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Proton exchange membrane fuel cell degradation prediction based on Adaptive Neuro-Fuzzy Inference Systems

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ABSTRACT

This paper studies the prediction of the output voltage reduction caused by degradation during nominal operating condition of a PEM fuel cell stack. It proposes a methodology based on Adaptive Neuro-Fuzzy Inference Systems (ANFIS) which use as input the measures of the fuel cell output voltage during operation. The paper presents the architecture of the ANFIS and studies the selection of its parameters. As the output voltage cannot be represented as a periodical signal, the paper proposes to predict its temporal variation which is then used to construct the prediction of the output voltage. The paper also proposes to split this signal in two components: normal operation and external perturbations. The second component cannot be predicted and then it is not used to train the ANFIS. The performance of the prediction is evaluated on the output voltage of two fuel cells during a long term operation (1000 h). Validation results suggest that the proposed technique is well adapted to predict degradation in fuel cell systems.

Introduction

Fuel Cell Systems (FCS) and in particular Proton Exchange Membrane Fuel Cells (PEMFC) appears to be an alternative to reduce the dependence on fossil energy, one of the economic and environmental challenges of modern society. The advantages of this technology include high efficiency, low emissions, fast system start-up ability, and high power density. However, they have several drawbacks such as complex water and heat management, intolerance to impurities in incoming gases and slow kinetics of oxygen reduction reaction. FCS are not yet ready

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to be considered for large scale industrial development, indeed further efforts must be undertaken to optimize this technology, particularly by increasing its reliability and lifespan [1–4]. PEMFC durability is affected by factors such as stack design and assembly, materials degradation, operating conditions, impurities and contaminants [5–8]. The operation of the fuel cell causes degradation which always involves a reduction in the output voltage and then a loss of performance because of the reduction in the output power. Moreover, each fuel cell has a unique degradation profile based on its history and operating conditions. Degradation is an unavoidable condition; nevertheless it can be minimized and even mitigated with effective prognostics and diagnostics tools.

Prognostics is the process of predicting the future condition of a system based upon current and previous system states. Prognostics systems aim to predict the Remaining Useful Life (RUL) of the system and to determine when maintenance should be performed for avoiding equipment breakdown [9–15]. Several recent studies focus on the implementation of Prognostic and Health Management (PHM) methods to guarantee a safe longer term operation and to increase reliability and availability while reducing maintenance and operating cost. PHM encompasses the following core areas: avionics [16–18] electronic systems [19–22], power and energy systems [23–25], structural degradation [26–29], healthcare and medical technology [30,31] and so forth. Prognostic of FCS is a relatively new field of research where only few works have been published. Among these works, Wang et al. [32] proposes to use Kalman Filters, in Ref. [33] the authors propose a Solid Oxide Fuel Cell model based on Neural Networks, and Jouin et al. [34] summarizes the current state of the art on prognostic and health management for PEM fuel cell systems.

Prognostics approaches are classified into three categories: model-based also known as Physics of Failure (PoF), data-driven, and fusion approach. Model-based methods assume that an accurate mathematical model can be constructed from physical understanding of the system [35–38]. Data-driven approaches use historical data to estimate degradation, their main interest is their ability to represent complex and non-linear relationships among data [39–42]. The fusion approach combines the advantages of data-driven and model-based methods [13,43–45].

Fuel cell systems are complex multi physics (electric, fluidic, electrochemistry, thermal and mechanical phenomena) and multi scale (time and space) systems. The modeling of their degradation is a difficult task, as consequence of its nonlinear nature, the non-reversibility of their reactions and the interactions between their multiple subsystems. PHM tools must be implemented in a FCS to anticipate and avoid failures, to estimate mid-term and/or long-term State of Health (SoH) and to decide upon mitigation and control strategies. This is the reason why data-driven are more adapted than model-based approaches for performing prognostics of fuel cell systems.

Data driven approaches for prognostic can be divided into two categories: statistical techniques and artificial intelligence techniques (such as neural networks, fuzzy systems, neuro-fuzzy systems). Among these techniques, Adaptive Neuro-Fuzzy Inference Systems (ANFIS) are considered because they do not require complex mathematical models, they are fast and adaptive and the developed prediction tool can be implemented on-line, which is essential for PHM of fuel cell systems. Their principal drawback is that the performance of the predictions is highly depending in quantity and quality of data [46–49]. Approaches based on the use of experimental data to construct neuro-fuzzy inference systems have been used in a variety of applications such as medical [50–52], motors [53–55] and fuel cell diagnosis [56]. Moreover, ANFIS has been used to performance (current–voltage curve) prediction of a PEMFC [57].

The first contribution of this paper consists in defining the architecture of the ANFIS prediction system that is defining the inputs and outputs of the system as well as to determine the parameters to train. This is done by considering not only the accuracy of the system but also its ability to be implemented into real-time. The second main contribution of this paper consists in proposing a method to reduce the error in the predictions caused by external perturbations in the output voltage (such as transients when the fuel cell is started). Therefore, the paper proposes to split the signal in two components: the voltage due to normal operation and a second caused by external perturbations.

This paper is organized as follows: Section 2 provides the research context about fuel cell systems, prognostics and health management, and ANFIS. Section 3 introduces the ANFIS-based prediction methodology and the evaluation of its performance. Section 4 illustrates the implementation of the methodology by predicting the Mackey-Glass temporal series, the prediction of this time-series is a benchmark problem widely used in the literature as reference to evaluate the performance of prediction tools [58–60]. The methodology to predict the output voltage in a fuel cell is presented in Section 5. The final section presents the conclusion and outlooks.

Research context

One of the challenges to develop fuel cell systems in an industrial scale is to optimize them, particularly by increasing their reliability and lifespan. FCS degradation has to be studied to quantify their Remaining Useful Life (RUL) and therefore reduce the risk of failure. As the stack voltage is the simplest indicator of the SoH and performance of the FCS, this paper proposes a methodology to predict the voltage decrease due to the degradation under nominal operating condition. Operation of the PEM fuel cell system under nominal conditions is referred to the parameters that have to be set by the user to keep the system in its optimum performance. Taking into account the high complexity of fuel cell systems, the methodology is based on ANFIS. In general, ANFIS enables diagnostics/prognostics because of its abilities to learn, to model nonlinear functions without explicit knowledge of its physical behavior [61–63]. Thus, it can be used to lifespan estimation and then integrated in the maintenance activities to ensure the reliability of FCS.

Fuel cell prognostics and health management

Prognostics and health management of fuel cell systems is performed by following the next four stages: data acquisition, data preprocessing, diagnostic and prognostic, and decision