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Fuel cell stochastic deterioration modeling for energy management in a multi-stack system

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Fuel cells use hydrogen and oxygen as reactants to produce electricity through electrochemical reactions with the only byproduct of water. They are widely used in various applications, e.g. transport, due to their high efficiency, energy density, and limited impact on environmental resources, however fuel cells deployment is held down by multiple barriers such as their high cost or their shorter than required lifetime. To cross over these barriers, using multi-stack fuel cells (MFC) instead of a single one is a promising solution. Firstly, MFC offers improved reliability thanks to the multi-stack structure. Another advantage is that the durability of multi-stack FC can also be increased by optimally distributing the power demand among different stacks by an efficient Energy Management Strategy (EMS), and thus avoiding degraded mode operation [1]. In short, MFC systems are relevant to meet this challenge if properly dimensioned and managed by an appropriate EMS taking into account the deterioration of the cells. In order to implement such a degradation-aware EMS, it is mandatory to build a degradation model that integrates the dynamic behavior of MFC according to the operating conditions. Fuel cell performance degradation is linked to complex electrochemical, mechanical, and thermal mechanisms, which are difficult to model using a "white-box"approach, relying on the exact laws of physics. Within this context, the aim of the present work is to propose a fuel cell degradation model adapted for the energy management of MFC.

The deterioration behavior of an MFC is characterized by two main features : (i) it is load-dependent, i.e. the degradation is affected by the load distributed by the stack ; (ii) it is stochastic and exhibits a stack-to-stack variability. A degradation-aware energy management system allocates a load to deliver to the different stacks of the MFC system as a function of their degradation state and of their predicted degradation behavior. The deterioration dynamics must thus be modeled as a function of the load power. Another specificity of fuel cells is their individual deterioration variability, which can be due to stochasticity in the intrinsic fuel cell deterioration phenomena. This stochasticity varies the deterioration levels even for the identical stacks operating under identical load profiles.

In order to meet these modelling requirements, this work develops a load-dependent stochastic deterioration model for an MFC. First, the overall stack resistance is chosen as the degradation indicator, as it carries the key aging information of a fuel cell stack. Then, a stochastic non-homogeneous Gamma process is used to model the deterioration of the fuel cell, i.e. the increase in the fuel cell resistance. The shape parameter of the considered Gamma process is further modeled by an empirical function of the fuel cell operation load in order to make the resistance deterioration load-dependent. Finally, to model the individual deterioration heterogeneity, a random effect is added to the Gamma process on its scale parameter, taken as a random variable following a probability distribution (a Gamma law is chosen in this work).

Resistance degradation paths can then be simulated based on the proposed deterioration model, based on which the first hitting time distribution of a failure threshold (or equivalently a remaining useful life distribution) can be estimated and the reliability of the system can be analyzed. The proposed model can also be used to optimize the load allocation strategy for an MFC [2].

Keywords: Multi-stack fuel cells, load-dependent deterioration model, stochastic modelling, Gamma process, random effect.

References:

[1]Marx, Neigel, et al. "On the sizing and energy management of an hybrid multistack fuel cell–Battery system for automotive applications." International Journal of Hydrogen Energy 42.2 (2017): 1518-1526.

[2] Zuo, J., C. Cadet, Z. Li, C. Bérenguer, and R. Outbib (2022). Post-prognostics decision-making strategy for load allocation on a stochastically deteriorating multi-stack fuel cell system. To appear in Proc. Inst. Mech. Eng - Part O: Journal of Risk and Reliability.

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