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Extended Kalman Filter for prognostic of Proton Exchange Membrane Fuel Cell

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HIGHLIGHTS

- A degradation model of PEM fuel cell is developed.
- Extended Kalman Filter is proposed for online estimation of the SoH and its dynamic.
- RUL predictions are evaluated over lifespan.
- An analysis of robustness of the method to model errors is carried out.
- Results with experimental data verify the effectiveness of the method.

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ABSTRACT

The Proton Exchange Membrane Fuel Cell is a promising energy converter for various fields of application: stationary, portable and mobile. However durability avoids its widespread deployment. Deterioration mechanisms are not all fully understood and that is the reason why the prognostic of such device is gaining attention. This helps determine the present and future state of health of Fuel Cell, to deduce the remaining life in order to take corrective actions. The work presented in this paper attempts to address this issue by proposing a method based on a degradation model. An observer, based on an Extended Kalman Filter, estimates the state of health and the dynamic of the degradations. This result is extrapolated until a threshold is reached and the residual life is deduced. This method allows estimating the lifespan with a single model, robust to uncertainties, whatever the operating conditions are. Simulations are conducted to validate the method. Finally, this framework is used on a set of experimental data from long term test on a 5-cell stack operated under a constant current solicitation.

1. Introduction

In a context of declining fossil energy resources and global warming, it is imperative to begin an energy transition. This transition involves the use of renewable energy, highly intermittent in most cases. The storage of this energy is complex and most of the storage device does not meet the requirement of efficiency, lifespan, power density and cost [1]. The use of hydrogen as an energy vector and the Proton Exchange Membrane Fuel Cell (PEMFC) to convert it into electricity seems to be a promising alternative to fossil energy [2]. Besides the transportation domain, PEMFC showed also their interest to supply energy to systems of small size such as mobile electronic devices [3] and also for micro-CHP (Combined Heat and Power) applications [4]. However, PEMFC systems suffer from multiple impairments that lower their lifespan and prevent their widespread deployment. These degradation mechanisms are irreversible and are not all fully understood. They include the deterioration of the carbon support, the dehydration of the membrane, or a catalytic degradation [5].The voltage drops associated to these phenomena are difficult to predict because they depend also on the operating conditions [6].

This is the reason why the Prognostic and Health Management (PHM) of PEMFC is gaining attention. This allows monitoring, diagnosis, prognostic, and help determine corrective action to extend the life of the power converter [7]. Using relevant data from the system to monitor, one can build indicators of the state of health as well as their trends. It allows to plan preventive maintenance at the right time, and so reducing costs. Moreover, knowing the state of health and remaining life of a fleet of energy sources (e.g. batteries and PEMFC), one can estimate the power that can

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be delivered individually by these sources and decides to adapt the energy distribution. It allows to increase the service time of the system or to ensure that the mission is completed successfully. Although papers concerning pronostic of fuel cell begin to appear, the range of application of the methods developed is limited to a single operating condition. One of the major objective of this paper is to tackle this limitation by proposing an algorithm able to perform prognostic for different operating conditions, static or dynamic.

In this context, this paper contributes to observer-based prognostic of PEMFC. It deals with the estimation of the State of Health (SoH) and its evolution in future time using a degradation model and an Extended Kalman Filter (EKF). The determination of the Remaining Useful Life (RUL) of a PEM fuel cell is therefore deduced. This novel method has the advantage of working for different operating condition (current, temperature etc.) without extra training or reconfiguration of the model. In Section 2, some generalities about prognostic and a state of the art of prognostic applied to PEM fuel cell are introduced. A description of the experimental setup and the performed test can be found in Section 3. Section 4 presents a model of degradation of PEMFC, a damage tracking and a damage prediction algorithm based on an Extended Kalman Filter to estimate the RUL. The parameterization of this algorithm and its robustness to model errors are also discussed. An application of this method to a 5-cell stack is then shown. Finally, a conclusion is provided in Section 5.

2. Prognostics of PEM fuel cell

2.1. Background

PHM is an advanced system maintenance strategy which aims to improve the safety, reliability while reducing maintenance costs. It combines different tools that can be separated into seven layers (Fig. 1) [8,9].

