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Journal of Chemical and Pharmaceutical Research, 2014, 6(5):1664-1670

Research Article

ISSN : 0975-7384
CODEN(USA) : JCPRC5

Simulation research of PEMFC gas starvation diagnosis based on wavelet analysis and harmonic theory

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ABSTRACT

Using wavelet and harmonic methods, he paper has developed a new approach for PEMFC gas starvation diagnosis. By a self-designed 3D diagnostic PEMFC distributed parameter model, the research established a model-based diagnostic method, which is more simple and economical compared with experiment methods. Further, based on the model and its UDF (user-defined functions), the typical faults of gas starvations in anode, cathode and both side, and the dynamic boundary conditions have been embedded. Under the different faults, the simulation experiments of PEMFC were carried out. Another benefit for the research is that the diagnostic method is only based on the output stack voltages. By using two different methods of wavelet analysis (Morlet and Daubechies) and harmonic analysis (mainly using the Total Harmonic Distortion Analysis, THDA) respectively, the gas starvation faults in anode, cathode and both side are recognized and distinguished successfully.

Keywords: Wavelet Analysis, Harmonic Theory, Gas Starvation Diagnosis, Simulation Research

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INTRODUCTION

Comparing with experiment methods, the advantages of the simulation methods based on models are that different affecting factors are visible and the results are universal. Also, they can be the theoretical basis of guiding the experimental study and verifying the new numerical calculation method. For such research, Pei, etc [1, 2] studied the PEMFC typical faults based on a 1D semi-empirical model and a 3D distributed parameter model respectively, and has carried on a comparative study of these diagnostic models. Zhou, etc. [3] established a 1D stack model, which can reflect the differences of single cells, and analyzed the dynamic characteristics of the important physical quantities, such as temperature, water content and output voltage, etc, under the special operating conditions.

Currently, a variety of new diagnostic approaches, such as the polarization curve analysis, EIS analysis, neural network method, wavelet analysis, and THDA method are developed. For EIS method, Wang, etc. [4] discussed their AC impedance diagnostic instance in detail by using a 500 w PEMFC system. For the neural network method, by establishing a dynamic PEMFC model, Liu, etc. [5] studied its system thermal management strategy and put forward a temperature fault diagnosis method based on the neural network. For the wavelet method, Pei, etc. [6] studied the typical faults identification and classification of a PEMFC system based on a 1D semi-empirical distributed parameter stack model, such as temperature fault, membrane dehydration fault, and inlet flow inefficiently supplying fault, Nadia, etc. [7] put forward a diagnostic method for fuel cell ‘flooding’ based on DWT (discrete wavelet transform). Using the THD method, Ramschak, etc. [8] developed a new approach for inefficient gas supply detection based on a self-designed PEMFC system.

Based on a self-constructed 3D distributed parameter model By ANSYS / FLUENT and its UDF, the paper has carried out the simulation experiments of PEMFC gas starvation faults. On this basis, by only adopting the output stack voltage and using the wavelet analysis and harmonic analysis respectively, the insufficient gas supply faults in anode, cathode and both side are identified and distinguished. Further, the two analytic methods are compared. Overall, the paper has provided a fresh idea for the model-based faults diagnosis research.

1. 3D Diagnostic Fluent Model and UDF

The FLUENT software, which the paper adopts, is the most popular CFD (Computational Fluid Dynamics) software on the market. In order to meet the special needs of professional fields, it has developed special modules, such as Fuel Cell Module and Magneto Hydrodynamics Module etc [9]. A self-constructed 4-Cells PEMFC stack is built based on the Fuel Cell Module, as shown in Fig.1. The technical specifications are as shown in Table 1. Nevertheless, due to the dynamic boundary conditions, internal parameter variations, and user defined sources are difficult to be imported by the dialog boxes of Fluent Standard Module, the model needed dynamic boundary conditions and embedded faults in mechanism must be input by UDF (User Defined Function).

