Investigation of feature effectiveness in fault diagnosis of PEM fuel cell system

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Abstract—**This paper investigates effectiveness of various features in fault diagnosis of polymer electrolyte membrane fuel cell (PEMFC) system, including RMSF (root mean square frequency), ACSD (autocorrelation standard deviation) and kurtosis. Test data is collected from a PEMFC system with various conditions, such as normal operation, flooding and drying out scenarios. By extracting selected features from PEMFC voltage, the performance of various features in isolating PEMFC states is investigated using k-means clustering. Results demonstrate that the combination of RMSF and ACSD could provide reliable fault diagnostic performance. Moreover, kurtosis might be used as a fast diagnostic indicator for various PEMFC degradation mechanisms.**

Keywords-PEM fuel cell; fault diagnosis; feature extraction; kurtosis; k-means clustering.

I. INTRODUCTION

Due to the scarcity of petroleum energy and the concern of environmental pollution, alternative energy sources used in applications including portable power and vehicle power systems have attracted increasing interest in the past few decades. Among various alternative energy sources, PEMFC system receives more interest owing to its advantages of zero pollution and high efficiency. Nevertheless, reliability and durability are still bottleneck to be surmounted for its large-scale commercialization.

Since a PEMFC system integrates multiple disciplines, including chemistry, electrical science, machinery and thermal management, its performance decay can be caused by various mechanisms, such as inappropriate water management strategy, and contamination of MEA, fuel starvation, etc. Therefore, it is necessary to identify different PEMFC malfunctions, for adopting mitigation techniques to lengthen the PEMFC system lifespan. On such basis, several researches are performed regarding PEMFC fault diagnostic techniques, consisting of model-driven techniques, data-based approaches, and knowledge-driven methodologies. With model-driven approaches, mathematical models of PEMFC and its ancillary systems should be established, and malfunctions can be distinguished by analyzing the outputs of the model and experimental data [1-2]. However, the complexity of PEMFC system increases the difficulty of constructing a precise model [3-4]. With regard to a data-based approach, data processing methods could be taken using the test data from PEMFC systems, where features representing PEMFC actual state could be extracted and discriminated [5-9]. Knowledge-based approaches could integrate prior information and expert knowledge about the performance degradation mechanisms of PEMFC. On this basis, inference analysis is carried out to identify various faults [10-11]. It should be noted that massive data from PEMFC systems have to be processed so as to obtain prior knowledge, and knowledge obtained from experts may be even contradictory regarding PEMFC performance degradation mechanisms. In addition, the combination of the above methods, i.e. hybrid approaches, has also been applied [12].

For the above reasons, data-based methodologies have been applied more frequently in fault identification of PEMFC systems, where extraction of features representing actual PEMFC state becomes a key factor for reliable fault identification. Benouioua et al. [13] presented a technique of feature extraction for identifying PEMFC faults, where PEMFC faults were identified by applying pattern recognition technique to features extracted with wavelet transform. Li et al. [14] extracted features from individual cell voltages, then a dimensionality reduction based classifier was developed to distinguish features at different states, including flooding, membrane drying out and normal operation. Kim et al. [15] calculated the values of ACSD and RMSF using PEMFC stack voltage signal at hydrogen starvation and air undersupply conditions, and earlier detection of hydrogen starvation and air undersupply could be achieved. In [16], PEMFC voltage was decomposed using DWT (discrete wavelet transform) for obtaining different signature components, and PEMFC flooding and dehydration could be distinguished with decomposed details coefficients. Mao et al. [17] proposed a failure identification method for processing multi-sensor data, where several signal processing techniques, including dimensionality reduction, feature extraction and selection methods are employed. Results indicated that the proposed method can effectively distinguish various failures of PEMFC system.

According to previous studies, it could be found that various features were extracted and applied in different PEMFC system fault identification, while only limited researches have been performed to compare various feature performance in fault

Hundred-Talent Program-Young Talents 2018-050 (Chinese Academy of Sciences)', and 'Anhui Provincial Natural Science Foundation 1908085ME161'.
978-1-7281-0860-5/19/$31.00 ©2019 IEEE

identification of PEMFC systems, which increases the difficulty in selecting proper features in practical PEMFC applications. Moreover, some features achieving reliable fault diagnostic performance in other applications haven't been implemented in PEMFC systems, which also requires further investigation. Therefore, a comparative study regarding to performance of different features, including features used in fault identification of PEMFCs and other applications, is urgently required.

