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A Study on PEMFC Faults Diagnosis Based on Wavelet Analysis

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Abstract. The study of Proton Exchange Membrane Fuel Cell (PEMFC) faults mechanism and diagnosis can afford theoretical and technical supports for the future mass production and applications of PEMFC stacks and systems, which need modularization and high reliability. Most of the existing fault diagnosis methodologies, such as Cell Voltage Monitoring (CVM) method, require the knowledge of numerous parameters which may lead to a special inner parameter monitoring setup. The corresponding devices increase the cost and are not suitable for stack modularization and system application. In this paper, a simple and low-cost PEMFC faults diagnosis method using discrete wavelet transform is described. The method only uses the stack information for signal feature extraction. After that, by faults identification and classification, several typical faults including temperature fault, inlet flow inefficiently supplying fault and membrane dehydration fault have been distinguished. A semi-empirical distributed parameter stack model is employed for simulating typical faults that may occur. The simulation results demonstrate that the application of wavelet theory to PEMFC diagnosis is feasible, reliable and promising.

Introduction

According to electrochemistry theory, fuel cells are energy conversion devices which directly transform chemical energy into electrical energy [1]. Fuel cell power generation technology, as a new energy power generation technology followed by the fire, water power and atomic energy generation, is considered to be the main clean energy power method of the 21st century [2-3]. At present, the technology has been widely applied in many fields such as automotive, aerospace and military industry. Moreover, as an essential testing technology, fuel cell faults diagnosis technology is developed to ensure that the quality, performance and security index of the fuel cells.

Currently, the general fault diagnosis methods are divided into the electrochemical methods and physical/chemical methods. The widely applied electrochemical methods chiefly contain Electrochemical Impedance Spectroscopy (EIS) method and CVM method. Physical/chemical methods mainly include: the pressure drop measurement, meteorological chromatographic analysis, neutron imaging technique, magnetic resonance imaging technique and optical diagnosis method rely on optical transparent fuel cell [4]. As a linear sweep and potential step methods, CVM device has the drawback that needs to measure hundreds of cell voltages channels, which significantly increase the wiring, contacting and cost [5]. Commonly, EIS method and physical/chemical methods, which rely on expensive special precision instruments, are applied on laboratory study and are not suitable for online practical system applications. Consequently, a new approach needs to be developed.

Because wavelet analysis has the characteristic of time-frequency localization and analysis, which is extremely suitable for signal feature extraction, processing, and thus structure the characteristic quantities in faults diagnosis, wavelet analysis can be the ideal tool of PEMFC faults diagnosis. At present, the faults diagnosis methods based on wavelet analysis have been successfully applied to the industry, medicine, chemical and many other areas. However, according to the published literatures, wavelet transform is rarely related to PEMFC faults diagnosis. The only report of single fault research using wavelet transform is that Nadia etc. proposed a diagnosis method base on discrete wavelet transform to judge the water flooding of PEMFC [6]. Using discrete wavelet transform, the paper developed a faults diagnosis method which is only based on PEMFC stack information of a PEMFC dynamic distributed parameter model.

The paper is organized as follows. After the introduction, the paper describes the diagnosis principle, which includes discrete wavelet transform and wavelet packet decomposition, PEMFC dynamic distributed parameter model, signal feature extraction and characteristic quantities definition. Subsequently, the simulation application is illustrated and the obtained results are shown and discussed. Conclusion and future work are given at last.

Diagnosis Principle

Discrete wavelet transform and wavelet packet decomposition. Essentially, Wavelet Transform (WT) belongs to the multi-resolution analysis class, which projects a signal (time function) onto the 2D time-scale phase plane and makes expansion and approximation of its mathematical expression by wavelet basis function in a specific space. It permits examination of the signal and its local features under different scale and time localizations, and could be applied to classify the stack information into different faults.

Given a 'mother wavelet' $\psi(t)$, 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 represents the dilatation or the scale parameter (a>0), b represents the time translation parameter.

