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Online remaining useful lifetime prediction of proton exchange membrane fuel cells using a novel robust methodology

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HIGHLIGHTS

- Applicability of different prognostic approaches is considered in terms of data types.
- PAM removes the non-stationary trend to obtain static time series.
- The identified ARMA model filters the linear component of the stationary time series.
- The remaining nonlinear component of time series is used to train TDNN.
- The proposed method guarantees robustness due to proper data preprocessing.

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ABSTRACT

This paper proposes a novel robust prognostic approach that contains three phases for degradation prediction of proton exchange membrane fuel cell (PEMFC) performance and its remaining useful lifetime (RUL) estimation. In the first detrending phase, a physical aging model (PAM) is used to remove the non-stationary trend in the original fuel cell degradation data. In the second filtering phase, the order of autoregressive and moving average (ARMA) model is determined by autocorrelation function (ACF), partial ACF and Akaike information criterion. The linear component in the stationary time series is then filtered by the identified ARMA model. In the third prediction phase, the remaining nonlinear pattern is used to train the time delay neural network (TDNN), in order to provide the final prediction result. Since the proposed prognostic approach uses appropriate methods to analyze and preprocess the original degradation data (i.e., the PAM maintains stationary trend, and then the identified ARMA filters linear component), the remaining nonlinear pattern of stationary time series can thus guarantee a good convergence performance of TDNN. In order to experimentally demonstrate the robustness and prediction accuracy of the proposed approach, degradation tests are performed using two types of PEMFC stack.

1. Introduction

Fuel cell has been considered the attractive candidate for the future power applications due to the worldwide energy crisis and environment pollution [1]. As one of the fuel cell technologies, the proton exchange membrane fuel cells (PEMFCs) have higher power density and energy efficiency at lower operating temperature and pressure [2]. Thus, they are particularly suitable for power mobile applications, such as portable power supply or fuel cell hybrid electric vehicles (FCHEVs) [3].

However, during the PEMFC operation, its performance is suffered from multiple failure mechanisms [4–6], mainly including losses of conductivity, catalyst reaction activity, and mass transfer, as shown in Fig. 1. These degradation mechanisms are generated by multiple uncertain circumstances and thus cannot be fully studied. That is the reason why the durability and reliability become the barriers to the mass deployment of the fuel cell.

In order to indicate the PEMFC state of health (SOH), estimate its remaining useful lifetime (RUL), and further minimize its maintenance costs, as well as increase its utilization and operational availability, the prognostic and health management (PHM) technologies are gaining attention [7–9]. As an important part of PHM, the prognostic modeling aims at predicting the PEMFC future degradation characteristics based

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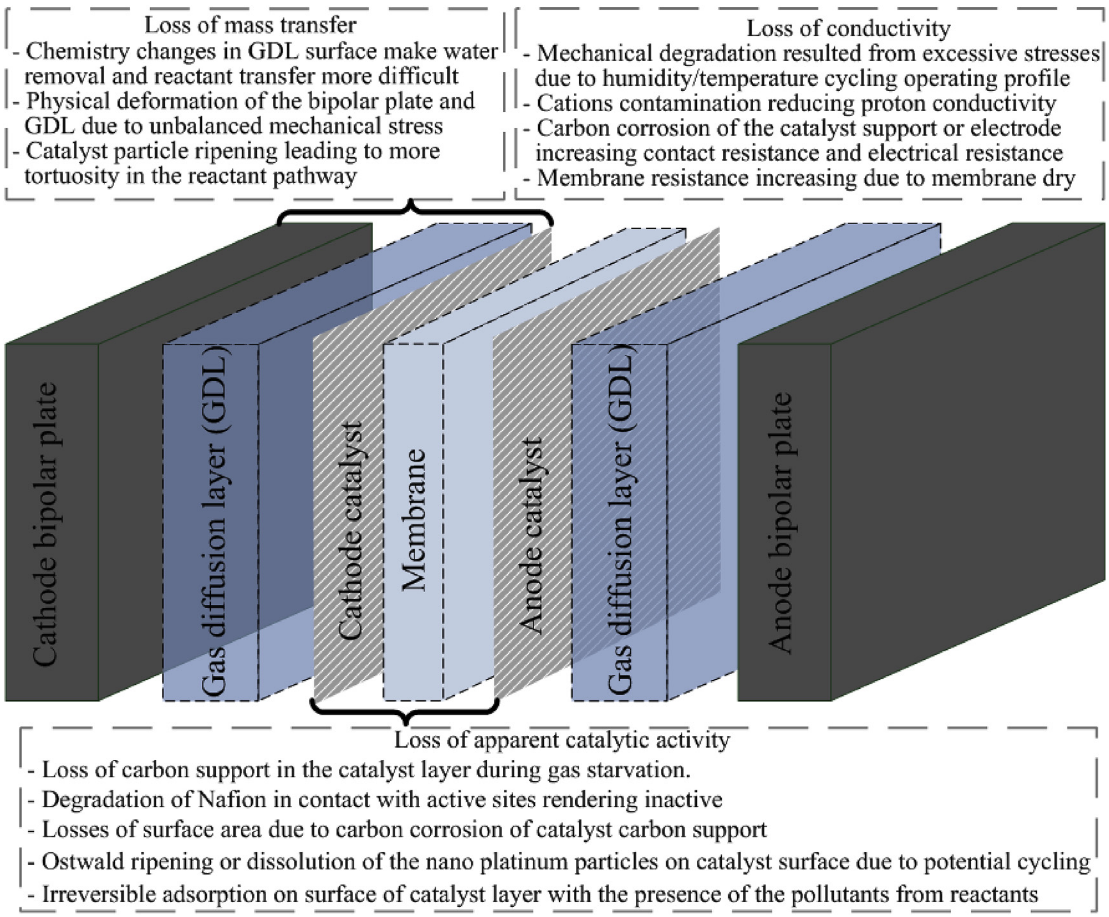

