undertake fault diagnosis of short circuit, cooling system failures, high/low air stoichiometry faults. In general, embedded computing design and on-line updating of trained models are two critical tasks in researches.

Similar to SSM-SVM, a multi-class classification method called directed acyclic graph SVM (DAGSVM) was proposed in Ref. [99], which can effectively identify useful features from raw data for fault diagnosis. Moreover, a novel hybrid method that combined orthogonal linear discriminant analysis (OLDA) and relevance vector machine (RVM) was proposed to achieve water management failures diagnosis [100], in which OLDA is utilized to extract features, and individual cell voltages are regarded as variables of diagnosis. Besides, RVM is employed to achieve lower-dimension features classification into various types, and such strategy is applied based on an experimental database extracted from a 90-cell PEMFC stack, which can achieve an on-line adaptive diagnosis of flooding fault with high accuracy. Besides, a Dempster-Shafer (DS) evidence theory based extreme learning machine (ELM) was utilized for a rapid fault diagnosis of PEMFC system [101], in which kernel ELM (K-ELM) algorithm and on-line sequential ELM (OS-ELM) are both utilized for modelling while DS evidence theory is adopted for diagnostic output fusion. The database used for verification is collected from a laboratory 14.4-kW liquid-cooled FC test platform, upon which high air stoichiometry (HAS) with four different degrees are diagnosed accurately.

3.3. Data driven based methods

3.3.1. Signal processing methods

Signals acquired from PEMFC systems can accurately reflect oscillations caused by harmonic or stochastic nature, or even both, upon which fault diagnosis can be detected by these signals changes during processing. Signal processing methods are mainly composed of two subcategories, i.e., WT and empirical mode decomposition (EMD), respectively. In Ref. [102], pressure drop signals based steady-state and dynamic performance monitoring of PEMFCs was achieved by fast Fourier transform (FFT), which can effectively detect water management failures occur in cathode or anode. The change of stack voltage can be predicted according to the water behaviors in the cathode/anode that is acquired by the dominant frequency of pressure drop signal. Particularly, such strategy is implemented on a 10-cell commercial PEMFC stack under various conditions to predict voltage increase/decrease. The main challenge is to extract data for various FC stack configurations under different operation scenarios.

Moreover, a discrete WT (DWT) analysis based diagnosis method was adopted for fault estimation and classification [103], upon which flooding problems can be effectively identified via WT packet coefficients. The diagnosis is firstly based on signal feature extraction via multiscale decomposition based on DWT, and then fault detection and classification is achieved. Such method is implemented and verified on MATLAB simulation environment, which aims to accurately identify flooding faults. Under this case, the main difficulty is to accurately determine the inner parameters for transportation. Similarly, Pahon et al. applied WT on PEMFC systems to classify different signals, such that features can be extracted and correlated to relevant operation scenarios [104], which can effectively reduce the number of required sensors and extracted parameters. Moreover, a signal based wavelet decomposition strategy was employed to identify HAS fault of PEMFC systems via existing sensors [105], which shows desirable accuracy under various input signals. The input signals used for diagnosis need no additional intrusive sensors, and wavelet decomposition is applied to achieve quick diagnosis that has been implemented on an electrochemical 40-cell stack assembly.

Besides, continuous WT (CWT) and DWT both have been validated for water management failures diagnosis in literature [106], which shows that DWT owns higher accuracy for fault localization and less computation time. FC output voltages provided the information that used for faults location based on the characteristic patterns in voltage signals, and then the analysis tool, i.e., WT is applied to classify various faults signatures/patterns, upon which flooding and drying out faults are identified. WT has also been applied to identify PEMFC's SoH according to the energy contents in voltage signals [107], upon which HIS fault was successfully detected.

Another representative signal processing method is EMD, which is an empirical, intuitive, direct, and adaptive signal processing strategy. In Ref. [108], EMD was utilized for flooding and drying FDD without pre-determined basis functions, which is mainly based on the decomposition of a non-periodic signal into a set of intrinsic mode functions. Moreover, it can acquire the basic functions via the original signal without predetermined functions, which significantly increases its applicability. The proposed strategy is devised to undertake on-line fault diagnosis on a sliding window, which adopts the output voltage of PEMFC as the only measurement. Furthermore, unlike other widely used approaches, the proposed method requires no excitation signal or stabilization period, such that the FC remains continuously available to the user, even while the diagnosis is being performed. It has been implemented on an experimental set that consists of a 50 W single cell, which shows high diagnostic accuracy in flooding and drying faults detection and isolation. The most crucial and challenging work is the design and selection of decomposition principles.