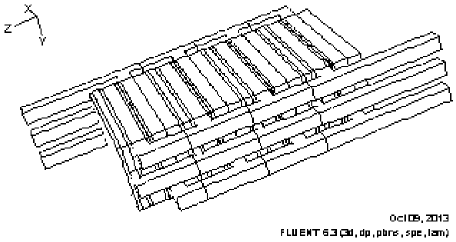


Fig.1 Self-constructed 4-Cells PEMFC Stack

Table 1 Technical Specifications of PEMFC

Number of Cells	4	Excess coefficient	3	Operating Temperature (K)	353
Cell Area (cm^2)	2	Open-circuit voltage (V)	0.95	Diffusivity of air (m^2•s^{-1})	7.35×10^{-5}
Membrane Thickness (mm)	0.04	Porosity of GDL/catalyst layer	0.5	Operating Pressure (bar)	1.5
Reference Current Density (mA·cm-2)	500	Diffusivity of Hydrogen (m^2•s^{-1})	1.1028×10^{-4}	Diffusivity of oxygen (m^2•s^{-1})	3.2348×10^{-5}

UDF is an extended programming interface based on C language, and its internal communication with FLUENT module must through predefined macro to achieve. UDF specific compiler is classified into Interpreted UDF and Compiled UDF. This research mainly adopts Compiled UDF, which solved the problems of dynamic boundary conditions and defined material properties, the specific applications is as shown in Table 2.

Table 2 UDF Faults Simulation

Faults	Boundary Conditions and Parameters	UDF predefined macros	Position
Inlet Flow Inefficiently Supplying	Current Density	DEFINE_PROFILE(CurDen_wallc, t, i)	Collecting Electrode
	Cathode Inlet Flow	DEFINE_PROFILE(inletAir, t, i)	Cathode Gas Channel
	Anode Inlet Flow	DEFINE_PROFILE(inletH2,t,i)	Anode Gas Channel
Membrane Dehydration	Porosity	DEFINE_PROFILE(porosity,t,i)	GDL
	Diffusivity	DEFINE_DIFFUSIVITY(mykuosanxishu,c,t,i)	GDL/Membrane/Catalyst Layer
Flooding	Porosity	DEFINE_PROFILE(porosity,t,i)	GDL
	Diffusivity	DEFINE_DIFFUSIVITY(mykuosanxishu,c,t,i)	GDL/Membrane/Catalyst Layer

2. Wavelet Packet Decomposition Principle

2.1 Wavelet Theory and its Application in Diagnosis

Fundamentally, WT (Wavelet Transform) is a projection of a signal or a time function onto a 2D time-scale phase plane. In a specific space, using the wavelet basis function makes the expansion and approximation of its mathematical expression. The wavelet basis functions $\Psi_{(a,b)}(t)$are obtained by translations and dilation of the 'mother wavelet'$\Psi(t)$.

$$\Psi_{(a,b)}(t) = \frac{1}{\sqrt{a}}\,\Psi\left(\frac{t-b}{a}\right) \tag{1}$$

Where 'a' is the dilatation or the scale parameter (a>0), 'b' is the time translation parameter. By given the wavelet basis function, the equations of CWT (Continuous Wavelet Transform), DWT (Discrete Wavelet Transform), and

HDWT (Half Discrete Wavelet Transform) are as shown in equations (2-4)

$$WT_x(a,b) = \frac{1}{\sqrt{a}} \int x(t)\ \Psi^*\left(\frac{t-b}{a}\right) dt \tag{2}$$

$$\Psi_{j,b}(t) = \frac{1}{\sqrt{2^j}}\ \Psi\left(\frac{t-b}{2^j}\right) \tag{3}$$

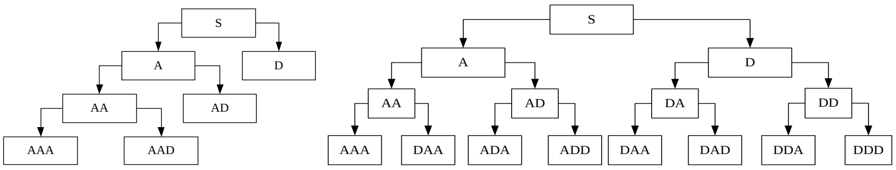
$$WT_x(j,b) = \frac{1}{\sqrt{2^j}} \int x(t)\ \Psi^*\left(\frac{t-b}{2^j}\right) dt \tag{4}$$

Where j represents the scale variations and b represents the time translation variation DWT and HDWT are developed for realizing the wavelet transform on the computer.

