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Estimating the end-of-life of PEM fuel cells : guidelines and metrics

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Abstract

Prognostics applications on PEMFC are developing these last years. Indeed, taking decision to extend the lifetime of a PEMFC stack based on behavior and remaining useful life predictions is seen as a promising solution to tackle the too short life’s issue of PEMFCs. However, the development of prognostics shows some lacks in the literature. Indeed, performing prognostics requires health indicators that reflect the state of health of stack, while being able to interpret them in an industrial context. It is also important to propose criteria to set its end of life. Moreover, to trust any prognostics’ application, one should be able to evaluate the performance of its algorithms with respect to standards. To help launching a discussion on these subjects among scientific and industrial actors, this paper addresses some of the issues encountered when performing prognostics of a PEMFC stack. After showing the link between prognostics and decision, this paper proposes guidelines to set the limits of a prognostics approach. The definitions of healthy and degraded modes are discussed as well as how to choose the time instant to perform predictions. Then, three criteria based on the power produced by the stack are proposed as indicators of the state of health of the stack. The definition of the end of life of the stack is also discussed before proposing some criteria to assess the performance of any prognostics algorithm on a PEMFC. Some perspectives of works are also discussed before concluding.

Keywords: Proton exchange membrane (PEM) fuel cell, Prognostics, Remaining useful life, PHM

1. Introduction

In the current context of energy transition, replacing fossil energies by alternative power sources such as fuel cells appears as a promising solution [1, 2]. Fuel cells can be used in a great number of applications such as transportation, mobile electronic devices, micro-CHP (Combined Heat and Power), etc. [3, 4]. Despite their great industrial potential and large scale projects all around the world, fuel cells experience difficulty to enter the energy market and this industry remains brittle [5]. Actual obstacles are, among others, high exploitation cost, public acceptance and life duration that remains to short [6]. Indeed, for the fuel cells of interest in this paper, namely Proton Exchange Membrane Fuel Cells (PEMFC), current lifetimes are around 2000-3000 hours when 8000 hours are needed for transportation applications and 100 000 hours for stationary. Different options are available to tackle the lifetime issue: working on the material, reducing the causes of degradation, improving the stack design, implementing new supervision and management strategies, etc. This last solution appears to be of great interest and has started to appear in the PEMFC field through Prognostics and Health Management (PHM) [7, 8].

PHM is an engineering discipline originated from the predictive maintenance. It is defined by [9] as “a maintenance and asset management approach utilizing signals, measurements, models and algorithms to detect, assess and track degraded health, and to predict failure progression”. In other terms, by continuously monitoring the system, it is possible to detect and anticipate, thanks to prognostics, the occurrence of failures and to take decisions at the right time to preserve the system. These actions enable the system to reach the end of its mission. Prognostics is widely accepted as a key stage of PHM. Indeed, based on the system knowledge and historical data, it allows predicting the future State of Health (SoH) of the system. Prognostics is defined as the “estimation of the operating time before failure and the risk of existence or later appearance of one or more failure modes” [10]. The operating time before failure is more commonly known as the Remaining Useful Life (RUL).

During the last years, prognostics has started to be applied to PEMFC. Different types of approaches are proposed: model-based approaches [11, 12, 13], data-driven approaches [14, 15, 16] and a combination of both, hy-
brid approaches [17]. The growing interest of the scientific community to that subject has also been shown thanks to the IEEE PHM data challenge 2014 [18] in which different propositions for SoH predictions [19, 20] and RUL estimates [21, 22] were presented.

Despite those recent works, a deep thinking and standards proposal on how to perform prognostics on PEMFC are needed. Although different considerations about prognostics standards are available [9, 23], they are too general and further questioning is required for the PEMFC case.

1. Which level of granularity should be chosen on the PEMFC?
2. How to define the healthy and degraded modes for a PEMFC?
3. When prognostics should be performed?
4. Which health indicator should be used to perform prognostics?
5. How to define the End-of-Life (EoL) of a PEMFC?
6. How can the prognostics’ performances be evaluated?

To the authors’ knowledge none of these questions are answered in the literature. Consequently, this paper intends to propose solutions and guidance to start answering these questions and going towards standardization. The main contribution is to propose general solutions that are completely independent of prognostics tools and that can be adapted with any approach. New practitioners can use these guidelines as tutorial to start performing prognostics of PEMFC.