This paper investigates effectiveness of various features in fault identification of PEMFC, where various conditions of PEMFC were tested, including normal operation, membrane drying out and PEMFC flooding. Two commonly used features, i.e., RMSF and ACSD are selected in the paper. Although they have been used in previous studies for PEMFC fault identification, but their effectiveness in both drying out and flooding scenarios hasn't been fully clarified. Moreover, kurtosis is also selected in fault identification of PEMFC, which was widely used in failure identification of other systems [18-19]. In Section II, the details about extraction of different features are presented. Section III presents the details of PEMFC test bench and test data at different conditions. The performance of classification using these three features are demonstrated and compared in section IV. Section V provides the conclusions.

II. FEATURE EXTRACTION METHODS

In this section, extraction algorithms of three features, including RMSF, ACSD, and kurtosis, are presented.

A. Kurtosis

Kurtosis is a numerical statistic reflecting the distribution characteristics of random variables and is a normalized fourth-order central moment. When different PEMFC faults occurred, the output voltage curves would decline following different path, which will lead to variation of kurtosis. Therefore, kurtosis has the ability to inflect the impact composition of a signal, which can be calculated with Eq. (1):

$$k = \frac{\sum_{i=1}^{N}(Y_i - \overline{Y})^4 / N}{s^4} \tag{1}$$

where $Y_i (i = 1,2,3...N)$ stand for univariate data, i.e., fuel cell voltage in the analysis, $\overline{Y}$ is the average value of the signal, s served as the deviation, and N is data length.

B. RMSF

In this analysis, a windowed fast Fourier transform is implemented to fuel cell voltage for frequency analysis, which can be written as follows:

$$w_H(n) = (1-\beta) - \beta\cos(\frac{2\pi n}{N-1}) \tag{2}$$

$$X(k) = \sum_{n=0}^{N-1}(x(n)\times w(n))e^{-j\frac{2\pi}{N}nk}$$

$$= \sum_{n=0}^{N-1}(x(n)\times w(n))W_N^{nk} \tag{3}$$

where $w_H(n)$ stands for window function, $X(k)$ works as frequency ingredients value from various parts, and N serves as window width. In this study, $RMSF$ of the frequency component can be calculated as follows:

$$RMSF = \sqrt{\frac{1}{n}\sum_{k=1}^{n}X(k)^2} \times 10^5 \tag{4}$$

C. ACSD

As the correlation measure for a data with a lagged version of itself, autocorrelation is similar to the calculation of correlation between two different time series. Autocorrelation function is usually utilized to strengthen the harmonic feature of a signal. For a certain signal $x(t)$, its autocorrelation function, $Rxx(t)$ can be calculated with Eq. (5):

$$R\mathrm{xx}(t) = \sum_{k=0}^{N-1}x(k)\cdot x(t+k) \tag{5}$$

where N serves as the bound of sampling scope width. In the study, Eq. (5) is used with the output voltage of PEMFC. Then standard deviation of autocorrelation function is calculated with Eq. (6):

$$ACSD = \sqrt{\frac{1}{N}\sum_{k=1}^{N}(Rxx(k)-\mu)^2} \times 10^7 \tag{6}$$

where μ stands for autocorrelation function arithmetic average. $ACSD$ is utilized to monitor the changing situations of autocorrelation function and frequency variation of output voltage signal with the operation time.

III. PEM FUEL CELL TEST RIG AND TEST DATA

A. PEMFC experiment description

In the test, a PEMFC system with rated power of 80W was used, including reactant gas supply systems, coolant system, and a PEMFC stack. Fig. 1 illustrates the PEMFC test bench.