In diagnosis field, the applications of WT mainly include three aspects: the singular signal detection, signal/noise separation and band analysis. Additionally, the diagnostic applications of wavelet analysis have been involved in the fields of mechanical, chemical, pharmaceutical etc. However, the application of WT in fuel cell faults diagnosis is still incredibly novel. [10]

2.2 Wavelet Packet Decomposition Technique

According to Equations (3-4), in order to realize multiresolution for WD (Wavelet Decomposition), the time window width reduces and its corresponding frequency domain window width increases along with wavelet basis function j decreasing. However, the frequency domain resolution of WD is fixed, that is to say, the multiresolution of WD only decomposes the Scale Space A, but no further decomposition of Wavelet Space D. WPD has overcome the drawbacks of WD, which can decompose the Wavelet Space D (into $U_{i,\,j}$) as well. As a result, the broadened spectrum window along with j will be more detailed, and the most appropriate analytical window and best resolution of the signal will be found. The schematic diagram of WD and WPD process is as shown in Fig.2.



(a) **(b)**

Fig.2 Wavelet decomposition at level 3 (a) and Wavelet packets decomposition at level 3 (b)

In digital signal processing terms, WD algorithm is equal to a high/low pass filter to the original signal. Given the orthogonal scaling function ϕ (t) and the wavelet function ψ (t), their two-scaling relations are as shown in equations (5-6).

$$\phi(t) = \sqrt{2}\sum_k h_{0k}\phi(2t-k) \tag{5}$$

$$\psi(t) = \sqrt{2}\sum_k h_{1k}\phi(2t-k) \tag{6}$$

Where h_{0k} and h_{1k} are the filter coefficients of multiresolution analysis. When n = 0, w_0(t)= ϕ(t), w_1(t)= ψ (t). Wavelet packet $\{w_n(t)\}_{n\in Z}$ is a set of functions including scale function w_0(t) and wavelet function w_1(t).

$$w_{2n}(t) = \sqrt{2}\sum_{k\in Z} h_{0k}w_n(2t-k) \tag{7}$$

$$w_{2n+1}(t) = \sqrt{2}\sum_{k\in Z} h_{1k}w_n(2t-k) \tag{8}$$

The two-scaling equations are as shown in equations (7-8). [10, 11]

3. Harmonic Analysis Principle

The word ‘harmonic’ is originally from acoustics. For the power system, the difination of harmonic is that: when do the Fourier series decomposition for a periodic non-sinusoidal electric quantity, in addition to get the same component as the grid fundamental frequency component, there also be a serious of components greater than the fundamental component, which is named ‘harmonics’. The primary reason of these harmonics is caused by nonlinear loads. When the current flow gets through the load and has a non-linear relation with the applied voltage, the non-sinusoidal current will be formed and harmonics will be generated. The harmonic frequency is an integral multiple of the fundamental wave frequency.

The THD (Total Harmonic Distortion) is defined as ratio of the total energy of the Harmonics to the fundamental energy, or the RMS (root mean square) value of the total harmonic voltages amplitudes divided by the amplitude of its fundamental voltage, as shown in equation (9).

$$THD = \frac{\sum Hp}{Fp} = \frac{Vh}{V1} = \frac{\sqrt{(V_2^2 + V_3^2 + ... + V_n^2)}}{V1} \tag{9}$$

Where Fp is fundamental energy, Vh is the RMS value of the total harmonic voltages amplitudes, and V1 is the amplitude of fundamental voltage.

The principle of THDA technique using for PEMFC faults diagnosis is that: by adding small amplitude and fixed frequency signals, if the voltages vary in some cells for certain reasons, the output stack voltage will be corresponding warp and distortion, and then through a series analysis of out coming effects of the critical voltage drops, the faults can be accurately judged, and the action can be take. The advantage of this new approach is that: barely through the analysis of the real-time stack output voltage, whether the stack or even the single cell operates in a safe and reliable condition can be judged [12]. For instance, such as simulating the insufficient air supply in cathode, which is often happened in a fuel cell, the insufficient air inflow generates the decreased oxygen proportionally, leading to a high diffusion resistance in cathode, and thus caused a slightly drop of the voltage. By superposing an input disturbance, the PEMFC system will produce a certain harmonic distortion in the output. The harmonic distortion will be analyzed in frequency domain, and compared with the original superposition frequency, in order to achieve the purpose of faults diagnosis.