Fig. 1. Major causes of fuel cell performance degradation.

on the currently measured data from the actual PEMFC system. The PEMFC output voltage is commonly considered as the characteristics to indicate and evaluate the degree of PEMFC performance aging since during the fuel cell operation its voltage can be easily measured.

The prognostic approaches of the fuel cell system can generally be divided into three categories: model-based approaches, data-driven approaches, and hybrid approaches.

Model-based approaches include physical-based methods and empirical-based methods. Physical-based methods describe the real physical aging process, such as the materials aging or failure mechanisms. Bressel et al. [10] propose a physical-based aging model to predict the fuel cell future degradation behaviors. In this prognostic method, the Extended Kalman Filter is used to indicate the fuel cell state of health and further predict its remaining useful lifetime. The advantage of this prognostic approach is that it can work for different operating conditions of the fuel cell system. In our previous work [11], a multi-physical degradation model is developed for PEMFC prognostic. The proposed aging model uses three parameters to predict different degradation phenomena inside the fuel cell, including losses of conductivity, catalyst reaction activity, and mass transfer. Based on suitable pairs of parameters and curve fitting functions, the presented prognostic strategy can achieve a reliable prediction result.

Empirical-based methods use empirical models with fitted parameters to represent the fade trend of PEMFC performance during its aging process. Jouin et al. [12] have proposed three empirical models for PEMFC prognostic, including linear model, log-linear model, and exponential model. In this prognostic method, the empirical parameters are estimated using a particle filter framework during the training process. The updated empirical model is then used to forecast future voltage degradation. The exponential functions can be also used to describe the capacitor fade trend of lithium-ion batteries, and further estimate their SOH and RUL [13]- [14].

However, it is very difficult to develop a reliable physical-based aging model for prognostic application due to the complexity and uncertainty of the failure mechanisms. From the data mathematical-statistical point of view, the data-driven method uses classification or regression techniques to learn and forecast the future performance of PEMFC without considering the real aging phenomena. Marra et al. [15] have developed a predictor of solid oxide fuel cell (SOFC) for the prognostic based on artificial neural network (ANN). The solid oxide fuel cell experimental data, such as current density, reactants temperature, gas mass flow rate, and the operating hours are used to train the neural network. As a soft-computing technique, the autoregressive moving average (ARMA) model has a good ability to describe and predict the linear characteristics of stationary time series [16].

The third hybrid approach combines the previous two methods. In our previous work [17], a data fusion based prediction approach is proposed for PEMFC prognostic.

It should be noted that an appropriate selection of approaches is very complicated for different prediction problem, since knowing all the data characteristics is a difficulty. For example, the ARMA model is not suitable for non-stationary time series [18], the prediction performance of ANN model can be significantly affected by the data nonlinear degree [19]. Therefore, there is no universal method for every forecasting situation. In other words, it is not wise to directly use a prediction method without considering the data types. Such an important issue in terms of the applicability of fuel cell degradation prediction approaches for specific data types has not been reported so far in the literature.

This paper proposes a novel robust prediction approach for the fuel