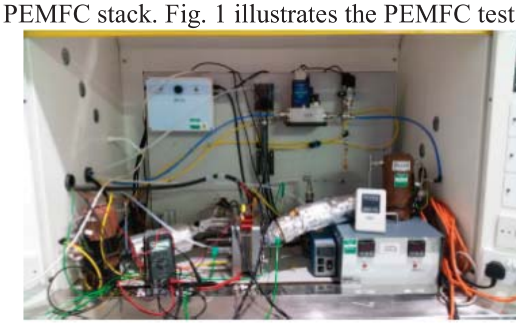


Figure. 1. Test bench of PEMFC system

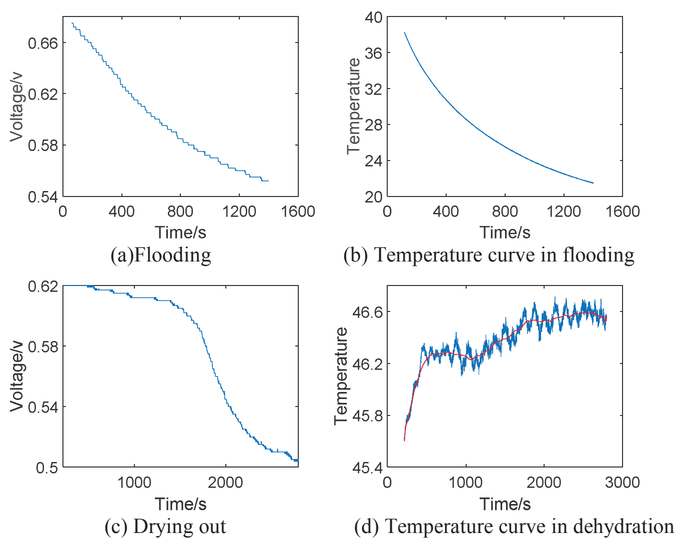
The fuel cell with active area of $100cm^2$ was used in this test, and was fabricated by Pragma Industries using commercial PEMFC materials and technologies, including a PEM, silicone-sealing gaskets, and carbon diffusion materials. Table I lists the technical parameters of tested PEMFC.

TABLE I. Tested PEMFC variables

Variable	Value
Thickness of membrane(μm)	25
Surface area(cm^2)	100
Loading of platinum(mg / cm^2)	0.2
Thickness of gas diffusion layer(μm)	415

B. *Test procedure*

For acquiring different PEMFC fault scenarios, i.e., drying out and flooding in the analysis, two different tests are carried out with test bench in Fig.1. Liquid water within PEMFC was produced by reducing the temperature (Fig. 2(b)) of the fuel cell, which can cause liquid water concentration preventing reactants from entering the catalyst layer, thus generating flooding and resulting in a decline of PEMFC output voltage, as observed from Fig. 2(a). Membrane drying out was accomplished by injecting un-humidified reactants into the PEM fuel cell to increase the stack temperature and the temperature rise curve which had been smoothed was exhibited in Fig. 2(d), where membrane dehydration could be achieved and fuel cell voltage would drop, and this can be found in Fig. 2(c).



(a)Flooding (b) Temperature curve in flooding

(c) Drying out (d) Temperature curve in dehydration

Figure. 2. Different PEM fuel cell fault scenarios in the test.

C. *Test data*

Fig. 2 shows that PEMFC faults could be easily discriminated from normal operation by analyzing the voltage drop, but voltage drop could be caused by either f drying out or flooding, although they follow different degradation paths, i.e., the transition between normal operation and fuel cell fault would be different for various degradation mechanisms. It can be found from Fig. 2(b) that voltage drop at flooding scenario is consistent with the reduction of temperature, indicating the gradual generation and accumulation of liquid water in this case; while at dehydration shown in Fig. 2(d), the initial temperature rise could not change membrane resistance and thus fuel cell voltage significantly, but when the temperature rise reaches to a threshold value, approximately 46.2℃ in this case, which is determined by fuel cell physical property, a slight further temperature increase could lead to clear voltage drop. Therefore, flooding and dehydration could cause voltage drop through different paths, which can be utilized to discriminate various faults. This will be further investigated in the following section.

In addition, considering the fact that the fuel cell flooding is reversible fault, which can be removed using effective mitigation strategies, while membrane dehydration is irreversible fault, but its effect can still be reduced with proper actions. Thus the discrimination of PEMFC two fault scenarios is required, such that its reliability and durability can be guaranteed, which will be investigated in the following section.

IV. COMPARATIVE STUDY OF VARIOUS FEATURES IN PEM FUEL CELL FAULT DIAGNOSIS

As described in section II, three features, including RMSF, ACSD, and kurtosis, are extracted from fuel cell voltage at different fault scenarios. Furthermore, each voltage is separated into six segments to represent evolution of fault severity, thus a total of 18 features could be obtained in each fault scenario. Fig. 3 depicts the classification results between flooding and dehydration using three features. It should be noted that value β in Eq. (2) is set to be 0.46 based on the previous studies, and all the features are normalized for better illustration purpose.

