Reliability Engineering and System Safety 148 (2016) 78–95

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

journal homepage: www.elsevier.com/locate/ress

Degradations analysis and aging modeling for health assessment and prognostics of PEMFC

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ARTICLE INFO

Article history:
Received 30 January 2015
Received in revised form
16 November 2015
Accepted 10 December 2015
Available online 19 December 2015

Keywords:
Proton Exchange Membrane Fuel Cell (PEMFC)
Health assessment
Prognostics
Critical components
Aging model

ABSTRACT

Applying prognostics to Proton Exchange Membrane Fuel Cell (PEMFC) stacks is a good solution to help taking actions extending their lifetime. However, it requires a great understanding of the degradation mechanisms and failures occurring within the stack. This task is not simple when applied to a PEMFC due to the different levels (stack - cells - components), the different scales and the multiple causes that lead to degradation. To overcome this problem, this work proposes a methodology dedicated to the setting of a framework and a modeling of the aging for prognostics. This methodology is based on a deep literature review and degradation analyses of PEMFC stacks. This analysis allows defining a proper vocabulary dedicated to PEMFC's prognostics and health management and a clear limited framework to perform prognostics. Then the degradations review is used to select critical components within the stack, and to define their critical failure mechanisms thanks the proposal of new fault trees. The impact of these critical components and mechanisms on the power loss during aging is included to the model for prognostics. This model is finally validated on four datasets with different mission profiles both for health assessment and prognostics.

1. Introduction

Considered as a promising technology for chemical energy conversion into electricity, Proton Exchange Membrane Fuel Cells (PEMFC) are no more far from a large scale deployment. However, some improvements are still required to extend the lifetime of these systems. Prognostics and Health Management (PHM) appears as a great solution to help tackling this issue. Indeed, PHM is composed of a set of activities starting from monitoring and data processing. This leads to health assessment, diagnostic and prognostics, to finally use all the gathered information for decision making. This whole proposition aims at taking the right decisions at the right time to help preserving a system and extending its lifetime until its mission is complete. PHM of PEMFC is still a very recent research topic and a lot of challenges can be highlighted, particularly regarding prognostics [1].

Prognostics can be considered as the key process of PHM at it enables predicting the future behavior of a system as well as its remaining useful life (RUL) [2]. Prognostics applications on PEMFC are still rare in literature but are developing. Different approaches can be identified: (1) data-driven approaches [3–5], and (2) model-based or hybrid approaches [6–8]. However, they do not include explicitly the mission profile making their applications limited.

To support PHM, failure analysis and reliability modeling of PEMFC should be developed. Different dependability analyses are already existing regarding PEMFCs such as [9,10] if the whole system is considered. As the stack is the major concern of this work, let us go down to that level. Some interesting works focusing on failure and dependability analysis of PEMFC stacks can be found in literature: fault tree analysis [11–13], Petri nets [14] or other classifications created for the needs of the authors [15,16]. The major drawback of these works is the lack of explicit hypotheses preventing to know in which context these studies can be used. It is widely asserted that PEMFC are reliable systems as they do not have any moving part. Nevertheless, numerous degradation mechanisms tend to shorten their lifetime.

To built a degradation model suitable for health assessment and prognostics, a great understanding of all the aging mechanisms occurring within a PEMFC stack is needed. Current reviews on PEMFC degradations [15,17–19] are becoming too old, new experiments and understandings have appeared since then.

This paper aims at developing a degradation and failure analysis dedicated to PHM and more precisely to health assessment and prognostics of PEMFC stacks. Indeed, with this focus, a deep understanding of degradation will help selecting critical components which degradation strongly impact the outputs of the stack, namely the power and the lifetime. Once these critical components selected,

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http://dx.doi.org/10.1016/j.ress.2015.12.003

the main aging mechanisms are chosen and their impact is integrated in a degradation model that can be used for prognostics. The main contributions of this work are:

1. the proposal of a standardized vocabulary for PHM of PEMFC;
2. the definition of a working framework for reliability analysis and PHM of PEMFC;
3. a new degradation and failure analysis based on an updated literature review;
4. and based on this analysis, a new degradation model of the stack is proposed, analyzed and partially validated.

To achieve these goals, the paper is organized as follows. First, the background of PEMFC functioning is briefly reminded. This allows defining the vocabulary necessary for the study as well as a working framework for PHM. Section 3 is dedicated to the degradation and failure analysis, critical components are selected before choosing their main degradations that will appear in a degradation model. This is used in Section 4 to set a degradation model based on physics that includes both the aging and the current demand. Finally, the capabilities of the model for health assessment are demonstrated on four datasets in Section 5 before concluding.