- Data acquisition.
- Data processing (signal processing, features selection).
- Condition assessment.
- Diagnostic.
- Prognostic.

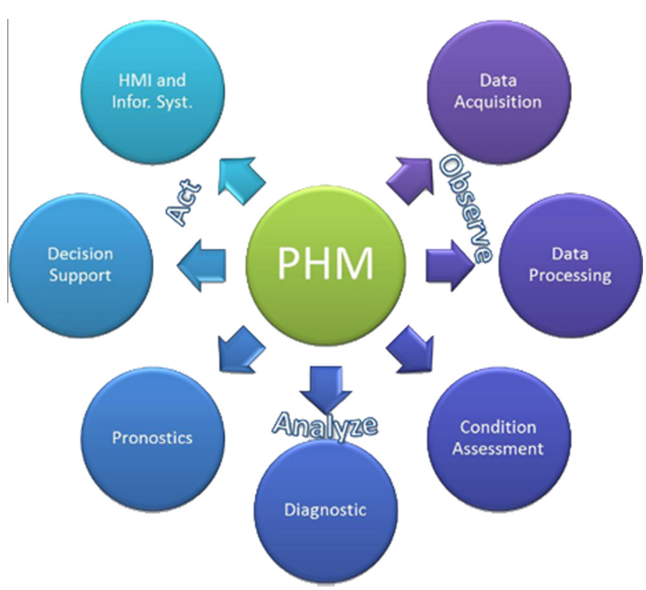

Fig. 1. PHM scheme [9].

- Decision support.
- Human Machine Interface.

This paper mainly focuses on the prognostic layer. It is defined by the International Organization for Standardization as "the estimation of time to failure and risk for one or more existing and future failure modes" [10]. In other words, it is the prediction of the remaining time of a system before a failure occurs. The failure is defined as the inability of a system to perform a given task. In the case of a PEMFC, the US Department of Energy (DoE) considers that the power converter no longer fulfilled its function when it lost 10% of its nominal power [11] (for transportation applications). The prognostic activity is therefore divided into two subactivities; the first is to estimate the current state of health of the system and to predict its evolution until the chosen failure criterion is reached. The time difference between the predicted end of life $t_{failure}$ and the time when the prediction is made t_{pred} provides the RUL at time t_{pred}

$$RUL(t_{pred}) = t_{failure} - t_{pred} \tag{1}$$

Prognostic can be categorized into three approaches:

- Model-based: use an empirical or physical model of degradation. This method does not require a lot of data. However, building such a model is not a trivial task. Indeed, the degradation phenomenons might not be fully understood and require investigations. It is this approach that has been implemented later in this paper.
- Data-based: This method does not require*a priori*knowledge of the system and captures strong non-linearity. However this approach requires a large amount of data.
- Hybrid: is a combination of the two previous methods. This approach improves the training, although, it remains computationally expensive.

Model-based methods have been used for prognostic in different fields:

- Mechanical systems [12,13].
- Electronic systems [14].
- Turbines [15,16].
- Electrochemical devices [17–20].

Such a success in various areas has motivated the work presented in this paper.

2.2. Literature review

Despite the advantages PHM tool offers, there are still few applications of RUL estimation of PEMFC in the literature. Indeed, only three papers were identified.

Zhang and Pisu [21] proposes a physics-based degradation model of the Electro-Chemical Active Surface Area (ECSA) which is used as an indicator of the fuel cell aging process. The estimated degradation of this surface is linked to the measured voltage, and the algorithm is able to predict its evolution. When the predicted surface becomes too small, the estimated voltage reaches a threshold, the End of Life (EoL) is declared and the RUL is given. The damage tracking and damage prediction algorithm are based on an Unscented Kalman Filter (UKF). This method was successfully applied in simulation with a dynamical load. However, as explain above the ECSA is not the only indicator of the aging of the fuel cell. Therefore research has to be carried out to overtake this limit.

Jouin et al. [7,22] proposes an adaptation of Particle Filtering (PF) based on a Monte Carlo method for PEMFC prognostics. Three