Post-Prognosis Decisions for a Multi-Stack Fuel Cell System

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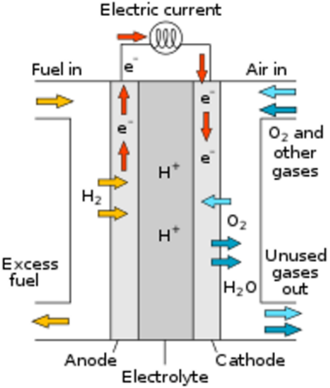
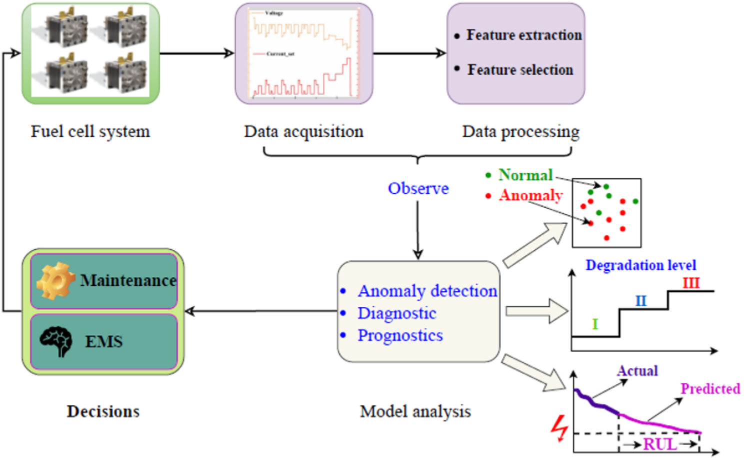
Réunion du GT S3

Context

- **Why Fuel Cells!**
  - High efficiency (direct conversion).
  - Zero emissions (water and heat).
  - External reactant storage (easy refuelling).
- **Challenges:**
  - Cost challenges.
  - Durability.
- **Possible Solutions:**
  - Durable materials.
  - Optimizing operation conditions
  - Prognostics and Health Management (PHM).



Prognostics and Health Management For Fuel Cells



Outline

Degradation Data

Source: IEEE PHM Data Challenge 2014

Overview: The FCLAB Research Federation provides datasets featuring experiments on Fuel Cell Stack (FCS) ageing under varied conditions.

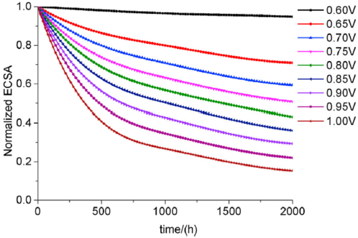
Tests:

- FC1: Durability under stationary nominal load
- FC2: Durability with current ripples

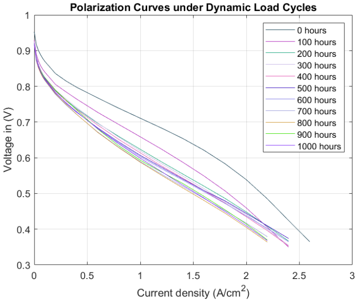
Characterization: Polarization curve tests and EIS.

Degradation Behavior in Fuel Cells

- **Rapid Early Degradation:** Degradation is faster at the beginning of a fuel cell's life, especially under variable loads.



Electrochemical Surface Area Degradation (ECSA)



Polarization Curves

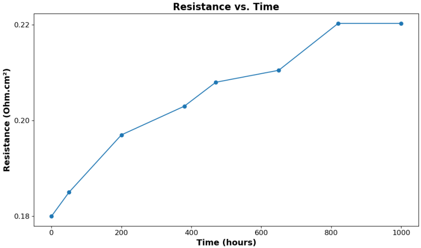
Health Index (HI)

The fuel cell internal resistance is chosen as a health index, which can be extracted from the polarization curves empirical equation:

$$V_{\text{fc}} = E - V_{\text{act}} - V_{\text{ohm}} - V_{\text{conc}} \quad (1)$$

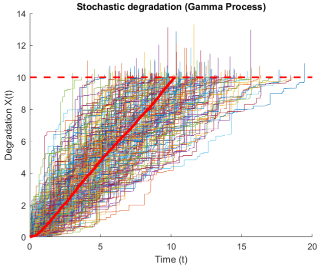
Components of the equation:

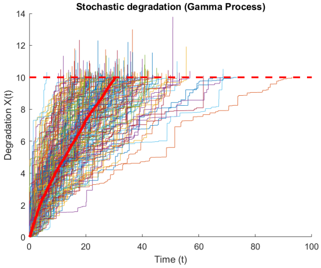
- **Activation Losses:** $V_{\text{act}} = A \ln\left(\frac{i}{i_0}\right)$
- **Ohmic Losses:** $V_{\text{ohm}} = i \cdot R_{\text{ohm}}$
- **Concentration Losses:** $V_{\text{conc}} = me^{(n \cdot i)}$



Homogeneous vs Non-Homogeneous Gamma Process

- **Homogeneous:** The degradation is stationary $A(t) = \alpha t$, $\alpha > 0$.
- **Non-Homogeneous:** $A(t)$ is non-linear, for example:
  - Power Law: $A(t) = \alpha t^{\beta}$, $\alpha, \beta > 0$.
  - Exponential Law: $A(t) = 1 - e^{-\beta t}$.