RESULTS AND DISCUSSION

The paper focuses on the inefficient gas supply in both anode and cathode. Based on a self-built 3D distributed parameter model, using two different diagnostic approaches, the distinct frequency responses under the anode fault and the cathode fault was analyzed. The research of the paper only adopts the stack voltage of the PEMFC. Under a 1 Hz sinusoidal ac disturbance, the stack voltages in normal and faults statuses are as shown in Fig.3. The simulation results shows that by comparing the different stack voltages in different statuses, the faults can be identified.

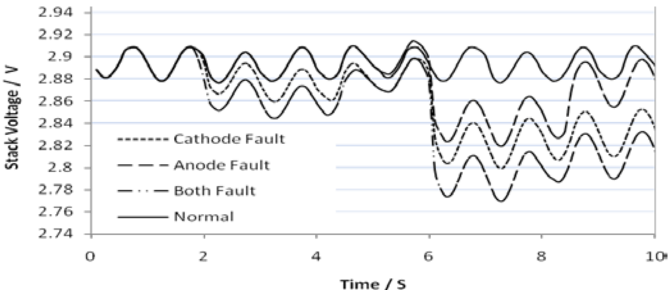


Fig.3 Voltages Comparison in Different Faults

Further, the study applied the Morlet wavelet and the Daubechies wavelet to decompose the stack voltage respectively, as shown in Fig.4, which is the decomposition results under the cathode fault. By comparison, the results difference from the Morlet WD in different gas supply faults is not obvious. Accordingly, the study adopts the Daubechies (db) WD/WPD do the further processing. Db wavelets family has different wavelets types (db1, db2 … dbn). The signals from db3 WT are closer to the triangular wave signal. The signal from db3, db5 and db8 WTs are smoother and closer to the sine wave. Generally, the db wavelet can decompose a signal on any scale according to the actual situation, which the vanishing moment is larger, the allocation effect of the frequencies bands is better, whereas it is smaller, the frequencies bands allocation is rough. However, if the order is too large, the calculation time will be increased and the efficiency of the algorithm will be reduced. Thus, the study selects the db3 wavelet packet of three layers for decomposition.

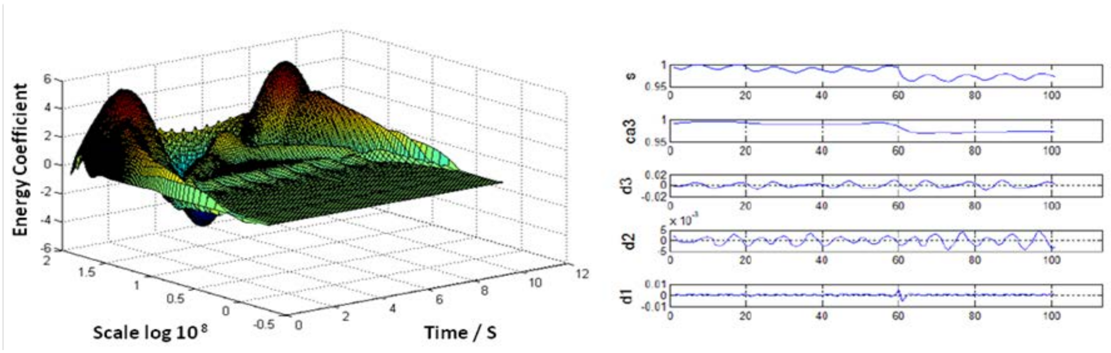


Fig.4 Morlet WD and Daubechies WD under the Cathode Fault

Through a further comparative analysis using WD, the wavelet packet ca3 (the approximation signal in the third layer) and cd3 (the detail signal in the third layer) are determined as the main parameters, which the identification effects of different faults are noticeable.

