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A robust data treatment approach for fuel cells system analysis

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A B S T R A C T

This paper describes the implementation of a practical approach for fuel cells system data analysis. A number of data treatment techniques such as data management and treatment, data synchronization, and data reconciliation are introduced and discussed in order to solve the issues raised in the practical case. These techniques are integrated in a software environment which provides user a fast, efficient, and rational electrochemical investigation. The performance of the approach is illustrated using an industrial fuel cell stack test system.

1. Introduction

A fuel cells stack is a collection of individual cells electrically connected in series. In an ideal fuel cells stack, every cell would be subjected to identical operation conditions and the overall stack performance would be obtained as the sum of the identical output of individual cells. However, due to manufacturing variability of components, stack configuration, and degradation with use, the individual cells in a real stack will typically show some variation in performance and so will the stack. Hence, in addition to overall system performance, individual cell performance needs to be detected in a fuel cells system. Several cell voltage monitoring systems have been developed for the fuel cells systems and battery systems [1,8], where the focus is given either on the design of cell voltage monitoring system, or the investigation of cell performance by means of the voltage monitoring.

A cell voltage monitoring system has been designed in our research group for a fuel cells system measurement. A tapping method is adopted to establish electrical connection to selected individual cells in a fuel cell stack to explore the coupling between adjacent cells. Knowledge of individual cells and power loss related to the interconnect between adjacent cells (i.e., bipolar plate) is thus obtained in combination with electrochemical performance of the overall fuel cell stack.

The analysis of data that are measured by the voltage monitoring system takes an important role in obtaining the useful information of a fuel cells system. Polarization curve is generally characterized for a fuel cell stack as it reflects the various sources of polarization (reduction of voltage from the thermodynamically reversible level) in a fuel cell. The polarization behavior for each individual cell provides important clues about the system's performance and efficiency.

Even though the voltage monitoring system has been investigated by fuel cell designers, the data analysis in the fuel cells stack testing still remains a challenge. There are some obstacles that hinder one to obtain the required information easily and appropriately. One of the problems is with the ease of data handling. There is a large amount of data collected from several measuring devices in the voltage monitoring system, the data are usually stored in several different files (which can be accessed with spreadsheet software, for e.g. MS Excel). The data have to be integrated into a statistical software environment (e.g. Origin) in order to undertake electrochemical calculation, plotting and analysis. Before a further electrochemical analysis, the raw data have to be manually examined, synchronised and then transferred from Excel to Origin. This will be a tedious work and time-consuming, especially when all the procedures have to be repeated for the new data in the cycle of experiment.

Another challenge is that electrochemical analysis of the data that are available after the above processing may not produce reasonable results when comparing the performance between overall fuel cells stack and individual cells. There are two critical phenomena that support this argument. It is found that an event (e.g. voltage change) happened in the experiment is usually recorded at different time instant and with different logging points by different testing devices (names of which are mentioned in the following section). It is difficult to synchronize the data so that the discrepancy in time presents a random fashion

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Nomenclature

Q,C	time series
m, n	number of points in time series
q_i,c_i	ith elements/points of time series
$d(q_i,c_j)$	distance $d(q_i,c_j)$ between the two points q_i and c_j
P	a warping path
$p_k=(i,j)_k$	kth element of warping path
$DTW(Q,C)$	warping cost for two time series Q,C
$\gamma(i,j)$	the cumulative distance in dynamic programming
x	estimation
$\hat{x}$	estimation
y	measurement
$W=\text{diag}(\alpha_1^2,\alpha_2^2,\ldots\alpha_n^2,)$	weight matrix with diagonal elements $\alpha_1^2,\ldots\alpha_n^2$
α_i	standard deviation of ith measurement noise
DAE	differential and algebraic equation
A	coefficient matrix of liner equation
V_{output}	voltage measurement of whole stack
V_i^{cell}	voltage measurement of ith individual cell
V_j^{int}	voltage measurement of jth individual interconnect
V_k^{sic}	voltage measurement of kth secondary interconnect

(not a regular fashion—for that case a constant time shift of data could be enough) as shown in Fig. 1, where two data profiles are horizontally compared. Such a time discrepancy complicates the analysis and (if not resolved) makes the reasonable analysis difficult. Another critical phenomenon that has been found in the investigation of raw data is that the data recorded do not appear sound in term of the first principles. The relationship between the voltage of the whole stack and the voltages of individual cell should satisfy some kind of conservative law, e.g., overall voltage equals to sum of individuals as one would expect in an ideal fuel cell stack. However, this constraint is usually not satisfied as shown in Fig. 1, where two data profiles are compared vertically. Also, there is no consistency of the discrepancy but it appears random. Apparently, directly applying electrochemical investigation methods to the raw data, even in a user-friendly handling environment, will hardly give reasonable results.