To adopt a logical reasoning, the paper follows the chronological order of the prognostics process’ stages (Fig 1). First, the time constants involved in the prognostics are discussed as well as the level of granularity recommended for prognostics in Section 2. Section 3 focuses on the data selection and their processing before defining health indicators in Section 4. This section also discusses the EoL definition. The SoH definition is considered in Section 5 in addition to the time instant to start predicting. Finally, some performance metrics are defined in Section 6 before concluding.

2. Decision levels and system granularity

2.1. Decision levels and time constants

Prognostics intends to provide the future SoH of a system and its RUL based on data, system knowledge and the expected mission profile. This generally creates a closed loop, Fig. 2. This figure could be completed with other PHM processes but only the ones of interest for this paper are kept.

The system initiates its mission based on an expected mission profile. Data are collected and processed continuously for health assessment. This provides an input for prognostics. These data are used, alone or combined with a model according to the prognostics’ approach, to predict the future SoH based on the planned mission profile. According to the predictions, this profile can be modified and adapted to the actual capabilities of the system. This process is repeated until the system reaches its mission or fails.

Different levels of decision exist with respect to different time scales (Fig. 3). Regarding PEMFC, the time scales go from the microseconds to months (Fig. 4). Among all the phenomena occurring within the PEMFC, the accumulation of degradation and ageing effects are the main factors that shorten the RUL [24]. Consequently, to perform prognostics, phenomena with time constants greater than the hour are considered. This enables making mid-term and long-term predictions and the consequent decisions. Lower
scales are more related to adaptive control or system re-
configuration.

Figure 3: Different levels of decision and link with prognostics

Covering all possible uses, events and configuration en-
countered by a PEMFC in a single paper would be a hard
task. Consequently, it is assumed that prognostics is per-
formed on a single stack working in its nominal conditions.
The decision is out of the scope of that paper, even if it is
mentioned later to argue some points.

2.2. Stack vs component level

From the previous paragraphs, it seems obvious to fo-
cus on degradation phenomena to perform prognostics.
Degradations occur at all levels of the stack granular-
ity: stack/cells/components and at the interfaces between
them [26]. All the published approaches are dealing with
prognostics at the stack level (Section 5). The main reason
is that the data acquisition is very often performed at this
level.
However, working at the cell level can be an interesting op-
tion. Indeed, the functioning of the stack can be suddenly
stopped when a cell reaches a minimum voltage value. This value is
given by the manufacturer to automatically shut down the stack when a cell seems too damaged and so prevent safety issues. Performing prognostics on cells would allow anticipating such events.

An issue appears with this type of prognostics: cells are
not degrading in a uniform way within the stack [27, 28].

Cells near the edges tend to degrade faster. As for an il-
lustration, Fig. 5 depicts the individual cell voltages for a
stack aged with a constant mission profile. Cell 1 refers
to the cell near to the hydrogen input. This figure clearly
shows the voltage heterogeneity among the cells. As an ex-
ample, at the end of the experiments, cell 1 has lost 21.6%
of its initial performance while cell 3 lost only 8.8%. Some
information can be extracted from these measurements,
such as the mean cell voltage value or the standard devi-
ation. It helps isolating the cells that may come prema-
turely to their EoL. Based on this information, it can be
decided to perform prognostics on the most degraded cells
only. It could be done on all cells but it would not be prac-
tical for stacks that have more than 10 cells. More-
over, nowadays, stack reconstructions to replace only these
faulty cells are not systematic due to all the assembly con-
strains. Also, a stack can still convert energy even with
faulty cells. So such a level of study can be questionable.

Another perspective for prognostics may be being per-
formed at a smaller level, namely the component level.
It has already been initiated in [13] in which the size of the
electrochemical active surface area (ECSA) is pre-
dicted with a model-based prognostics framework. Many
other critical parameters such as hydrogen crossover, re-
sistances (or conductivities) or materials integrity could
be predicted. Some failure thresholds have already been
proposed for some of them. For instance, a crossover cur-
rent of 10 mA cm$^{-2}$ is proposed in [29] as the EoL of the
membrane subject to hydrogen crossover. However, differ-
ent limitations appear when performing prognostics at the
cell or components levels:

1. the accessibility of the parameters: this point is dis-
cussed in [8]. Accessing the inner parameters of the
stack, when it is possible, almost always disturbs the
stack behavior and tends to accentuate its degrada-
tion;
2. the lack of validated degradation models;
3. the degradation at the interfaces between the com-
ponents or with the auxiliaries may not be taken into
According to all ahead considerations, in all the remainder of the paper, the discussion focus on a prognostics performed at the stack level.