Moreover, WT was combined with multifractal formalism to investigate PEMFC behaviors under different operation conditions [109], which aims two discriminate voltage signals under different operation conditions via multifractal spectrum. In fact, the WT modulus maxima representation is deemed as a quite effective and reliable numerical technique for scanning the singularities (the sudden variations in a temporal signal) of mathematics or physical signals. The basic operation rule of such strategy is to measure the singularity spectrum (or multifractal spectrum) of voltage signal, which can quantitively determine the relationship between abnormal operation conditions and the stack voltage. An on-line non-intrusive diagnosis of FC can be validated based on an 8-cell PEMFC test bench under various operating scenarios. Besides, pressure drop can be envisaged as a useful signal for system SoH monitoring, which can be referred to as references [33,110–112] for interested readers. To further improve diagnostic performance, WT can be combined with various fault classifiers, such as ANN and fuzzy logic to improve its practical efficiency and precision in the future.

3.3.2. Pattern classification methods

Pattern classification (PC) methods are empirical classifier which derived from prior knowledge and historical data. Literature [113] proposed a PC based fault diagnosis for PEMFC aims to realize various features extraction and classification, upon which water management faults in PEMFC stacks, e.g., flooding and drying out faults can be effectively diagnosed. It firstly marks the training data, and then a feature extraction procedure and a classification method are applied to achieve fault diagnosis based on a 1 kW test bench that is utilized for a 20-cell PEMFC stack testing. The most challenging task is the design and selection of feature extraction and classification approaches.

Besides, an on-line data-driven fault diagnosis strategy method called was proposed for health states classification [114], in which the individual cell voltages are designed as original diagnosis variables and FDA is employed for features extraction for classification. Then, SSM-SVM divides extracted features into different types to accomplish the diagnosis tasks, upon which the detection and isolation of the known faults, as well as the recognition of the diagnosis decision rules and the potential novel failure modes can be realized. Besides, an online adaptation method called incremental learning method is proposed to improve diagnosis performance. Finally, a 40-cell stack based database is implemented to validate the performance of such method on water management and hydrogen supply faults. Its main challenge during the application is its strong dependence on the data of specific fault modes.

Similarly, a sphere shaped multi-class SVM (SSM-SVM) was applied for FDI of PEMFC systems [115], in which a time-series analysis tool called shapelet transform was adopted for discriminative features extraction from the diagnosis observations. Then, the SSM-SVM is employed in the feature space to achieve FDI, which has been verified on a 64-cell PEMFC stack to diagnose high/low pressure fault, drying fault, and low air stoichiometry fault. Besides, FDA was combined with DAGSVM for useful features identification from raw data and features classification into different health states [116], which is promising for on-line applications. One main advantage of such method is that only single cell voltages are chosen as the variables for diagnosis while additional measurements are not required. During the off-line training stage, the samples for training in the dataset are distributed in various classes that represent while marked samples are utilized in the training of FDA and DAGSVM for feature extraction and classification, respectively. During the on-line operation stage, the features of real-time data are extracted based on the established FDA model, the features of real-time data are firstly extracted while DAGSVM is applied to classify different features into various classes. Two different stacks, that is, an 8-cell stack and a 40-cell stack are carried out for five common faults detection and isolation, e.g., short circuit, cooling system failure, HAS/low air stoichiometry, and CO poisoning. Similarly, its largest challenge is the acquirement of abundant training dataset that contains the data from a large variety of fault categories. In literature [117], parity space principle has been combined with multi-class SVM to achieve FDI, in which normal processing data can be directly estimated by parity space without modelling. This method contains both off-line and on-line testing. During the off-line operation, parity space is extracted from normal operating data while faulty data filtered from normal data based on parity space are conveyed to multi-class SVM for training. During the on-line diagnosis, the FDI for real-time data is achieved via the acquired parity space and trained multi-class SVM. Case studies are carried out for both normal operation conditions and faulty conditions while the input and output data are measured with the sampling frequency of 1 Hz. Four different faults, e.g., short circuit, cooling system failure, and HAS/low air stoichiometry are diagnosed based on a 40-cell 5 kW PEMFC testbench.