As can be seen from Fig. 3, drying out and flooding are not discriminated accurately with all three features. After further analysis, the kurtosis from two failure scenarios has similar values, thus could not provide positive contribution to fault identification, and should be removed from the analysis. Fig. 4 shows the fault discrimination results using RMSF and ACSD.

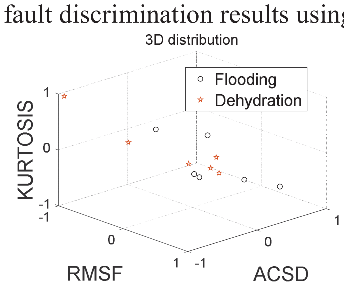
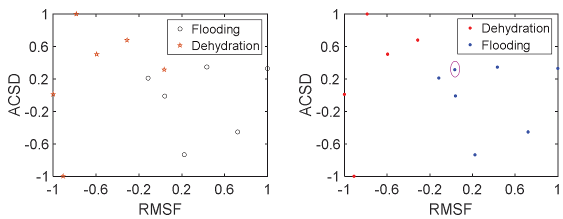


Figure. 3. Fault discrimination results using three features

It can be found from Fig. 4(a) that with RMSF and ACSD, these two different fault scenarios can be well distinguished. This can be further confirmed by using k-means clustering technique, an iterative clustering algorithm using distance as similarity index to find k categories from a given dataset, and the sort result was depicted in Fig. 4(b), where most faults can be classified correctly, only one membrane dehydration fault is misclassified as fuel cell flooding, which is the last segment in the voltage signal at membrane dehydration. The possible reason might be that at the end of transition period from normal operation to fault, fuel cell flooding and membrane dehydration have similar influence in PEMFC behavior.

Furthermore, kurtosis performance in identifying PEMFC failures is further investigated. The evolution of kurtosis during fuel cell operation at different fault scenarios is shown in Fig.5. It could be observed from Fig. 5 that kurtosis shows clearly different evolutions at PEMFC two fault scenarios. At the beginning stage of flooding scenario, kurtosis would have fluctuations at higher level, and reduce at the end of transition period; on the other side, kurtosis at membrane dehydration would remain at lower level, and jump to higher fluctuation at the end of transition period. On this basis, the kurtosis can be used as fast indictor for different faults, as various degradation paths could be represented accurate using kurtosis. In the future study, kurtosis performance in fault identification of different PEMFC systems would be investigated, so that its robustness in PEMFC fault identification can be validated.



(a) RMSF and ACSD (b) k-means clustering

Figure. 4. Fault discrimination results using RMSF, ACSD and k-means clustering

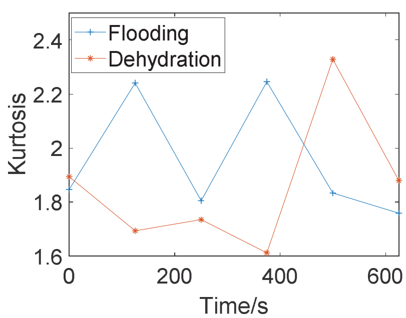


Figure. 5. Kurtosis change over time in two fault modes

V. CONCLUSION

In this study, the effectiveness of three different features in identifying PEMFC failures is studied, where PEMFC data containing drying out and flooding is used. Two commonly used features, including RMSF and ACSD, are selected in the analysis, while kurtosis, which has not been utilized in PEMFC system failure discrimination, is also included in this study.

From the results, it can be concluded the combination of RMSF and ACSD could provide accurate discrimination for drying out and flooding scenarios, while kurtosis could be used as fast indicator for fault discrimination.

In the future work, the consistency of kurtosis in identifying failures of different PEMFC systems will be studied. Moreover, more features from both time and frequency domains would also be included in the analysis. From the results, a guideline regarding to proper selection of features in identifying PEMFC failures could be provided.

ACKNOWLEDGMENT

This work is supported by 'Hundred-Talent Program-Young Talents 2018-050 (Chinese Academy of Sciences)', and 'Anhui Provincial Natural Science Foundation 1908085ME161'.

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