In this paper, a robust and fast data treatment approach is developed in order to practically process experimental data obtained from the voltage monitoring system and to analyze the complicated fuel cell performance. The approach includes data automation, data synchronization and data reconciliation.

Firstly, the focus is given on the alleviation of tedium of data handling cross two software environments. To do this, an interface for data analysis is developed in an Excel file. This interface includes the functionality with which one cannot only configure and process the data, but can also take electrochemical investigation. A computing engine (e.g. MATLAB) is connected with Excel spreadsheet at background where various algorithms of data processing and analysis run. It will not affect usage even though one has little knowledge of MATLAB. This data automation scheme saves much effort and improves efficiency for data handling in fuel cell testing, as it is much convenient for one to undertake analysis in a single software environment where all the data from different testing devices can be directly accessed and analyzed.

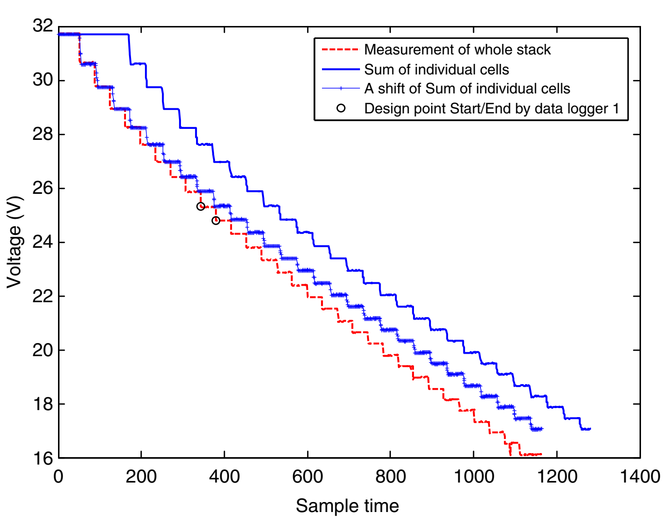

Fig. 1. The fuel cells stack voltages obtained by combining data from several different measuring devices during polarization curve scanning. The dash line represents the whole stack voltages measured by one device; the solid line represents the sum of individual cell voltages that is obtained by combining data from the other two measuring devices; the solid line with cross marker represents the shift of the solid line. The circle sign represents the specified point recorded by data logger file. This figure gives an example of the problems that are to be focused in the work. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)

In order to get the best estimate of data for electrochemical investigation, the raw data need to be further processed. It is desirable to identify the similarity among all the data sequences recorded in the individual testing equipments, and then align the data in term of a same time instant. (Fig. 1 shows a comparison of voltage changes measured by different testing devices. It can be found that the two data sequences have the approximately same overall component shapes, but these shapes do not line-up in X-axis (time). The steps (ramping) do not happen at same time, nor do they follow a consistent fashion.) Dynamic time warping (DTW) can be used to achieve a better alignment, as it is a method that allows a computer to find an optimal match between two given sequences (e.g. time series) with certain restrictions. It has been successfully used in speech recognition, gesture recognition, alignment of batch profiles and medicine [5,2,3,6,10]. Its application to fuel cell system data analysis will be a novel approach.

Another concern is to estimate the "real" values of the measurements from all the devices subject to the first principles. The vertical discrepancy between the two sets of data as shown in Fig. 1 is hardly acceptable and less meaningful in terms of the first principle; at least, the law of conservation should not be breached. Data reconciliation is a procedure of optimally adjusting measured data so that the adjusted values obey the conservation law and other constraints. Although data reconciliation has been applied to chemical processes for process optimization, monitoring and control [4,7], its application to fuel cells system testing has not been reported.

2. Experimental platform

The fuel cell stack tested in this study contained 30 cells connected in series. The test platform for electrochemical performance measurement of the fuel cell stack consists of a customized 500 W fuel cell test station and a TDI MCL488 electronic load. For individual cell voltage monitoring, conductive wires are connected to the anode or cathode of selected adjacent cells of the stack, which enables the voltage measurement of individual cell and power loss related to the interconnect. The cells' and