Besides, a novel feature extraction and pattern classification strategy with application-specific integrated circuits are proposed in Ref. [118], in which evaluation criteria are firstly presented for its on-line fault diagnosis, which can achieve accurate measurement of multi-channel signals. This method is implemented based on powerful feature extraction and pattern classification techniques on the basis of FC voltage signals processing. Both 1 kW and 10 kW experimental platforms for testing are carried out, upon which seven different faults, e.g., drying, flooding, short circuit, cooling system failures, HAS, low air stoichiometry, and CO poisoning are diagnosed. Based on this study, it is noteworthy that the measurement of individual cell voltages is one challenging but also promising solution.

Moreover, a hybrid diagnosis method that combined WT modulus maxima and pattern recognition methods was devised for fault diagnosis [119], which can achieve on-line and non-intrusive identification. This study aims to develop a powerful tool for FC malfunction diagnosis that is based on a minimum of instrumentation, which relies on the information in the singularities of the voltage signal to describe the operation condition of the FC in a dimensionally reduced representation. In order to quantitively reflect the singularities degree of the voltage based on the designed operation faults, continuous wavelets and multifractal formalism are adopted to determine the singularity spectrum of the voltage signal. This method utilizes the non-linearities associated with discontinuities introduced in the dynamic response data resulting from various failure modes. Indeed, the singularities signature of fault modes of PEMFC is determined based on multifractal spectra computation. The excellent classification rate shows WT modulus maxima based multifractal spectra can achieve excellent fault features classification. It has successfully diagnosed anode/cathode flow fault, inlet gas pressure fault, cooling circuit temperature fault, and CO poisoning.

3.4. Statistical methods

3.4.1. Principle component analysis method

Principle component analysis (PCA) method can effectively reduce the dimensionality of process variables while retaining the most valuable information contained in variables. In Ref. [120], combined PCA and multi-sensor signals were employed to enhance the system's diagnostic performance. It basically consists of two steps, i.e., (a) the correlations among various sensor signals are determined based on sufficient sample data training and (b) the main structure of online fault diagnosis is designed based on the simplified comprehensive index. Then, an experiment is undertaken to validate its specific performance, in which a voltage sensor fault and a system-level fault are diagnosed and dealt with. In particular, such method can timely diagnose and distinguish the fault based on the simplified comprehensive index, which can prevent the FC stacks from severe damage caused by inefficient operation. On this basis, two typical faults, e.g., a single sensor fault and a serious system failure can be rapidly identified based on two steps, i.e., sensor signals features are firstly extracted based on training data, and then a simplified statistic index based on-line diagnosis strategy is designed.

3.4.2. Bayesian network methods

Bayesian network (BN) is a typical and representative statistical classifier, which mainly consists of two steps, i.e., determine network structure and conditional probabilities calculation based on measured data. In Ref. [121], BN was utilized for on-line monitoring and diagnosis, in which effect relationship among processing variables can be explicitly qualified and quantified. Fault conditions of some variables are recorded containing some variables that are difficult to monitor in a real machine. It is worth noting that the record of all relevant variables is critical for the establishment of the network structure avoiding hidden variables, especially in intermediary layers. The fault diagnosis of such method is based on the on-line monitoring of easy-measured variables, upon which air-reaction blower faults, refrigeration system fault, fuel crossover fault, and hydrogen pressure fault are diagnosed. The development of a fault diagnosis supervisor is based on the comprehensive analysis of the FC operation under fault conditions. Its major challenge is the design of BN structure and the adjustment of its relevant parameters. Besides, a fault records database has also been created to save computational sources. Similarly, literature [122] developed a BN based graphical-probabilistic structure based on the utilization of databases and probabilistic methods to identify fault causes in PEMFC models according to observed effects, upon which an on-line supervisor can be established to diagnose air-reaction blower faults, refrigeration system fault, fuel crossover fault, and hydrogen pressure fault. It employs a diagnosis strategy only at one specific moment that any abnormal variable evolution is detected, which aims to connect this evolution with the characteristics of initial faults. The following step is to generate a vector containing the value of all variables, which corresponds to one certain case in the database with all variables' value in a certain period. Based on the experimental results, it can be seen that the cause-effect relationship can be accurately reflected, which further validates the implementation feasibility of a Bayesian network based on-line supervisor for fault diagnosis. Future studies still need to put high emphasis on the research of network structure design, fault reasons investigation, and fault treatment process.