3. Data selection and processing

3.1. Data collection

In an industrial operating environment, very few physical parameters are easily accessible with current technologies. It is the reason why, the existing prognostics methodologies focus on indicators built based on voltages measurements such as energy indicators. Voltages and current are the most common measurements on PEMFC as they allow obtaining the power provided by the system whenever during its life. Even if it is monitored, the current is supposed to be known as it is defined by the mission profile.

Also, some punctual measurements can be available. Often, an initial polarization curve as well as some EIS (Electrochemical Impedance Spectroscopy) measurements are given by the manufacturer or measured before the stack starts its mission. However, as it is not sure yet that these punctual measurements can be performed during the whole lifetime of an embedded system, there are left aside in the remaining of the paper.

Fig. 5 shows that limiting the measurements to the power still provide a good indicator of the stack aging. Indeed, constant current experiments are typically reflecting the “natural” aging of the stack, i.e., an aging not influenced by the mission profile if the operating conditions are kept nominal. The power decreases with time indicating the evolution of different degradation mechanisms inside the PEMFC. This explains why some papers use the voltage/power to evaluate the degradation rate of the system [30, 31]. Finally, [32] shows that almost all the degradations can be perceived in this signal.

Consequently, the focus is set on the use of voltage or, by proportionality with respect to the current, power measurements.

3.2. Degradation vs transient phenomena

Based on the previous comments, the focus is set on the observation of the degradation thanks to power measures. However, the degradations are mixed with transient phenomena when time scales in hours are considered (Fig. 4). Fig. 6 represents the power measured during the aging of two 5-cell stacks at a constant current of 60A [14], Lower part: Power during the aging of a 5-cell stack at a constant current of 70A [18].

3.3. Data processing

Data can be easily processed to work only on the degradation part of the signal. To do so, the raw signal power is reduced and filtered. As seen in Fig. 4, because the effect of the aging is noticeable within a few hours, the dynamic of degradation is easily separable among the others. The time constant of degradations is at least in hours while the data frequency acquisition is commonly in seconds. Reducing the data can be of great interest, as it often condition the speed of the prognostics’ algorithms as long as it does not remove any useful information. One should avoid over sampling: the SoH information is flooded among the other dynamics. In addition, the computational cost for performing the prognostics might be too high making the implementation of the real-time algorithm challenging. Finally, one should consider the memory required to store the huge amount of data induced by the over sampling. Different options are proposed in the literature: [12, 26] use a hourly sampling period while [14] prefers a sampling period of 50 hours.

Then, to remove all the components of the signal that are not linked to degradation, simple methods can be used. By representing, the spectrum of a PEMFC power signal in the frequency domain (Fig. 7), it can be observed that the main component of the signal is located in the low frequency, and that the signal is the sum of a very low frequency signal and high frequency noise. As the transient stages have a low duration with respect to the degradation, and the border between both of them is not always clearly defined, they should be taken with caution, or even removed, for prognostics.

![Figure 6: Upper part: Power during the aging of a 5-cell stack at a constant current of 60A [14], Lower part: Power during the aging of a 5-cell stack at a constant current of 70A [18]](image-url)
frequency domain. It allows using a simple low-pass filter, namely the moving average, to remove noise and fast phenomena from the signal. As it does not remove all the effects of the transient stages, the signal can also be smoothed, with a loess algorithm for example [26]. These stages of the signal processing are illustrated in Fig. 6.

![Spectra of the data proposed in Fig. 6 and 12](image)

Figure 7: Spectra of the data proposed in Fig. 6 and 12

4. Health indicators and stack’s EoL

4.1. Health indicators

Different indicators can be proposed as prognostics criteria, three of them are studied here:

1. the power;
2. the cumulative energy;
3. the efficiency with respect of the current.

The proper indicator should be chosen according to the PEMFC use. The power (or the voltage) is recommended for constant mission profiles while the cumulative energy and the efficiency are more adapted for variable mission profiles. Indeed, when the current varies, the power is not yet a monotonic indicator preventing from fixing a failure threshold. Further discussion on this issue is provided in Section 4.2.2. The case of the power as health indicator has already been evoked in the previous sections, so the emphasis is set here on the cumulative energy and the efficiency.