Gamma Process for Modeling Resistance Increments

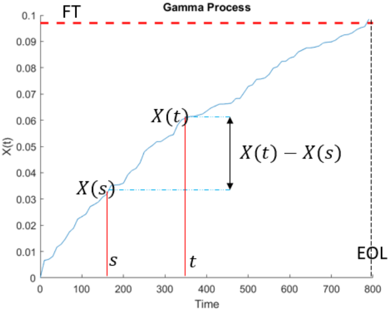
Definition: A continuous-time stochastic process $(X_t)_{t \geq 0}$ is called a gamma process with shape $A(t)$ and rate $b > 0$, denoted $\mathrm{Gam}(A(t), b)$, if:

- $X_0 = 0$ almost surely,
- $(X_t)_{t \geq 0}$ has independent increments,
- Increments follow $X_t - X_s \sim \mathrm{Gam}(A(t) - A(s), b)$.

Mean and variance of increments $X_{t,s}$ over $[s, t]$:

$$E(X_{t,s}) = \frac{A(t) - A(s)}{b}$$

$$\mathrm{Var}(X_{t,s}) = \frac{A(t) - A(s)}{b^2}$$



Gamma Process for Modeling Resistance Increments

Resistance increments can be modelled as a non-homogeneous gamma process with a shape function:

$$A(t) = \alpha t^{\beta}$$

Where:

- α: Shape parameter affecting the growth of increments
- β: Exponent defining the power law growth
- b: Rate parameter of the gamma distribution

The parameters α, β, and b can be estimated using the maximum likelihood method. However, these values describe degradation only under the nominal load observed in the data. To extend this model for load dependency, α is defined as a function of load L as follows:

$$\alpha(L) = A(L - L_{\text{nom}})^2 + B \tag{2}$$

Load Dependent Model

The degradation under a constant load L between times t_1 and t_2 is modeled by a non-homogeneous, load-dependent Gamma process:

$$\Delta R_L(t_1, t_2, L) \sim \text{Gamma}\left(\alpha(L) \cdot (t_2)^\beta - \alpha(L) \cdot (t_1)^\beta, b\right) \tag{3}$$

Therefore, the degradation rate due to load amplitude L during the time interval $[t_1, t_2]$, denoted $D(L, t_1, t_2)$, is given by:

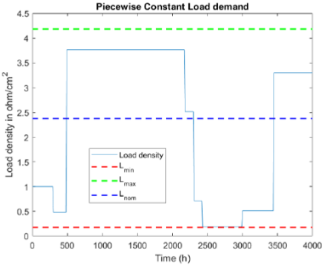
$$D(L, t_1, t_2) = \frac{\alpha(L)(t_2)^\beta - \alpha(L)(t_1)^\beta}{(t_2 - t_1)b} \tag{4}$$

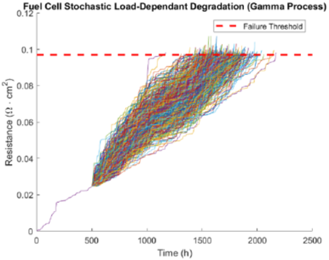
For static load, Reliability $R(t)$ and RUL are defined analytically by:

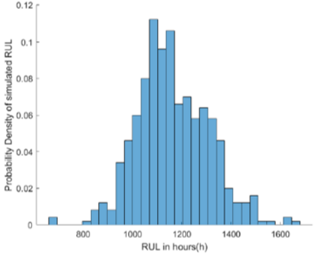
$$R(t) = 1 - \frac{\Gamma(\alpha(L)((t + t_0)^\beta - t_0^\beta), (FT - x_0)/b)}{\Gamma(\alpha(L)((t + t_0)^\beta - t_0^\beta))} \tag{5}$$

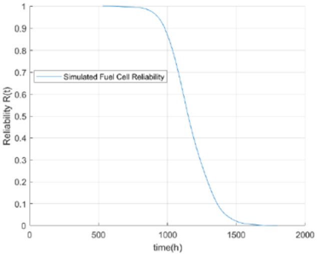
$$E[\text{RUL}] = \int_0^\infty R(t)\, dt \tag{6}$$