Besides, a high voltage impedance spectrometer was integrated with BN to realize classification and diagnosis of PEMFC systems [123], which is quite suitable for cases with high dimensional inputs. Six operation conditions (five fault types) are differentiated by twelve input variables. Meanwhile, an optimized Bayesian classifier is devised based on the investigation of parameters that can influence classification performance to achieve an effective fault diagnosis, which can detect 91% of samples included in a validation database. Case studies including fault effects in FC, improvement of BN structure for fault diagnosis, and fault treatment processes still need further studies. It has been verified on an experimental 20-cell assembly using EIS, and then the BN is employed to achieve the diagnosis of drying and flooding.

3.5. *Experiments testing methods*

3.5.1. *Magnetic field measurements methods*

In reference [124], an external magnetic field measurement based non-invasive strategy was proposed to distinguish FC current distribution, in which a truncated singular value decomposition technique has been employed for stabilization. A set of sensors that are sensitive to current heterogeneities are devised and employed, which are based on several magnetic sensors with high sensitivity and high dynamic equipped on three areas around the PEMFC stack. This work employs 30 sensors to conduct the magnetic tomography of a PEMFC stack that consists of 100 single cells, upon which various faults of PEMFC stacks, e.g., flooding and drying faults can be located based on magnetic field

Table 2
Summary and comparison of six types of PEMFC fault diagnosis methods.

Classifications	Methods	Benefits	Limitations	Application conditions
Analytical model-based methods	Parameter identification methods	a) High practicability and robustness with low cost; b) Accurate and fast on-line fault diagnosis.	a) Validation on more complex models; b) On-line diagnosis test.	a) Fault detection of individual cells and entire stack; b) Hardware and software implementation.
	Observer based method	a) High stability and efficiency; b) Simplified complex nonlinear PEMFC model.	a) On-line fault detection; b) Accuracy and applicability improvement.	a) State estimation and fault reconstruction; b) FDD with consideration of time delay.
	Parity space methods	a) On-line implementation; b) Reduced model complexity.	a) Complicated working conditions test; b) Non-linear extension.	a) Diagnosis for all failure modes of the oxygen stoichiometry; b) Diagnosis of flooding, drying, and compressor over-voltage.
Black-box model-based methods	Neural network methods	a) High precision with reasonable computation resources; b) Easy-to-monitor and high robustness	a) Validation on more complex systems; b) Diverse fault diagnosis validations.	a) On-board system diagnosis; b) FDD under varying load disturbance.
	Fuzzy logic methods	a) Promising results and easy implementation; b) On-line application with high accuracy and efficiency.	a) Model improvement on durability consideration; b) Combination with control strategies.	a) Performance degradation monitoring for FC stack; b) Health states estimation for PEMFC system.
	Machine learning methods	a) Potential failures can be detected with high accuracy; b) Faults can be detected and isolated in real-time.	a) Fault diagnosis in the high dynamic process; b) Robustness improvement with consideration of disturbances.	a) High speed diagnosis without data pre-processing; b) On-line adaptive fault diagnosis.
Data driven based methods	Signal processing method	a) Simple structure, low-cost, and minimal stack monitoring; b) High robustness and precision.	a) Real-time fault diagnosis; b) Wider study on fault tests.	a) Steady-state and dynamic behaviors investigation; b) Flooding and drying diagnosis.
	Pattern classification methods	a) Promising results and easy implementation; b) On-line application with high accuracy and efficiency.	a) Model improvement on durability consideration; b) Combination with control strategies.	a) Performance degradation monitoring for FC stack; b) Health states estimation for PEMFC system.
Statistical methods	Principle component analysis method	a) Simplified fault diagnosis index.	a) Tolerant control system establishment.	a) On-line fault diagnosis of PEMFC system.
	Bayesian network methods	a) High execution efficiency; b) Easy implementation.	a) Network structure improvement; b) In-depth fault treatment study.	a) On-line supervisor for fault diagnosis; b) Fault characterization and diagnosis.
Experiments testing methods	Magnetic field measurements method	a) High sensitivity and reduced maintenance costs; b) Non-intrusive and easy to replicate.	a) Robustness improvement; b) On-line applications.	a) Root causes identification of FC; b) Fault diagnosis for FC stack o under varying operation modes.
	Fault conditions test method	a) Excellent predictive ability; b) Promising location efficiency and estimation accuracy.	a) Development of fault tolerant control strategies; b) On-line FDD.	a) Water management failures diagnosis; b) Fault diagnosis for different types of stacks.