From the view of mathematics, WT is a convolution of signal x (t) with a group of wavelet basis function.

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

where *WT* represents the similarity between the signal and the basis wavelet function at each time and scale.

In order to realize effective wavelet transform on the computer, a, b and t should take discrete values to translate the formula into discrete wavelet transform (DWT). The general discretization method for 'a' is that step up 'a' by power series form. Namely make a= a_0^j , a0>0, $j \in Z$. If take a0=2, Eq.

And Eq. (2) becomes

$$C_s(j,k) = \frac{1}{\sqrt{2^j}} \int_{-\infty}^{+\infty} x(t) \psi^* \left(\frac{t-k\times 2^j}{2^j}\right) dt \tag{3}$$

where j represents the scale variations and k represents the time translation variation [7].

In this particular case, the wavelet decomposition algorithm is equivalent to the signal filtering using a low-pass and a high-pass filter. As shown in Fig.1 (a), at the first decomposition level, the signal is decomposed into Approximation A (as the low-pass filter output) and Detail D (as the high-pass filter output). Nevertheless, for wavelet decomposition algorithm, only the approximation signals will be filtered in the same way which can be understood as the signal approximations [8]. To overcome the problem, wavelet packet decomposition (WPD) can be used to decompose the approximation signal and also the detail signal, which is more complete [6], as shown in Fig.1 (b).

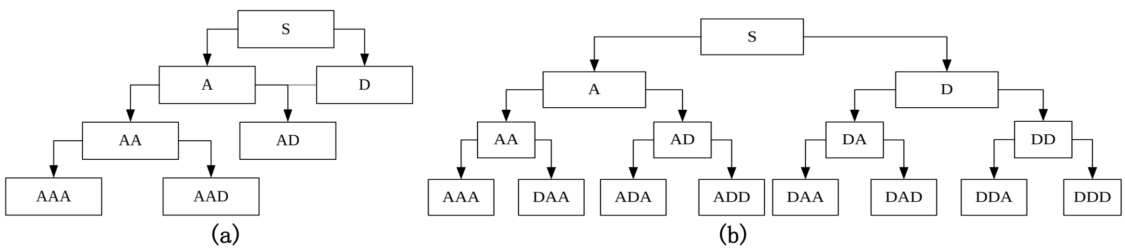

Fig.1 Wavelet decomposition at level 3 (a) and Wavelet packets decomposition at level 3 (b)

PEMFC dynamic distributed parameter model. The paper adopted faults diagnosis simulation research using a PEMFC dynamic distributed parameter model. The reason of simulation research is: 1) The cost of PEMFC faults experiments is incredibly expensive and the failure is difficult to repeat in different cells; 2) when typical failure mechanism is embedded into the PEMFC model, the typical faults can be simulated regularly or randomly. The study of fault mechanism embedding and the wavelet analysis based on simulated data will provide a theoretical guidance and reference for further fuel cells online fault diagnosis applications.

A 60 cells PEMFC stack model is established, which is divided into 15 modules and each module contains 4 cells with no performance difference. Each single cell of the model has 5 control volumes: collector, cooling channel, anode gas channel, MEA+GDL and cathode gas channel. According to energy conservation law, heat conduction and transfer theory of material, a single-cell temperature dynamic model and the temperature model between adjacent cells are built. The temperature dynamical equation of each control volume $T_{i,k}$ is as follows:

$$\sum m_{i,k}^{r} Cp_{i,k}^{r} \frac{dT_{i,k}}{dt} = Q_{i,k}^{M} + Q_{i,k}^{amb} + Q_{i,k}^{ex} + S_{i,k} \tag{4}$$

where Q^M represents the heat caused by material flow, Q^{amb} represents the heat generated by heat exchange between control volume and air, Q^{ex} represents the heat generated by heat exchange between adjacent control volumes, Cp is specific heat capacity, m is mass and S is a source item.