4.1.1. The cumulative energy

A classical approach in prognostics is to construct a monotonic indicator based on measurements. For a PEMFC stack the energy produced during the lifetime is accessible thanks to the voltage measurement \( U \), the current profile \( i \) and the time of operation \( T \) and is written:

\[
E(t = 0 : T) = \int_0^T U(t).i(t).dt
\]

(1)

It provides a quantitative indicator of the PEMFC performance and as it is monotonic, fixing a failure threshold becomes easier.

The data proposed further in Fig. 12 are used for illustration purpose. Representing the measured cumulative energy is quite simple based on the measurements. However, it has to be compared to a reference and building it may not be simple.

The first solution to build the reference is based on the hypothesis that an initial polarization curve is available. It gives the voltage corresponding to a particular current solicitation when no degradation has occurred yet. Usually, only a few points are measured to obtain the polarization curve, so some voltages corresponding to the current encountered in the mission profile may be missing. A simple method to solve the problem is to fit the data to the polarization equation [6]:

\[
E = E_{\text{ref}} - E_{\text{conc} + \text{cross},a} - E_{\text{conc} + \text{cross},c} - E_{\text{ohm}} - E_{\text{act},a} - E_{\text{act},c}
\]

(2)

Different strategies can be found in the literature to perform that fitting [35, 36] but using a simple algorithm of the least squares family seems sufficient. This fitting enables covering a larger range of current values. Once the fitted curve built, obtaining a reference for the cumulative energy is straightforward (see Fig. 8). For each current value, the corresponding voltage can easily be calculated with the fitted equation.

The second solution to build the reference is to use a behavioural model that describes the evolution of the voltage or the power according to the current profile as if no degradation was occurring within the stack. As an example, the reference in Fig. 9 and 12 are built based on the model proposed in [26] making the current varying at time \( t=0 \) to remove the effect of degradations. However, such models are still scarce and have to be further validated.

Once the reference is set, the collected data are used to build the observed cumulative energy and compared to the reference (Fig. 9). The difference between the observations and the reference \( (\Delta CE) \) can be calculated at each time instant and converted into a percentage of energy loss to help estimating the RUL.

Working with the cumulative energy has the advantage to work with a monotonic indicator. So, it can be adaptable whatever the mission profile. Also working in terms of cumulative energy (so in the watt.hour unit) enables...
4.1.2. The efficiency

The efficiency is a classic measure for energetic system. For a PEMFC, the efficiency $\eta_{stack}$ is defined as [37]:

$$\eta_{stack} = \frac{P_{stack}}{P_{chemical}}$$  \hspace{1cm} (3)

where $P_{stack}$ refers to the output electrical power previously defined $(U \times I)$, and $P_{chemical}$ refers to the energy flux contained in the reactants:

$$P_{chemical} = -\dot{n}_H \Delta h_f$$  \hspace{1cm} (4)

where $\Delta h_f$ is the enthalpy of formation of a mole of water. It also corresponds to the heat released by the complete combustion of a mole of hydrogen; and $\dot{n}_H$ is the molar flowrate of hydrogen consumed by the cell to supply the power.

As seen in these equations, the efficiency is strongly linked to the mission profile and the nominal conditions set for each current value $I$. If the nominal operating conditions can be maintained each time the stack supply a current $I_0$, during the aging of the stack, $P_{chemical}(I_0)$ should remain constant through time, and the efficiency should decrease with $P_{stack}$.

There is not an unique criterion to perform prognostics. One has to be selected according to the industrial needs of the prognostics’ applications.

4.2. EoL definition

Two thresholds can be defined for prognostics of PEMFC stack:

1. a threshold of conformity to a mission;
2. a definitive End of Life threshold.

The first allows to decide if the fuel cell stack is able to perform a given mission (e.g. providing 1kW during 1 year) which does not mean that the stack is out of use once that it can be operated in degraded mode. The definitive EoL is the inability for the PEMFC to deliver power in safe conditions. It is more difficult to define with a stack scale parameter once that the EoL is usually related to the component level (e.g. massive hydrogen crossover).

4.2.1. Conformity to a mission threshold

Defining the conformity criterion is the responsibility of the user and depends on his needs. For instance, if the fuel cell is operated at constant power, the criterion might be the ability to produce a requested power as illustrated in Fig. 10. In this example, the requested power density is 0.4 $W/cm^2$ which corresponds to the nominal power density given by the manufacturer. At time 500 hours, the PEMFC is no longer able to provide that power density and can not pursue the given mission.