Table 3
Summary on thirteen other techniques for PEMFC fault diagnosis.

Methods	Year	Characteristics	Applications	Merits	Drawbacks	Future developments	Complexity
Electrical signals based method [130]	2008	Voltage pattern based classification	Localization of failed cells in PEMFC stacks	Satisfactory identification accuracy.	Lack of sufficient discussion on the mechanism of employed method	High power availability	*
Fault tree analysis method [131]	2011	Fault tree analysis based estimation	Degradation degree evaluation of system components	Acceptable identification accuracy	Lack of verification on real PEMFC system	Validation on more fault modes	**
Leak diagnosis method [132]	2014	Based on practical guidelines and explanation of FDD	Leak sources and types in FC stacks detection	Desirable detection accuracy	The degradation rates utilized are subject to uncertainties	Exploitation for more efficient hybrid methods	**
Causal and Fault Trees Analysis [133]	2015	Based on analysis of FC's internal state	Degradation degree estimation of FC	High accuracy on aging process evaluation	High sensitivity to nitrogen flow rate	Validation for more fault types	***
Current steps technique [134]	2016	Based on responses correction and virtual stack reconstruction	Water management of a 500 W PEMFC stack	Satisfactory classification performance	Lack of in-depth analysis of the evolutions, and internal interactions	Overall structure simplification	**
Expert diagnosis method [135]	2017	Based on fuzzy logic and expert knowledge	Water management failures diagnosis	High diagnostic accuracy and speed	False-positives might appear	Other degradation modes validation	****
Structural analysis and Causal Computation method [136]	2017	FDI based on stack voltage and temperature sensors	A set of faults correspond to auxiliary components, stack, and sensors are diagnosed	Strong FDD ability for any system layout or model structure	More advanced measurements need to be applied	Higher complex scenarios validation and on-line application	**
Reservoir Computing (RC) [137]	2017	Based on virtual recurrent neural network	CO poisoning, low air flow rate, defective cooling, and natural degradation diagnosis	High efficiency and low computation cost	The stability of diagnosis accuracy needs to be further improved	On-line realization	****
Decision-making Tree Classifier [138]	2018	Pre-processed data classification	Drying and hydrogen leakage faults identification of a PEMFC stack	High diagnostic accuracy	Lack of verification on real PEMFC system	On-line diagnosis under high data dimensions	**
Generic analysis tool [139]	2018	Voltage pointwise singularity strengths based analysis	Operation faults identification on two different PEMFC stacks	Satisfactory performance for more complicated states	Lack of validation under various operation conditions	Real-time estimation under various operation conditions	*****
Sensor sensitivity based method [140]	2018	Abnormal sensors detection for fault measurements	Unreliable sensors can be identified during PEMFC operation	High accuracy and reliability	Feature threshold setting needs to be improved	Feature threshold definition	**
Hierarchical fault diagnostic method [28]	2019	Fault diagnosis based on the multi-stage approach	On-line FDD of a stack and balance of plants (BoPs) in a PEMFC system	Desirable accuracy	Lack of verification on real PEMFC system	Improvement of FC health management system	****
Sensor selection method [141]	2020	Investigation on information in sensors without numerical modelling	Water management faults and ancillary systems faults identification	High fault identification quality and reduced maintenance cost	Lack of validation under various operation conditions	Combination of mitigation strategies	*

measurements. In general, 2D or 3D variations of current density distribution caused by water management failures or material degradation can be identified by external magnetic measurement in a PEMFC stack. In future studies, the local electrochemical measurement has the potential to apply in degradation analysis on stack-level and act as an efficient tool to mitigate the degradation effects caused by load cycles or faults. It is quite meaningful for diagnostics and prognostics, which can be devoted to the development of fault tolerant control strategies. Besides, more focus should be placed on the development of new generations for more robust stacks with an optimized design based on the observation of the interaction among different cells.