According to mass conservation equation of anode/ cathode gas channel, a material flow model is set up. Its governing equation is:

$$Mm^{j} \frac{dn_{i,k}^{j}}{dt} = M_{i,k}^{j\_in} - M_{i,k}^{j\_out} - M_{i,k}^{j\_re} \tag{5}$$

where $n_{i,k}^{j}$ represents the component molar weight of a single cell, j represents H_2,O_2,N_2 or H_2O, $M_{i,k}^{j\_in}$ represents the inlet mass velocity of each component, $M_{i,k}^{j\_out}$ represents the outlet mass velocity of each component, $M_{i,k}^{j\_re}$ represents the reaction velocity of reactive gas.

According to the relationship between the resistance and pressure drop of reactant gas transmission in the stack, an anode/ cathode inlet flow and pressure-plotting model is founded. The relation between pressure drop and initial flow is:

$$\Delta P = K' q_0 \left[\left(\frac{1 - e^{-\alpha l_c}}{\alpha} \right) + \sum_{i=0}^{m} 2 l_e e^{-\frac{i \alpha l_c}{m+1}} \right] \tag{6}$$

where ΔP represents the pressure drop when fluid runs through the channel, K is frictional drag coefficient, q_0 is initial volume flow, α is fluid consumption ratio constant, lc is the length of single cell channel, le is local resistance equivalent length.

According to that the stack voltage is the sum of single cell voltages, a single cell voltage empirical model and a stack voltage model are founded. The single cell voltage can be indicated as:

$$E_i = E_i^0 + \eta_i^c - \eta_i^\alpha - \eta_i^{ohm} \tag{7}$$

where Ei is single cell voltage, E_i^0 is ideal open-circuit voltage, η_i^c is cathode polarization voltage, η_i^a is anode polarization voltage and η_i^{ohm} is Ohms voltage.

In view of the key equations upon, a PEMFC stack model is built up by MATLAB/Simulink, as Fig.2 shown. The PEMFC dynamic distributed parameter model provides a basis of diagnosis [9].

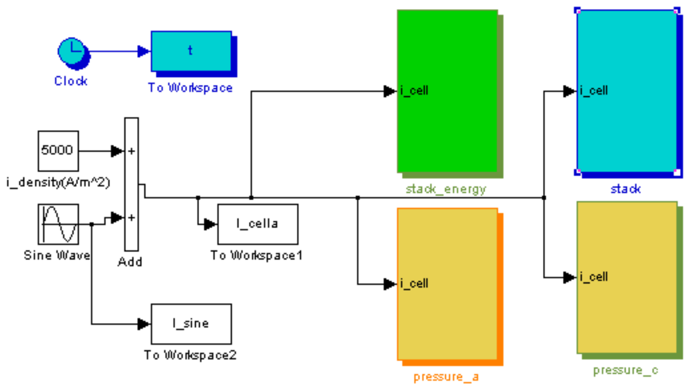

Fig.2 PEMFC stack model schematic diagram

Signal feature extraction and characteristic quantities definition. According to the formation reasons, PEMFC faults can be divided into external operating conditions caused failures (such as air/fuel supply shortage and low relative humidity of gas at the entrance, etc.) and internal factors caused failures (such as proton exchange membrane aging, carbon carrier corrosion, water flooding and local fuel hunger, etc.)

As the premise of PEMFC faults diagnosis, the faults types need to be defined, which means build a fault set X= ｛F1， F2， F3， ⋯ Fi⋯ Fn｝. The research mainly studied the faults as follows: F1-Temperature fault； F2-Inlet flow inefficiently supplying fault； F3-Membrane dehydration fault.