As stated earlier, when variable mission profile is considered, a threshold on the power might not be suitable anymore. This is the reason why a threshold on the cumulative energy is proposed. Lets consider the difference between reference and real cumulative energy:

$$\Delta CE(t) = CE_{ref}(t) - CE_{real}(t)$$  \hspace{1cm} (5)

One can defined a threshold of 10% of the reference cumulative energy:

$$\Delta CE_{max}(t) = \frac{10}{100} CE_{ref}(t)$$  \hspace{1cm} (6)
\[ \int_0^T P_{\text{real}}(t) \, dt = \frac{90}{100} \int_0^T P_{\text{ref}}(t) \, dt \] (7)

which is strictly equivalent to the power threshold for constant solicitation. However, this threshold is a function of the power profile and so can also work for variable requested power.

Chen et al [38] proposes an economical lifetime threshold where the fuel cell (that powers an electrical bus) has to be replaced when its average cost is the lowest (see Fig. 11). It is a compromise between the profitability (that increase with time) and the performance (that decrease with aging). This threshold takes into account the price of the stack $Q_{\text{stack}}$, the consumption of hydrogen $Q_{\text{H}_2}$ (that increase with aging) and the system efficiency $Q_{\text{ope}}$ (because auxiliaries consume power).

\[ Q_{\text{total}}(t) = Q_{\text{stack}} + \int_{t=0}^T Q_{\text{ope}} \, dt + \int_{t=0}^T Q_{\text{H}_2} \, dt \] (8)

The authors states that using the fuel cell after the economic lifetime is reached is cost-effective for the users. Nevertheless, this approach supposes a known speed of degradation for a given bus route so the future SoH can be forecasted.

4.2.2. Definitive End of Life threshold

There is currently one definition of the EoL based on the power. The US Department of Energy (DoE) defines the EoL as a loss of 10% of the initial performance [39]. Even if the value could be discussed, it is not the main problem of this definition. Using a fixed threshold for constant current application is very convenient and does not create any problem. The EoL of the stack is defined as a ratio of the initial performance as illustrated in Fig. 6.

However, it does not work so well when the mission profile exhibits current variations. Fig. 12 shows an example of power measured under a $\mu$-CHP (Combined Heat and Power) profile with the theoretical power that should be expected if the stack was not aging. It can be seen that according to the level of current, the loss of performance does not follow a constant percentage with respect to the reference. Indeed, at 170 A, 15% of power is lost in only 300 hours while a few hundreds of hours later, only 10% is lost at 50 A and in 700 hours. Consequently, using the 10% of power loss proposed by the DoE would have led to a EoL in the very early life of the stack showing that another proposal need to be found. In such a case, using the cumulative energy or the efficiency to define the EoL seems more appropriate.

The definitive EoL threshold is closely linked to the application. It refers to the inability for the PEMFC to deliver power in safe conditions. The safety constrains may vary from an application to another as the conditions and the norms are not the same. For example, safety constrains are quite different for stacks used in air travel applications and ones used to supply technical pylon [37]. Consequently, fixing threshold values need an important feedback from the industry.

5. Health assessment and prognostics

This stage of the prognostics’ process raises two main questions. The first one is “when should one start predicting?” Indeed, when a new PEMFC starts to operate, one can expect a good SoH and the prognostic is not required. In the contrary, as the system ages, the necessity to know
Defining the healthy and degraded modes of a PEMFC is not trivial. The system starts degrading since its starting up and the power signal does not exhibit clear degradation levels. This can clearly be seen with a constant current solicitation (Fig. 6) where the power starts decreasing continuously after only a few hours. So how to define the different degraded modes of the PEMFC?

When representing the voltage measured during a stack lifetime with an histogram, it can be seen that different states seem to appear, see Fig. 13. The issue is to formalize that observation and propose a method to identify the different degraded modes.

![State evolution during the aging](image)

Figure 13: Histogram of the voltages for a stack aged under a constant current profile (data from Fig. 6 lower part)

In the case of a constant mission profile, the power loss could be kept to distinguish the different SoH. As an example, one can define:

- From 0 to 5% of power loss: Good health;
- From 5% to 10% of power loss: Acceptable;
- Over 10% of power loss: Degraded SoH.