Similarly, a magnetic field induced by FC stack internal currents was utilized as a monitoring tool [125], in which a 3-D simulation can accurately reflect the relationship of cause and effect between FC faults and corresponding magnetic signatures. Due to the current density distribution might be modified via the faults in FCs, which can further change the resulting magnetic field. After determining the electrical operation point of FCs, the magnetic field is calculated via the magnetic vector potential. The main purpose of this work is to design a series of guiding principles that can promote the application of nonintrusive FC malfunctioning detection. Then, the faults that can be easily detected via magnetic measurement methods are determined, upon which the precautions for relevant measurements and diagnosis are investigated. It has been validated to diagnose anode/cathode channel defects under the simulation environment. In general, the simulation results validate the effectiveness and reliability of such magnetic field measurements, test bench design, and the associated sensors. Its implementation on an experimental test bench is a challenging and promising research direction in further studies.

3.5.2. Fault conditions test methods

Fault conditions test methods mainly rely on fault operation modes, which aim to obtain system optimal operating state parameters via fault operation experiments under different operation conditions to guarantee the system's stable and normal operation. In literature [126], flooding experiments under different scenarios are designed and the hydrogen pressure drop is studied based on a two-piece PEMFC. A two-level characteristic of hydrogen pressure drop is investigated combined with water droplet accumulation in channels. It undertook water flooding experiments under various conditions to divide the flooding process into four different stages, upon which an efficient water management strategy is proposed to prevent PEMFC from flooding nor dehydration. It is implemented on an FC testing system that consists of FC assembly, along with mass flow controllers, sensors, etc. Experimental results indicate that the growth rate of the two levels is barely influenced by current and temperature, while largely influenced by pressure and hydrogen stoichiometry. The growth rate can be determined based on the channel dimensions and is highly matched with simulation results, upon which the boundary to avoid flooding is also defined.

The design of experiments under extreme conditions that can validate its water management ability is one of the most significant challenges. In Ref. [127], a superposition principle based fault diagnosis method was developed, in which cell voltage drop acts as a critical index to reflect system nonlinearity degrees due to the linear system turns into a nonlinear system. For the purpose of detecting the sharp cell voltage drop, an FC stack is excited by two input direct test-currents that possess smaller amplitude than an operating stack current.

This approach developed a simulation model based on superposition principle to diagnose stack degradation, in which the linear case and the nonlinear case of the FC stack are defined as normal state and abnormal state, respectively. It has been experimentally verified via the static experiment and the dynamic experiment under MATLAB/SIMULINK testing environment. Future studies can be focused on the design and application of an intelligent decision-maker, which aims to develop improved diagnosis strategies combined with fuzzy logic and artificial neural network (ANN).

Besides, an efficient temperature and current density distributions based diagnosis strategy for a single PEMFC was proposed to diagnose flooding and drying out faults [128]. In general, this method is implemented based on two steps, i.e., a 3D model that can estimate local parameters is firstly established, and then an ANN is employed to achieve fault localization within various segments of each FC. The investigated faults in this study, e.g., flooding and drying with two different severity degrees respectively are simulated via generating abnormal operating condition variations for water management, such as temperature, gas relative humidity, stack current density, etc. Besides, in order to train the ANN model to design an ANN algorithm for localization and evaluation of flooding and drying faults, the faults are also simulated in certain zones of the 3D model. Similarly, a temperature distribution based fault diagnosis technique was devised with benefits of simplicity and convenience [129], in which only thermocouples are used while voltage sensors can be removed to reduce costs. The variation of voltage results from the temperature changes in FC stacks is the main focus during the investigation. Besides, all parameters are detailedly discussed and verified via experimental tests on individual cell and FC stacks. One of its most prominent merits is that it doesn't need to measure the voltage during the fault detection due to it only depends on the FC stack temperature variation.