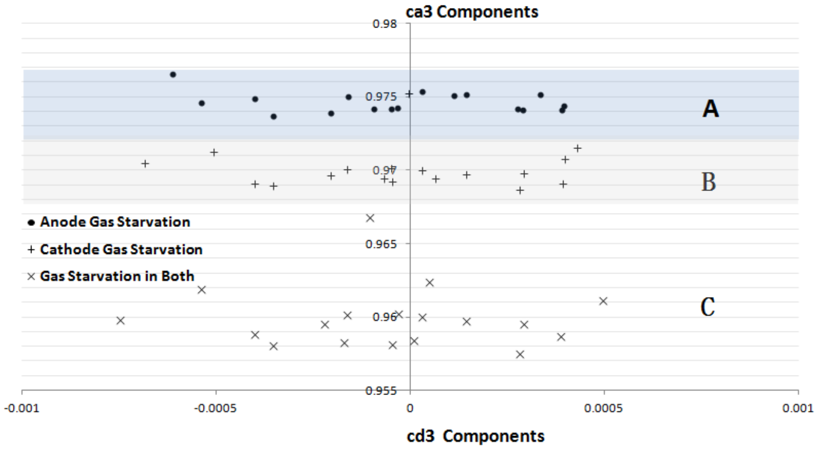


Fig.5 the Statistical Diagram of Daubechies WPD

Hence, as shown in Fig.5, the statistical information of ca3 and cd3 are used for the faults recognition at different poles. The figure shows that when the insufficient gas supply reaches the fault level, the anode gas starvation data are mainly concentrated in A region, the cathode gas starvation data are mainly concentrated in B region, and the starvation happened in both side are mainly concentrated in C region. Accordingly, when a fault occurs, by the results of these wavelet packets fall in which region, the gas starvation in anode, cathode or both side of PEMFC can be judged.

Moreover, WPD decomposition is taken as a further solution. Two feature vectors are defined for each packet: $f_1 = \left[E_s^1 + E_s^2 + .. + E_s^{14} \right]$, $f_1 = \left[E_n^1 + E_n^2 + .. + E_n^{14} \right]$. The normalized energy Es in a specific wavelet packet P is given by:

$$E_s = \frac{1}{N_p} \sum_{j,b} \left| C_{j,b}^P \right|^2, P = 1, 2, .., 14 \tag{10}$$

Where P indicates the packet number, $C_{j,b}^P$ are the coefficients contained in the packet N. En is En divided by the energy of all the packets. A statistical data representation of f_1 is given in Fig.6. It shows that packets 1,3,7 are appropriate to discrimination. Thus, the energy value of packets 1,3,7 are chosen to reduce the size of discrimination data from 14 packets, which compare with the WD method.

Fig.7 represents the features f_1 and f_2 obtained for these packets, which are the results of the projection of the features corresponding to the gas starvations in anode, cathode and both side. The projected features occupy three different areas of the plane, which could be separated by a simple linear function.

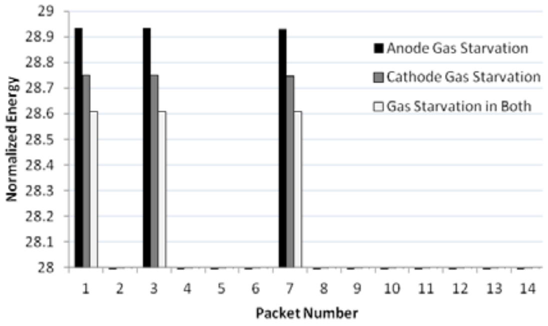


Fig.6 Statistical Representation of the features contained for Gas Starvation at Anode, Cathode and Both Side (Energy Contained in Each Packet)