By looking at Fig. 6, this is not illogical as the power drop faster after the 10% limit. Of course, more classes might be identified before those 10%, as suggested by the histogram in Fig. 13. Some unsupervised classification methods are available, such as Hierarchical Ascendant Clustering [41, 42], to refine the number of classes.

For mission profiles with variable currents, no clear answer can be given. Some work trails should be explored in the future:

- using the cumulative energy or the efficiency and finding different classes by analogy with the constant current example;
- using the maximum power achievable for a very low or very high current value and following its evolution;
- etc.

5.2. Prognostics

Let’s assume in this paragraph that a satisfying definition of the SoH is available. A time instant to start performing prognostics should be decided. In all the published approaches, the prognostics is performed on datasets from finished experiments. So, the beginning of the predictions is very often chosen to get the best prediction horizon without taking the SoH into consideration. It is important to test and validate the algorithms but in industrial applications, this practice is obviously not possible.

Two possibilities appear:

1. for model-based approaches: setting a threshold on the error between theoretical and real stack power in percent. Nevertheless, the latter requires that the threshold is a function of the operating conditions (see the loss on Fig. 12). If the residual crosses a threshold, an anomaly is detected and the prognostic procedure is executed (see Fig. 14 where the prognostic should be performed at $t = 38s$) [43, 44].

2. for data-driven approaches, two solutions:
   - setting a threshold on the SoH indicator and on the gradient of the latter (to capture a performance drop or improvement);
   - using the histogram of the chosen SoH indicator to track the state evolution and to decide in consequence if the prognostic has to be performed.

Then the prognostics algorithm can be launched. The reader can refer to Table I for more information on different approaches currently available.

![A residual and thresholds to trigger the prognostics procedure](image)
6. Evaluating prognostics’ performance

6.1. Prediction horizon

It is important to evaluate the duration needed between the prediction instant and the decision and/or action instant. The horizon may depend on the goal of prognostics. Consequently, the reasoning is proposed on an example, and can be transposed in other applications. Let’s take the example of the maintenance rescheduling for a transportation or a µ-CHP PEMFC. It is assumed that the mission rescheduling can be done remotely, so only the maintenance constraints impact the prediction horizon expected. To perform maintenance, different time durations have to be taken into account: (1) the planning of the maintenance operations, 1-2 days; (2) the delay to obtain spare parts, 10-20 days; (3) the maintenance realization, 1-7 days. It gives a total duration between 12 and 29 days. It means that the prognostics should give results with a horizon between 300 and 700 hours to be considered as a good performance. Obviously, this time interval should be discussed with respect to industrial feedbacks in the future.

6.2. Acceptable error on RUL estimates

Regarding the RUL estimates, there are two cases: (1) the estimate is smaller than the actual RUL, it is an early prediction, or (2) the estimate is greater, it is a late prediction. The acceptable error cannot be the same in each case. Indeed, by validating a prediction with a consequent delay, one may risk a complete shutdown of its power source. It is intolerable in most PEMFC applications. Consequently, according to the horizon discussed earlier, it is proposed to allow a maximum delay of one day. It represent an error of 8% for a horizon of 300 hours. The case of the early prediction allows more flexibility. Anticipating a maintenance is less disadvantageous than being late, even if it can create some extra costs due to the replacement of a functioning system. It is proposed to set the early prediction limit at 16% of the actual RUL, whatever the time instant. It represents 48h for a horizon of 300h and 4 days (112h) for a horizon of 700 hours. The acceptable error is depicted in Fig. 15.

![Figure 15: Acceptable error on RUL estimates](image)

6.3. Acceptable uncertainty

Defining the uncertainty allowed in the prediction is not trivial as no standards are available for PEMFC on that subject. So let’s try to reason on the current standard on electricity production. Nowadays, electricity suppliers in Europe have to provide a voltage of 230 V ±10% (at 50 Hz) [46]. This constrain evolves according to the world location. In North America, the standard impose a nominal voltage of 120 V with a tolerance of ±5% (at 60 Hz) [47]. Even if, the standards

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Table 1: Characteristics of a few works developed in the field of PEMFC prognostics

