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Proton exchange membrane fuel cell system diagnosis based on the multivariate statistical method

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ABSTRACT

Although electric-powered vehicles have developed rapidly in recent years, with significant progress in the lithium power battery industry, the Fuel Cell Electric Vehicle (FCEV) is still a competitive choice for a clean transportation solution, because of its extended driving range, zero emissions, and fast fuel recharging capability. In particular the fuel cell hybrid bus used for city traffic is the FCEV type most likely to be commercialized. Demonstration programs for a fuel cell bus fleet have been operated for a few years in China. It is necessary to develop comprehensive diagnostic tools to increase the reliability of these systems, because fuel cell city buses serve large numbers of passengers using public transportation. This paper presents a diagnostic analysis and implementation study based on the Principal Component Analysis (PCA) method for the fuel cell system. This diagnostic system was successfully implemented for detecting a fuel cell stack sensor network failure in the fuel cell bus fleet at the Shanghai Expo in 2010.

1. Introduction

Over the past decade automanufacturers around the world have launched important development programs for fuel cells [1] as major alternative energy solutions, because hydrogen offers high fuel economy and substantially lower emissions, particularly CO_2. Proton Exchange Membrane (PEM) fuel cells use simple compact stacks which do not have complex requirements with respect to fuel, oxidant and coolant supplies. PEM fuel cells deliver high power density and offer the advantages of low weight and volume when compared to other fuel cells. Therefore PEM fuel cells are used primarily for automotive applications. The State Key Lab of Automotive Safety and Energy at Tsinghua University started research on the fuel cell vehicle in 2002 [2], and it mainly focused on commercial vehicles. With the support of the China National 863 Hi-tech Research Program, several fuel cell bus fleets were brought into service for the Beijing 2008 Olympic Games [3], the Shanghai 2010 Expo [4] and the Singapore 2010 Youth Olympic Games [5]. These fuel cell buses transported athletes, officials and visitors between stadiums, exposition halls and the athletes' village. These fuel cell buses demonstration projects accumulated a large amount of engineering experience [6,7] and on-road test data [8]. When fuel cell buses operate as green energy vehicles for public transportation, the safety of the fuel cell system becomes a significant factor, because faults and breakdowns of the fuel cell system could result in casualties and loss of income. Therefore fault

Abbreviations: AC, alternating current; ACO, ant colony algorithm; DC–DC, DC–DC converter; EWMA, exponentially weighted moving average; FCEV, fuel cell electric vehicle; PCA, principal component analysis; PCS, principal component subspace; PEMFC, proton exchange membrane fuel cell; SPE, squared prediction error; SPM, singular pencil model.

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Nomenclature

$\mathbf{C}_{fcs}$	projection array of fuel cell system
I_{fc}	fuel cell current output (A)
I_{inv}	invertor current (A)
$\mathbf{M}_{fcs}$	mean vector of training matrix of fuel cell system PCA model
P_{air}	manifold pressure (kPa)
$P_{co,in}$	deionized coolant pressure (kPa)
$\mathbf{R}_{fcs}$	covariance matrix of fuel cell system
$\mathbf{S}_{fcs}$	construct matrix of fuel cell system
$T_{ad,in}$	air temperature of enthalpy wheel inlet (°C)
$T_{ad,out}$	air temperature of enthalpy wheel outlet (°C)
$T_{ah,in}$	humidified air temperature of stack inlet (°C)
$T_{ah,out}$	air temperature of stack outlet (°C)
$T_{co,in}$	stack inlet temperature of deionized coolant (°C)
$T_{co,out}$	stack outlet temperature of deionized coolant (°C)
U_{fc}	total output voltage of fuel cell system (V)
$\mathbf{U}_{fcs}$	unit characteristic vector matrix of fuel cell system
U_{inv}	invertor voltage (V)
U_{sk1}	voltage of the first sub-module of the fuel cell stack (V)
U_{sk2}	voltage of the second sub-module of the fuel cell stack (V)
U_{sk3}	voltage of the third sub-module of the fuel cell stack (V)
U_{sk4}	voltage of the fourth sub-module of the fuel cell stack (V)
$\mathbf{X}_{fcs}$	training matrix of PCA model of fuel cell system
λ_i	eigenvalue of covariance matrix
$\sigma_{fcs,i}$	average variance of sensor data in Row i
$\boldsymbol{\Psi}_{fcs}$	variance matrix of fuel cell system

detection and diagnosis of the fuel cell system is an important aspect when promoting the commercialization of fuel cell powered vehicles.