4. Discussions

4.1. Overall summary

In order to undertake a systematic comparison of the aforementioned methods, a critical evaluation is provided in this section which aims to elaborately summarize the benefits/contributions and shortcomings/limitations of each subcategory based on their basic characteristics to offer guidance for future in-depth investigation, as illustrated in Table 2.

4.2. Other fault diagnosis techniques

Besides the aforementioned fault diagnosis strategies, plenty of other advanced fault diagnosis techniques have also been utilized in PEMFC fault diagnosis. An overall and systematic summary is presented chronologically in Table 3.

5. Conclusions and perspectives

Inspired by widespread interests towards fault diagnosis of PEMFC systems, a critical classification and summarization on different diagnosis approaches for PEMFC systems is undertaken in this paper, which divides various approaches into five main categories. The techniques in each category are systematically introduced and analyzed based on a detailed and comprehensive comparison. In general, this paper aims to provide a state-of-the-art guidebook for related researchers/engineers. At last, six perspectives/recommendations for future researches are summarized as follows:

- *Improvement on system fault models.* A common and standardized PEMFC system fault model which possesses strong practicability for fault diagnosis has not been developed yet due to its complex internal operation mechanism, such that development and implementation of diagnosis methods are largely restricted. Thus, it is critical to develop a comprehensive and general system fault model with consideration of various faulty conditions, upon which most of common faults can be detected and predicted for a more precise diagnosis;
- *Multiple fault diagnosis under various conditions.* Most of the existing fault diagnosis methods are devised and validated completely under laboratory conditions. However, PEMFC systems usually operate under complicated or even severe conditions, such as transportation applications, temperature change, mechanical vibration, and load disturbance. These conditions can somehow distort fault characteristics and information, thus multiple faults might simultaneously exist in PEMFC systems and fault features might influence each other, which considerably increases the complexity of fault diagnosis. Thus, the development of multiple-fault real-time diagnosis strategies is required for practical engineering applications;
- *Development of on-line & hybrid fault diagnosis methods.* With ever-increasing applications of PEMFC systems on medium/high power fields, such as automobiles and rail locomotives, it is critical to ensure a safe, reliable, and stable operation of whole systems. Therefore, on-line fault diagnosis methods of PEMFC systems are extremely important to guarantee a reliable and timely response for practical applications. Besides, the combination of multiple single based methods can effectively utilize their superiorities simultaneously, which can considerably improve diagnosis structure and efficiency, such as ANN and fuzzy logic, ANN and WT, etc. Besides, future researches also need put higher emphasis on fault tolerance control strategies development, upon which fault diagnosis and controller design can be combined to enhance overall systems reliability and durability;
- *Combination of fault diagnosis and control strategy.* Based on mature fusion intelligent technologies, fault diagnosis strategies and corresponding reliable control strategies can be effectively integrated. Based on fault diagnosis and location techniques, the impact of various failures can be remarkably reduced or even eliminated via reasonable control strategies, which can considerably enhance operation stability and reliability of PEMFC systems. Simulation and industrial applications can further verify its implementation feasibility and reliability, which is of great significance to practical applications;
- *Improvement on ancillary systems components.* PEMFC systems require collaborative cooperation of various system components, such that high component stability under various operation conditions is required. For instance, the core FC component is fragile and vulnerable to severe working conditions, especially for harmful gases, which can cause irreversible damage to FCs that leads to rapid and significant FC performance losses. Hence, FC filters are quite necessary to isolate and filter harmful substances in the air, and sensors can also be employed to detect whether pollutant concentration exceeds the standard to further determine whether filters need to be replaced;
- *Researches on fault diagnosis methods of multiple high power PEMFC systems.* In recent years, PEMFC technology in transportation applications has achieved rapid development. However, one set of PEMFC systems apparently cannot satisfy current power demand, such that exploitation and utilization of multiple high power PEMFC systems

are imperative. However, current fault diagnosis methods of PEMFC systems are only limited to a single medium and small power supply. Therefore, studies on fault diagnosis methods of high-power availability, e.g., multi-stack generators under large-load change, are a targeted and core development direction of PEMFC fault diagnosis technologies in future.

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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