According to the PEMFC dynamic distributed parameter model, As Fig. 3 shown, the study simulated several typical fault types Fi. By doing wavelet packet decomposition of the model produced stack voltage signal, several appropriate features can be extracted from the detail information in various frequencies (such as variance, energy, similarity, etc.). Here, the normalized energy En is calculated and obtained after the WPD which is given by:

$$E_n = \frac{1}{Ni}\sum_{j,k} \left|C_{i,k}^{i}\right|^2, i = 1,2,3,4...14 \tag{8}$$

Where i represents the packet number, and $C_{i,k}^{i}$ is the coefficients contained in packet i.

A vector set of En is expressed as

$$A = \{E_{n1}, E_{n2}, ..., E_{ni}\}^t \tag{9}$$

And then through the recognition of fault types, that is establishing the corresponding relations between faults characteristics fault types. Further, by fault characteristics collation and classification, the state of health (SOH) of PEMFC stack can be estimated.

Fig.3 PEMFC Diagnosis Schematic Based on Wavelet Transform

Simulation Results and Discussion

Algorithm and simulation analysis. The simulation analysis is based on a 60 piece PEMFC dynamic distributed parameter model. The fault features extraction algorithm for stack voltage signal is based on Daubechies wavelet packets decomposition at level 3. The 'MATLAB wavelet toolbox' is applied in the study. In the research, the stack voltage signals were transformed into a WP domain. The feature En is applied to classify the stack voltage behaviors. The vector set A is used to gather the features for each simulation experiment. Therefore, it will have an 'i·t' matrix, where 'i' is the packets number.

Set the simulation conditions as: input current density for 5000 A/m^2, superimpose a sinusoidal signal on this signal with amplitude for 200 A/m^2 and the frequency of 1 Hz. In this simulation condition, separately simulate the temperature fault, inlet flow fault and membrane dry fault in different cells. The research simulated the temperature fault through changing the dynamic behavior of single cell temperature. Cathode inlet flow inefficiently supplying fault: when physical quantities in PEMFC stack reach a steady-state value, mutate the cathode inlet flow of 0.15, 0.2, 0.25 times for initial value. Membrane dehydration fault: when physical quantities in PEMFC stack reach a steady-state value, drop the membrane water content down to the 15%-20% of initial value.

Results and discussion. For simply demonstrating the wavelet theory analysis of fuel cell faults diagnose, three faults, i.e. temperature fault, inlet flow inefficiently supplying fault, membrane dehydration, are artificially integrated into the PEMFC stack model which has already described previously. When the sine wave current as the main input is supplied, the corresponding stack voltage information can be obtained in Fig.4. The fuel cell faults (eg. temperature fault, inlet flow inefficiently supplying fault, membrane dehydration) can be easily identified compared to the normal case (see the solid line in Fig.4) in the time domain. Although the information contained in Fig.4 is still insufficient for recognizing the types of the faults. The following contents will discuss the faults identification by applying the wavelet theory based on the data supplied in Fig.4.