Recent literature has provided several fuel cell stack and system diagnostic methods. T. Escobet et al. [9] gave a mathematical model of the hydrogen and air system in a fuel cell system and analyzed the system Relative Fault Sensitivity (RFS) to predict potential system failure. However this method demanded highly accurate modeling. C. Nitsche et al. [10] proposed a diagnostic method using adaptive identification modeling. This model processed a large number of test data to optimize the model parameters and estimated the status of the fuel cell by comparing the model output result and experimental polarization curves. L.A.M. Riascos et al. [11] analyzed observable variables of the fuel cell under fault conditions by the Bayesian network method and a simple fuel cell stack was implemented for the validation. Expert systems and the singular beam model (SPM, Singular Pencil Model) were also used on the fuel cell system for fault diagnosis. Various faults were classified and expert system rules were established [12]. Statistical tools were developed for diagnosis. X. Xue et al. [13] used the Hotelling T^2 statistical method for comparing the actual output and the model output by simulation. D. Hissel et al. [14] proposed a fuzzy diagnostic model of fuel cell, where output voltage and the current relation functions were optimized using a genetic algorithm. R. Wang et al. [15] introduced an off-board fuel cell diagnostic device, which improved the maintenance process of the fuel cell through the reproduction of the fuel cell vehicle parameters. Q. Chen et al. [16] analyzed sensor signals of the fuel cell with a joint Kalman filter, using the sensor deviation to determine the possible sensor fault diagnosis. However the author only completed the computer simulation. J. Guo et al. [17] used the Ant Colony Algorithm (ACO) to optimize the membership functions of the fuel cell fuzzy relational model. This method could detect the flooding status and the membrane dryness status. G. Ao et al. [18], Y. Kang et al. [19], and B. Cheng et al. [20] introduced several practical applications designed and developed for fuel cell diagnosis, respectively.

Although this literature provided various diagnostic methods for fuel cell systems in theory, most methods are based on solving the complicated calculations and differential equations on the condition that the fuel cell system model could be built precisely. Therefore they are in most cases too sophisticated to be applied in an embedded system for the real-time control of vehicles. This paper presents a diagnostic analysis and implementation study of the fuel cell system based on the multivariate statistical method. More specifically, the Principal Component Analysis method has been applied for identifying the fuel cell system malfunction caused by the sensor network's shift or failure. An advantage of this new methodology is that it does not require an accurate white-box model of the fuel cell and a powerful computing capability to provide a diagnosis. With the PCA method, the system identification process can be trained with sufficient test data in a black-box model to get the principal system components. This work is normally done off-line by means of computer calculations. After the principal components are determined, the diagnostic algorithm can be carried out by the in-vehicle control system and the fuel cell control system during road use. This diagnostic system was successfully implemented in the fuel cell shuttle bus at the Shanghai Expo 2010 and used in the fuel cell bus at the Singapore Youth Olympic Games in 2010.

The bus equipped with the fuel cell system and used at the Singapore Youth Olympic Games in 2010 is shown in Fig. 1. This hydrogen-propelled bus is powered by an AC motor with a rated power of 150 kW plus 75 kW of braking energy regeneration. Two fuel cell stacks with a total rated power of 80 kW and a 100 Ah power battery are provided as the hybrid power source. The fuel cell and battery are separated by a DC–DC converter.

2. Principal component analysis diagnosis theory

Research based on the multivariate statistical method mainly focuses on fault detection, with that based on the PCA fault