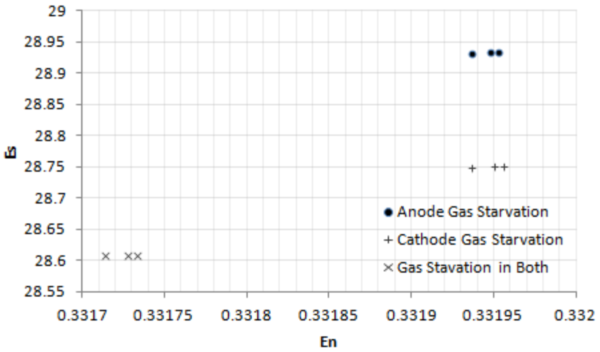


Fig.7 Feature Cluster using in different gas starvations

Meanwhile, by superimposing the different ac sine disturbances (1 Hz, 4 Hz, 10 Hz) under the different faults (anode insufficient hydrogen and cathode insufficient oxygen/ air), the critical stack voltages were got, and then by the FFT (fast Fourier transform), the frequency spectrum comparison diagram in Different Faults will be obtained. As shown in Fig.8, it is the comparison diagram under the 1 Hz sinusoidal ac disturbance. The figure shows that the difference of 3th harmonic, 4th harmonic, and 8th harmonic in the spectrum are extremely obvious, which can be used as the characteristic frequencies for the faults identification, as shown in Table 3, and as a criterion to faults distinguish.

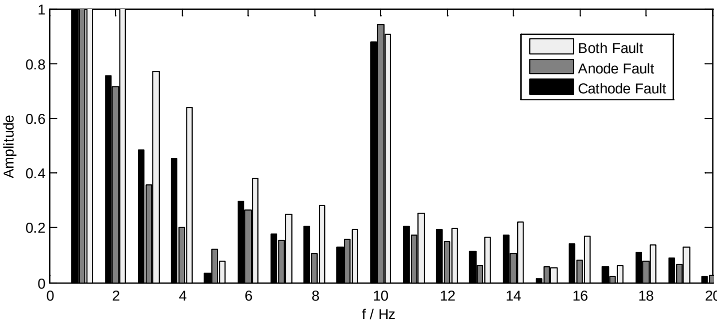


Fig.8 Frequency Spectrum Comparison in Different Faults

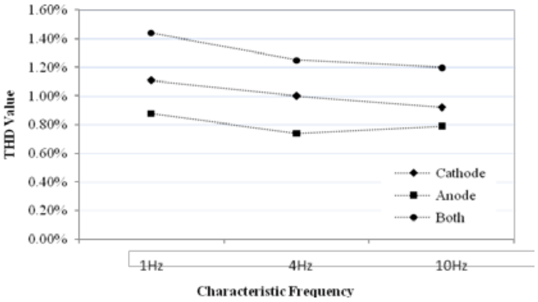


Fig.9 the THD Values in Different Input AC for Insufficient Gas Supply

Table 3. the Harmonic Values in the Characteristic Frequencies

	V1	Vn		
Cathode	288.915	0.484	0.452	0.204
Anode	290.764	0.359	0.201	0.106
Both	287.481	0.773	0.641	0.282

Table 4. the THD Values under Different Input AC Disturbances：

f	Cathode	Anode	Both
1Hz	1.11%	0.88%	1.44%
4Hz	1%	0.74%	1.25%
10Hz	0.92%	0.79%	1.2%

In addition, the THD values can provide a more accurate criterion. In different ac sine disturbances (1 Hz, 4 Hz, 10 Hz), as shown in Table 4 and Fig.9, which under the gas shortage in anode and cathode respectively, the THD values ranges are significant different in these faults (the THD value of 1.2% can be the distinguish line of the anode and cathode faults). Accordingly, the two kinds of faults can be differentiated.

CONCLUSION

Based on a self-constructed 3D PEMFC distributed parameter model and UDF, the study has simulated the gas starvation faults in anode, cathode and both side. On this basis, by applying the methods of WD, WPD and harmonic analysis, the three faults have be identified and distinguished. The conclusions are as follows: (1) No matter through the wavelet method or the harmonic method, the gas starvation in anode, cathode and both side can be distinguished independently; (2) As a more powerful tool for signal processing, wavelet analysis has a better ability of time-frequency analysis, comparing with the THD method based on FFT. Also, the wavelet method has more analyzable parameters; (3) Compared to the required multi-frequencies inputs (1 Hz, 4 Hz, 10 Hz) of THD method, wavelet method needs less input. (4) Compared with WD, WPD needs less size of discrimination data and has a better accuracy.

Based on the conclusions above, the paper has successful applied three diagnosis methods to the PEMFC model, and distinguished the starvation faults between the anode, cathode and both side. For future works, on the basis of the results above and the 3D model, the wavelets method and harmonic method will be applied further to identify more faults and carry on the corresponding experiments, such as membrane dry out, flooding, etc.

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