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A hybrid remaining useful life prognostic method for proton exchange membrane fuel cell

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ABSTRACT

Proton Exchange Membrane Fuel Cell (PEMFC) has become a promising power source with wide applications to many electronic and electrical devices. However, even if it is a competitive energy converter, PEMFC still suffers from its limited lifespan. Prognostics appear to be a good solution to helping take actions to extend its lifetime. Considering both advantage and disadvantage of model-based and data-driven based prognostic methods, this study proposes a hybrid prognostic method for PEMFC based on a data-driven method, least square support vector machine (LSSVM) and a model-based method, regularized particle filter (RPF). The main contributions of the proposed method include: 1) It can provide not only an estimated value but also an uncertainty characterization of RUL with a probability distribution; 2) It has a better capability to capture the nonlinearities in degradation data and a lower reliance on PEMFC degradation model; 3) The RPF method improves the standard particle filter algorithm by reducing the degeneration phenomenon and loss of diversity among the particles. Effectiveness of the proposed method is verified based on PEMFC dataset provided by FCLAB Research Federation. The results indicate that the proposed hybrid method can effectively combine both advantages of data-driven and model-based methods, providing a higher accuracy of RUL prediction for PEMFC.

Introduction

Proton Exchange Membrane Fuel Cell (PEMFC) has been considered as one of the most promising power source which can be widely applied in military, transportation, and combined heat and power systems by virtue of its high power density, environmental friendliness, light weight, and abundant resources [1–3]. However, its limited lifespan, long-term performances, and maintenance costs is a big obstacle for the deployment and commercialization of PEMFC [4,5]. Prognostics and health management (PHM), and particularly prognostics, has attracted increasing attention in resent years, which offers a good solution to extend the lifetime of PEMFC. PHM for PEMFC aims at utilizing real monitoring data to predict the health degradation of PEMFC and estimate the residual useful life (RUL) of PEMFC, so as to help making good decisions to take adequate actions at the right time. In this

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Nomenclature

$\boldsymbol{x}_i$	The ith input data
y_i	The ith output data
d	The dimension of $\boldsymbol{x}_i$
$\varphi(\cdot)$	Nonlinear function
$\boldsymbol{w}$	Weight vector
b	Bias term
C	Adjusting factor
ξ	Error variable
$L(\boldsymbol{w}, b, \xi, \alpha)$	Lagrange function
α_i	Lagrange multipliers
$\mathbf{K}$	Kernel matrix
K_{ij}	RBF kernel
x_k	System state
z_k	System observation
$f(x_{k-1}, \upsilon_{k-1})$	State transition function
$h(x_k, n_k)$	Measurement function
υ_{k-1}	System noise
n_k	Measurement noise
$p(x_k \| z_{1:k-1})$	Approximation of the prior probability density function at the kth cycle
$p(x_k \| x_{k-1})$	Transition probability distribution defined by the state model
$p(x_k \| z_{1:k})$	Posterior probability density function at the kth step
$p(z_k \| x_k)$	Likelihood function of the measurement model
$p(z_k \| x_k^i)$	Likelihood function of the ith particle at step k
N_{eff}	Effective sample
N_{thres}	Threshold of effective sample
$K(\cdot)$	Kernel density
K_h	Rescaled version of kernel density $K(\cdot)$
h	Kernel bandwidth
n_x	Dimension of the state vector x
K_{opt}	Optimal Kernel
c_{n_x}	Volume of the unit hypersphere in R^{n_x}
h_{opt}	Optimal bandwidth
σ	Standard deviation of n_k
$T_{EoL\_prognostic}$	Predicted EoL time
T_{EoL_true}	Actual EoL time
$RUL_{\_prognostic}$	Predicted PDF distribution of RUL
$RUL_{\_true}$	Time distance between the true EoL time and the prognostic start time

way, the lifetime of PEMFC can be extended with more adequate usage mechanism. In the full process of PHM, prognostics is the core technology which plays an important role for the following health management [6].

Prognostic techniques can be conditionally classified into long-term prognostic techniques and short-term prognostic techniques. Ref. [7] presents a good overview of short-term prognostic techniques, including neural networks, autoregressive integrated moving average, genetic algorithm, etc. The authors of Ref. [7] also presented an algebraic prognostic approach with mixed smoothing (APMS) for short-term time series. However, in the field of PEMFC, a long-term prognostic is more expected since it can provide more important degradation information to PEMFC users from a long-term perspective, so that adequate actions can be taken timely to prolong the lifetime of PEMFC. Moreover, APMS has a good performance for non-linear time series, but does not work well with non-stationary time series. Considering the variable working conditions and unknown external disturbance of PEMFC in real applications, the monitoring data of PEMFC are usually non-stationary. Thus, a prognostic approach which can successfully dealing with such uncertainties should be proposed. Most existing prognostic methods for PEMFC can be classified into two main categories: model-based methods, including extended Kalman filter [8], particle filter [6,9], and physical phenomena-based model which is based on the degradation law and electrical equivalent circuit [10]; and data-driven methods, including neural network [11], relevance vector machine [12], neuro-fuzzy inference systems [13] and some machine learning methods [14]. Model-based methods aim at establishing empirical or mechanism models to simulate the degradation process of PEMFC according to the complex degradation mechanism [2]. The advantage of this kind of method is that it doesn't require a large amount of data. It can also provide an accurate prognostic result given an accurate degradation model. However, the construction of accurate degradation model of PEMFC is usually difficult in real applications, since the complex degradation mechanism of PEMFC is not fully understood yet [2]. Data-driven based methods, on the other hand, don't need priory knowledge to establish an accurate degradation model, since they aim at mining the degradation law of PEMFC by learning the available degradation data using some intelligent computation methods. This kind of method doesn't need to fully understand the degradation mechanism of PEMFC and have a good capability to catch the nonlinearities contained in the monitoring signal [6]. However, the main drawback is that the performance of data-driven based method strongly relies on the amount and quality of data in the training process. Considering both advantage and disadvantage of model-based methods and data-driven based methods, this study presents a hybrid prognostic method for PEMFC in order to combine both advantages of model-based methods and data-driven based methods, thus improving the prognostic accuracy of PEMFC.

Particle filter, one of the typical model-based prognostic method, is based on Bayesian technique, which employs a set of weighted particles to form a posterior distribution of the system. Compared with Kalman filter, particle filter shows excellent performance in dealing with nonlinear systems with non-Gaussian noise [15]. Thus, particle filter-based prognostics have become a hot issue in recent years. However, in the particle filter method, particle degeneracy phenomenon and loss of diversity among the particles affects the prognostic accuracy heavily, which restricts its real application. In this study, a modified particle filter method, regularized particle filter, is proposed to solve the above mentioned problem. On the other hand, least square support vector machine (LSSVM) is a data-driven method, which is much easier and computationally simpler than standard support vector machine. Compared with neural networks, LSSVM has a better generalization performance [16]. Nowadays, LSSVM has been widely applied in the field of wind power prediction [16], electronic equipment [17], bearing degradation prediction [18],

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