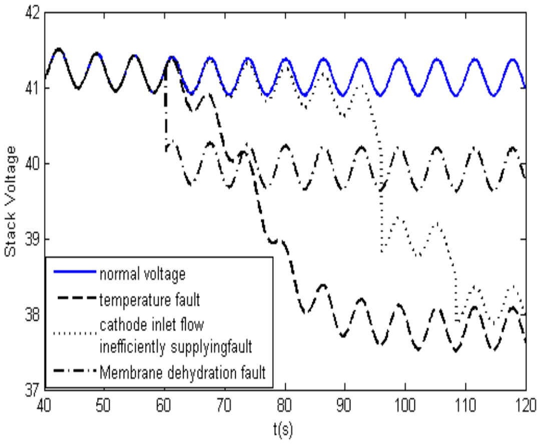

Fig.4 Wave Forms Comparison of Stack Voltage

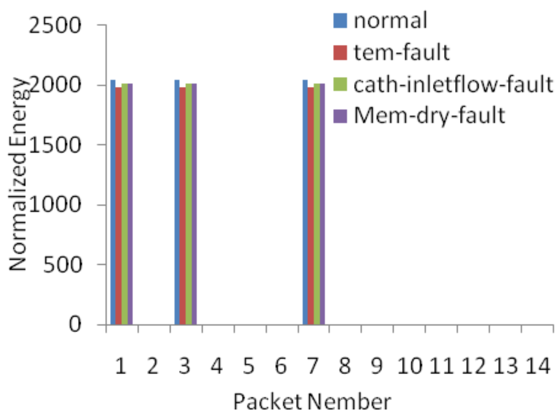

Fig.5 Normalized Energy in each packet for different faults

When the faulted stack voltage signals are available, by using the wavelet packet analysis, the normal energy feature En is calculated for the 14 packets. The statistical data are taken to make a comparative analysis, as shown in Fig.5. Packet 1, 3 and 7 are suitable for identification rely on their fine separation capacity between different states.

Here, packet 7 is chosen to reduce the size of identification data. By 6 simulation experiments for each fault, the characteristic quantity Es (Energy Scores), which is En divided by the energy of all the packets, are calculated to indentify the 3 typical faults. As it is shown in Table 1(Es_nor: Energy Scores in normal state; Es_temf: Energy Scores in temperature fault; Es_ciff: Energy Scores in cathode inlet flow inefficiently supplying fault; Es_dehf: Energy Score in membrane dehydration fault).As it is hard to distinguish between different faults. Further, the differences among the elements in the Table.1 is small, a corrected form (Da) for the Es is defined as $Da=1000\times(Es-0.33)$ in order to plot friendly. By the interval 3 to 3.05, and 2.9 to 3, the states are easily separated. Da of the temperature fault is approximately equal to 3.05. Da of inlet flow inefficiently supplying fault is between 3 to 3.05, and Da of membrane dehydration fault is between 2.9 to 3.

Table 1 Comparison of Es between different fault types

	1	2	3	4	5	6
Es_nor	0.33305263043	0.33305263044	0.33305263043	0.33305263044	0.33305263044	0.33305263043
Es_temf	0.33304689546	0.33304439949	0.33304731385	0.33304493095	0.33304578544	0.33304344144
Es_ciff	0.33296563489	0.33294818221	0.33293979023	0.33295909688	0.33292287825	0.33298634171
Es_dryf	0.33302553346	0.33300997853	0.33299809392	0.33302688191	0.33301122582	0.33299921391

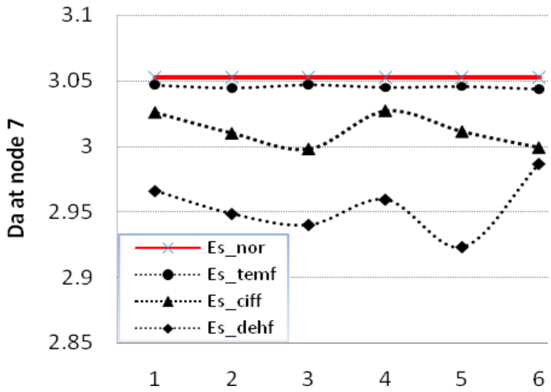

Fig.6 Comparison of Da between different fault types

Conclusion

Based on discrete wavelet packet transform, a trouble-free and inexpensive PEMFC faults diagnosis method was developed. The method only uses the stack voltage signal for signal features extraction, which greatly improve the stability and reliability of PEMFC faults diagnosis. By introducing a multi-scale analysis method of digital signal processing to PEMFC faults diagnosis, the study applied WPD method for detail information extraction in various frequency band and characteristic features structure, preliminarily reached the purpose of distinguishing several typical faults (including temperature fault, inlet flow inefficiently supplying faults and membrane dehydration fault).

The preliminary study in this paper is based on a dynamic distributed parameter model. The simulation results illustrate that introducing wavelet theory to PEMFC diagnosis is viable, reliable and promising. The further work of the study is that: based on the simulation experiments, put forwards a real-time faults diagnosis method using stack voltage and wavelet analysis. The innovative method may hopefully replace the general CVM method in the near future.

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