2. Toward a prognostics working framework

2.1. Proton Exchange Membrane Fuel Cells

PEMFC is a specific fuel cell type using air (oxygen) and hydrogen to produce electricity, water and heat [20]. It can be encountered in a wide variety of applications [21] such as transportation (car, boats, etc.), stationary applications (auxiliary power unit, combined heat and power generation (μ-CHP)) or powering of portable devices, alone or combined with other devices like batteries or ultra-capacitors.

Different levels of system granularity exist. First, a “PEMFC system” refers to a PEMFC stack and all its auxiliaries (reactant storages, pumps, etc.). The stack is the part that converts the energy and is referred as the fuel cell. The stack is an assembly of elementary cells. Their number may vary from a single one to several hundreds depending of the output power expected from the stack. Finally, a cell is composed of different components

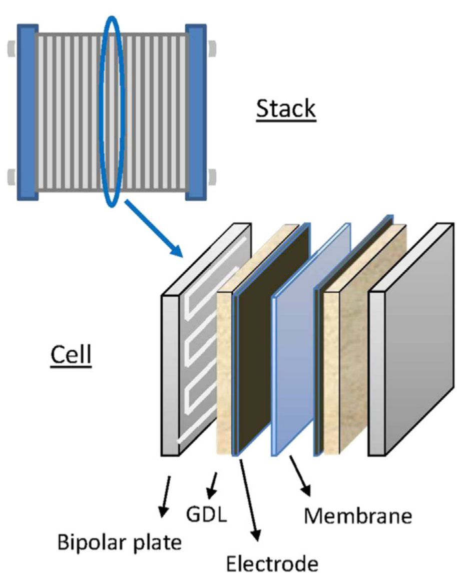

Fig. 1. The different components of a PEMFC stack.

(Fig. 1). To provide electricity, different oxydo-reduction reactions occur within the stack [7]. The global reaction equation of the system is:

$$H_2+\frac{1}{2}O_2\rightarrow H_2O+\textit{electricity}+\textit{heat} \tag{1}$$

Different output powers can be obtained from a stack. It depends on the input mission profile which can be expressed in terms of current (in Amperes) or power requirements (in Watts). In this work, the stack input is defined by the current whereas the power is the observed output. As it will be shown later, the mission profile strongly impacts the lifetime of the stack. To allow current variations the auxiliaries make the operating conditions varying (temperatures, pressures, etc.) to maintain the stack in its nominal operating conditions. If not, a degradation may happen. In this study, the focus is the stack and its subcomponents. The operating conditions are supposed always optimal and the auxiliaries never fail. In that way, a stack failure is only due to its own aging.

The vocabulary used in this work is now be defined.

2.2. Vocabulary definition

As fuel cell and reliability or PHM communities tend to use different vocabularies, it is important for a good understanding to define a precise vocabulary. Let us start with the terms “reversible degradation” and “irreversible degradation” used in a lot of PEMFC papers.

2.2.1. Degradation and reversible phenomena

During the aging of the stack, all the components age and their performance decreases. This can be seen in the power delivered by the stack particularly with a constant current profile where the power, instead of remaining constant, decreases slowly with time, Fig. 2. However, when the stack is stopped for a resting period or for characterizations, recoveries can be observed on the power. Indeed, some phenomena occurring during the aging are reversed, Fig. 2.

The existing expression, namely “reversible degradation”, regarding these phenomena may sound weird out of the FC community. In that community, this expression is often opposed to “irreversible degradation”. To use standardized vocabulary, the terms are re-defined according to the norm EN 13306 [22]. Degradation is defined as: “An irreversible process in one or more characteristics of an item with either time, use or an external cause”. Consequently, the expression “irreversible degradation” is reduced to the word degradation. “Reversible degradation” is a nonsense regarding the norm definition. It is replaced by reversible phenomena or reversible mechanism.

Reversible phenomena have been observed in different works [23,24] but are not fully explained. They appear in voltage and power measurements in forms of recoveries. Interruptions of continuous testing by resting periods, characterizations with *in situ* methods or major changes in gas flows seem to be some causes of the phenomena. When the stack goes through changing operating conditions, gas and water diffusion within the cells are affected, changing their spatial distributions. These reversible phenomena are part of transient regimes and disappear once the stack comes back to a permanent regime.

2.2.2. Modes and failure

Then, in the PEMFC literature, the notion of mode is unclear. For example the expression “degradation mode” can be found referring to the appearance and evolution of a degradation. In this paper, we prefer using “degradation mechanism” or “failure mechanism” to deal the degradation's appearance and evolution.