Simulations

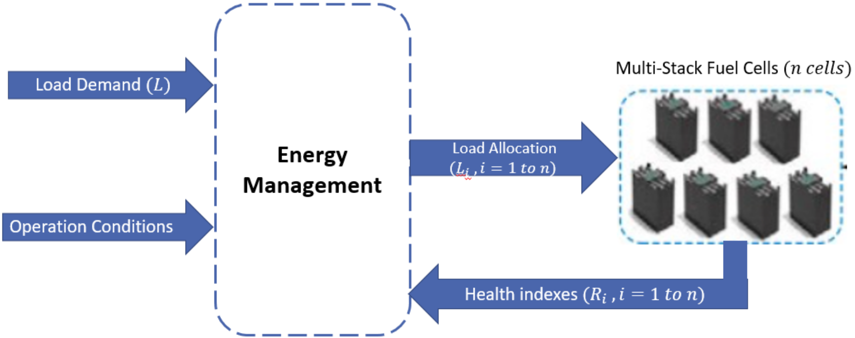








Energy Management Scheme



Objective Function Formulation

According to (4), in a system composed of n stacks, the total load L is allocated to minimize expected average resistance increments in the complete system over a future time horizon h:

$$J(L_i, t_i, h) = \sum_{i=1}^{n} \frac{\alpha(L_i)(t_i + h)^{\beta} - \alpha(L_i)(t_i)^{\beta}}{b} + K\Delta L_i \quad (7)$$

Subject to:

$$\sum_{i=1}^{n} L_i = L, \quad L_{\text{min}} \leq L_i \leq L_{\text{max}}$$

Where

- L_i is the load allocated to stack i.
- t_i is the age of stack i.
- $K\Delta_{L_i}$ is increment due to the load variation after allocation.

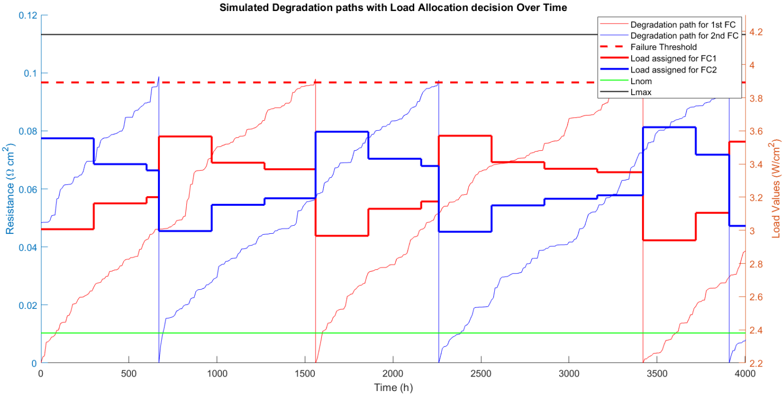
Simulation Setup

- Two stacks system is considered.
- Load allocation is done periodically at inspection times or after unit replacement.
- Stacks are immediately replaced upon failure.
- Comparison of load allocation strategy with average load split strategy for fuel cell lifetime.

Table: Simulation Parameters

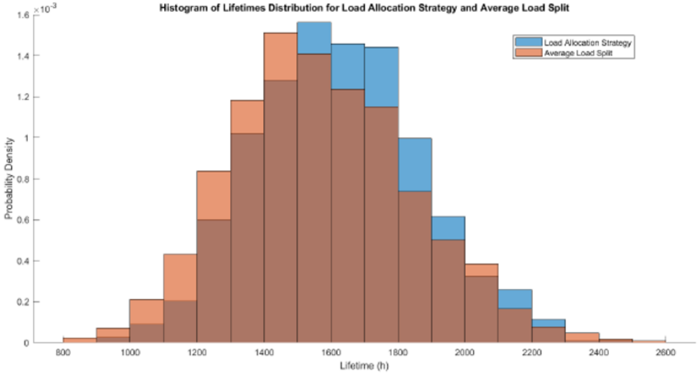
Parameter	**Value**
Run Time	10^6 hours
Time Step	10 hours
Load	$L_{nom} + L_{max} = 6.562\,\mathrm{W/cm^2}$
Failure Threshold	$0.1\ \Omega \cdot \mathrm{cm}^2$
Inspection Time	300 hours
Decision Horizon	300 hours

Load Allocation



Proposed Strategy vs Average Load Split

Parameter	Load Allocation Strategy	Average Load Split
Total Replacements	1235	1277
Mean Lifetime (hours)	1619.15	1566.00
95% CI for Mean Lifetime (hours)	[1605.37, 1632.93]	[1551.14, 1580.86]



Conclusion and Future Work

- **Main Results**: A non-homogeneous gamma process is used to model fuel cell degradation using resistance as health index, post prognostic energy management can enhance system lifetime.

Future Directions:

- Incorporate more real-time load data to improve model accuracy and to investigate load degradation relation.
- Extract more sophisticated health indexes that can reflect internal components state.
- Expand analysis to multi-stack systems under varying operational conditions like driving cycles.