<table>
<thead>
<tr>
<th>Year</th>
<th>Reference</th>
<th>Type</th>
<th>Health indicator</th>
<th>State estimation and/or prognostics tools</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[17]</td>
<td>data-driven</td>
<td>Stack voltage (I constant)</td>
<td>Particle filter</td>
</tr>
<tr>
<td></td>
<td>[14]</td>
<td>data-driven</td>
<td>Mean cell voltage (I constant)</td>
<td>Echo State Network</td>
</tr>
<tr>
<td></td>
<td>[19]</td>
<td>data-driven</td>
<td>Impedance</td>
<td>Equivalent circuit</td>
</tr>
<tr>
<td></td>
<td>[20]</td>
<td>data-driven</td>
<td>Impedance</td>
<td>Regressions</td>
</tr>
<tr>
<td></td>
<td>[21]</td>
<td>data-driven</td>
<td>Stack voltage (I constant)</td>
<td>Regime switching vector autoregressive (RSVAR)</td>
</tr>
<tr>
<td></td>
<td>[12]</td>
<td>model-based</td>
<td>Stack voltage (I variable)</td>
<td>Kalman Filter</td>
</tr>
<tr>
<td></td>
<td>[12]</td>
<td>model-based</td>
<td>Stack voltage (I variable)</td>
<td>Particle filter</td>
</tr>
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<td></td>
<td>[45]</td>
<td>Hybrid</td>
<td>Stack voltage (I variable)</td>
<td>Particle filter</td>
</tr>
</tbody>
</table>
The field of prognostics of PEMFC has just started and a great reflection effort is needed to develop approaches that, one day, can be transferable to the industry.

7. Conclusion

Developing prognostics for PEMFC can be a solution to contribute to extend the system’s lifetime. However, the lack of standards to guide current works may lead to the appearance of prognostics’ proposals with very poor adaptation capacities to actual industrial situations. To start a discussion on this subject, this paper proposes guidance on several aspects such as state definition, selection of prognostics’ criteria or performance evaluation. This is synthesized in Fig. 16.

This work first shows how important it is to set hypotheses of the prognostics application. Indeed, it limits its the prognostics’ approach to specific real life cases of PEMFC applications. Also, it makes appear some technological constrains, as the types of measurements available, as well as indications on the phenomena that should be taken into account (transient and/or permanent regimes).

To evaluate the current and future state of health of the system, it is important to know if the stack remains in an healthy mode or already is in a degraded one. There is currently no clear borders between these states. Defining which ones are degraded states is still to debate.

Performing predictions requires health indicators. According to the application, the criteria might be different and this leads to the proposal of several indicators such as the power, the cumulative energy and the efficiency. All depend on the mission profile and the pathway from one to another can be easily made. However, defining failure thresholds related to each criterion remains an open question. Moreover, this lead to wonder how the end of life of the stack is defined. Two solutions are proposed related to the first to the mission in progress and then related to an inability of the stack to provide power in safe conditions.

Finally, to help validating prognostics approaches, some performance metrics are proposed and discussed. They try to take into account real life constrains such as electrical safety norms and maintenance delays. Nevertheless, the lack of industrial feedback in the literature prevents a precise discussion on the subject.

To extend the proposals from this paper to short-term predictions for adaptive control, small time scales, as a minute, will have to be studied and discussed. As it may raise issue linked to the speed of the algorithm or the accuracy needed to use short-term predictions for example, this stage might wait that more prognostics’ approaches are available in the literature. The field of prognostics of PEMFC has just started and a great reflection effort is needed to develop approaches that, one day, can be transferable to the industry.

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References


Figure 16: Synthesis of proposed prognostics guidelines

1. **Decision level definition**
   - System/sub-system definition

2. **Data selection**
   - Data processing

3. **Health indicators setting**
   - End of Life definition

4. **Health assessment**
   - Prognostics

5. **Evaluation metrics definition**
   - Performance assessment

### Mission profile
- **Constant**
  - Hours
  - Stack level
- **Variable**
  - Voltage U, Current I
  - Reduction + Moving average
  - Smoothing
    - Power $\rightarrow 10\%$ loss
    - Efficiency $\rightarrow \eta_{\text{min}}$
  - Cumulative energy
  - Price $Q_{\text{total}} \rightarrow Q_{\text{min}}$

- Classes by % or Histograms

- Threshold on (1) Residual or (2) SoH indicator

- Horizon $\rightarrow 300$-700 hours

- Acceptable error $\rightarrow 16\% / +24$hours
- Uncertainty $\rightarrow \pm 5\%$

### References


