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A hybrid prognostic model applied to SOFC prognostics

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ABSTRACT

Poor durability is one of the major hurdles for Solid Oxide Fuel Cell (SOFC) commercialization. Prognostic technology is an important approach to improve system durability. However, the current prognostic methods for fuel cells are mainly applied to proton exchange membrane fuel cell (PEMFC) systems, moreover, there are still shortages of recent prognostic algorithms. Therefore, an improved prognostic model is developed to predict the remaining useful life of the SOFC in this study, which combines a hidden semi-Mark model (HSMM) with an empirical model. To build the hybrid prognostic model, an HSMM and an empirical model are firstly built. The merit and demerit of the respective prognostic methodology are then analyzed. According to the analysis results, the hybrid prognostic model is proposed and applied to six sets of SOFC run-to-failure data. The results show the proposed prognostic model has a higher prediction accuracy and a faster forecasting speed compared with the existed approaches for SOFC prognostics.

Introduction

Solid Oxide Fuel Cell (SOFC) is an electro-chemical device, which can convert chemical energy into electrical energy. Due to its low emission and high efficiency, SOFC is considered to be a promising generation technology [1]. Nevertheless, because of inadequate operational states, impurities in gases and materials deterioration, poor long-term performance is one of the major hurdles for the commercialization of SOFC [2].

In order to improve system's durability, in this study prognostic technology is proposed to predict the future condition of a system. According to International Standard Organization(ISO), prognostic is defined as "the estimation of the operating time before failure and the risk of existence" [3]. Based on the ISO standard, it allows to define the remaining useful life, which is "the estimation of the time between the current moment and the moment when the monitored system is considered as failed " [4]. Thus, the objective of prognostic is to estimate the remaining useful life of the system to be functional.

Various prognostic methods have been successful applied in the fuel cell systems, and they can be divided into two types of approaches: model-based and data-based approach. Model driven approach uses mathematical equations to describe the degradation process of the system, which requires a precise knowledge of the system failure mechanisms [5]. A physics-based model was firstly built, and then unscented kalman filter was proposed to capture the degradation of the proton exchange membrane fuel cell (PEMFC) [6]. A first-order mathematical model was established to estimate the remaining useful of the PEMFC [7]. A power degradation model

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was presented based on a detailed understanding of the degradation phenomena [8].

Data-based approach is also named a black box method, for it has no direct link with the physical phenomenon occurred in the system. In this case, the monitored historical data is employed to discuss the degradation process of the system [5]. Data driven prognostic approach can be classified into two categories: 1) degradation modeling; 2) direct prediction modeling.

For the degradation modeling, a degrading signal is firstly estimated, such as voltage or power. The remaining useful life of the system is then calculated when the degrading signal reaches a pre-defined failure threshold. Empirical models were built to follow the power degradation due to time varying parameters, and then the residual life of the PEMFC was predicted when the power intersected the failure threshold [9]. Four empirical models were used to predict the power degradation trend of the PEMFC [10]. Five empirical models based on weighted mean was developed to estimate the voltage [11]. Three empirical models of the voltage drop were proposed for PEMFC prognostic [12]. Summation Wavelet-Extreme Learning Machine algorithm was presented to estimate the voltage degradation of the PEMFC and then the residual life was predicted [13]. An echo state network was reported to forecast the voltage degradation of PEMFC [14]. An adaptive neuro-fuzzy inference system was studied to estimate the PEMFC voltage [15]. Using an improved relevance vector machine, the PEMFC degradation was predicted [16]. Based on the group method of data handling and the wavelet analysis, a short-term prognostics method was developed to predict the voltage for the PEMFC [17]. Using a neural network model, the SOFC voltage degradation was estimated [18].

Direct prognostic modeling can predict the remaining useful life of the system directly, by finding the similarity between the observed data and the training data. The approach does not define a failure threshold, and directly learns from the data. A hidden semi-Markov model (HSMM) was exploited to predict the residual life of the SOFC by the present author [19]. Despite the great progress in prognostic technique for the fuel cell, the existing literature still has several drawbacks:

* Using the model-based prognostic approach, it is a difficult task to build the degradation model to reflect the degradation process of the fuel cell, since the fuel cell system is a complex multi physics system, which involves mechanical, electric, thermal, fluidic and electrochemistry phenomena. Moreover, the system is a time and space multi-scale system.
* The degradation modeling is a very time-consuming process, because the models use the past degradation signal to predict the future value, which implies that if new data is available, the prognostic model should be rebuilt. Moreover, to obtain a precise prediction model, a group of models with various initialization is generally needed to be trained.
* The direct prognostic modeling depends on the similarity between the test and training data. For example, using the HSMM, if the drop trend of the test data is much different from the training data, the prognostic accuracy may not be high.

To address the above issues, a hybrid prognostic model based on data-driven approach is presented to perform the remaining useful life prediction for the SOFC, which integrates an HSMM with an empirical model of degradation. As described above, using the empirical model, it is time consuming to predict the remaining useful life; nevertheless, using the HSMM method, the prediction accuracy strongly depends on the similarity between the test and training data. The hybrid prognostic model can exploit the strengths and eliminate the weaknesses of the respective prognostic methodology, rather than continuing to select between the individual prognostic approach [20]. When the degradation trend of the test data is similar with the training data, the HSMM method is used to predict the residual life for the SOFC, which can avoid rebuilding the prognostic model when new data is provided and improve the prognostic speed. Otherwise, the empirical model which can improve the prediction accuracy is employed for SOFC prognostic. The main contributions of this paper are summarized below:

* The proposed prognostic algorithm not only guarantees a higher prediction accuracy, but also improves the prognostic speed compared to the existed prognostic approaches.
* The proposed hybrid prognostic model is applied to the SOFC. To the best of our knowledge, only two articles previously studied the SOFC prognostic technique.

The paper hereafter is organized as follows. Section Problem formulation explains SOFC prognostic problem. In Section SOFC prognostic using the individual model, the HSMM and the empirical model are respectively presented for SOFC prognostic. According to their own advantages and disadvantages, the hybrid model is proposed to predict the remaining useful life of the SOFC in Section SOFC prognostic using the hybrid model. Section Results draws the conclusion.

Problem formulation

For the SOFC anode, different kinds of fuels can be considered. Nevertheless, practical fuels often contain chlorine compounds at 100 ppm or higher concentration, especially in coal gas [21,22]. Degradation is occurred in the SOFC system when a high concentration of Cl_2 is supplied in the anode [21,22]. Therefore, it is necessary to discuss the influence of Cl_2 poisoning on the SOFC performance. Since the ambient air is continuously supplied to the cathode, it can not ignore the influence of water vapor in the air on the cathode performance to test long-term durability of the SOFC. Ref. [21,23] demonstrated a high concentration of water vapor supplied in the cathode could lead to the degradation of the SOFC performance. When the SOFC contains the impurities, such as Cl_2 at the anode or water vapor at the cathode, it generally experiences several health states (good, medium, bad, etc) to reach failure, which is illustrated in Fig. 1.

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