Health-Aware Load Allocation and Joint Energy–Maintenance Optimization for Multi-Stack PEM Fuel Cell Systems

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ABSTRACT

Multi-stack proton exchange membrane fuel cell (PEMFC) systems are promising for transportation applications because they are compact, provide high power density, operate at low temperature, and produce no direct CO_2 emissions during operation. However, high cost and insufficient durability still hinder large-scale deployment. Under real driving conditions, variable loads and frequent transients accelerate degradation and shorten system lifetime.

To address this challenge, this thesis develops a prognostics and health management (PHM) framework for improving the durability and lifecycle performance of multi-stack PEMFC systems. In a first stage, a load-dependent degradation and prognostics framework is developed to estimate the health state online and to predict end of life (EOL) and remaining useful life (RUL), together with associated uncertainty, under projected future load scenarios. In a second stage, these prognostic outputs are used for decision-making through health-aware energy management and maintenance planning. By coordinating load allocation and maintenance actions, the proposed framework aims to extend system lifetime, improve availability, and reduce lifecycle cost.

1. PROBLEM STATEMENT AND MOTIVATION

For commercial viability, automotive proton exchange membrane fuel cells (PEMFCs) are expected to achieve a lifetime of approximately $5{,}000$ h under typical operating conditions. In practice, reported lifetimes often remain in the 2,500–3,000 h range [1]. A major reason is that PEMFC degradation depends strongly on operating conditions, especially load level, load variations, and transient operation. Improving durability is therefore essential for reducing lifecycle cost and enabling wider deployment.

In multi-stack PEMFC systems, the demanded power can be distributed among several stacks instead of being imposed on a single unit. This additional degree of freedom creates an opportunity for health-aware operation, since equal power sharing is not necessarily the most durable strategy when stacks may have different health levels and different degradation sensitivities. In addition, multi-stack architectures enable selective maintenance actions, such as replacing one stack without necessarily affecting the entire system.

Energy management and maintenance are closely coupled. Load-allocation decisions shape the future degradation trajectory of each stack and therefore influence future maintenance needs, while maintenance actions modify the health configuration of the system and thus the best subsequent operating strategy. This motivates the development of a PHM-oriented framework capable of coordinating prognostics-informed energy management and maintenance decision-making in multi-stack PEMFC systems. The central question addressed in this thesis is therefore:

> *How can prognostics-informed energy management and maintenance decisions be coordinated in multi-stack PEMFC systems to improve durability and reduce lifecycle cost?*

2. EXPECTED CONTRIBUTIONS AND RESEARCH CHALLENGES

2.1. Gaps in the literature

Answering the above question requires a prognostic tool able to predict the health consequences of candidate operating and maintenance decisions. In particular, the model must be load-dependent so that it can evaluate degradation trajectories and RUL under alternative future load scenarios. It must also be suitable for online implementation from available input–

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output measurements, remain robust under different operating conditions, including dynamic load cycling, and quantify uncertainty arising both from health-state estimation and from the intrinsic stochasticity of the degradation process.

However, many existing PEMFC prognostic models do not satisfy all of these requirements simultaneously. In particular, the literature still lacks integrated frameworks that combine load-dependent degradation modelling, online state estimation, and uncertainty-aware mission-conditioned prognostics. Moreover, health-aware energy management (EMS) and maintenance planning remain relatively under-addressed for *multi-stack* PEMFC systems [2], and their integration with prognostics is still limited.

2.2. Expected contributions

As illustrated in Fig. 1, this thesis aims to develop an integrated PHM framework for multi-stack PEMFC systems that connects degradation modelling, online estimation, prognostics, and decision-making within a common formulation. A first contribution is the development of a load-dependent physical degradation model in which the dominant degradation states are physically meaningful, their dynamics explicitly depend on load demand and operating conditions, and their evolution is linked to performance decay, while also accounting for uncertainty and variability in the degradation process. On this basis, a health index (HI) is defined as a performance-oriented indicator and used to establish an end-of-life criterion. A second contribution is the design of an online state-estimation method, based on available input–output measurements, to reconstruct the dominant degradation states and track the state of health under dynamic operation. Building on the degradation model and the online estimates, a mission-aware prognostic framework is developed to predict HI evolution and RUL under projected future load scenarios, while accounting for uncertainty originating both from state estimation and from stochastic variability in the degradation process. A final contribution is the formulation and solution of a joint optimization problem that coordinates health-aware energy management and maintenance planning, using the outputs of the estimation and prognostic layers to improve lifetime, availability, and lifecycle cost at the multi-stack system level.

3. PRELIMINARY RESULTS

Building on the current progress of the thesis, the PHM core required by the framework in Fig. 1 has already been developed. It consists of a physical load-dependent degradation model with uncertainty, an online state estimator, and a mission-conditioned prognostic framework.

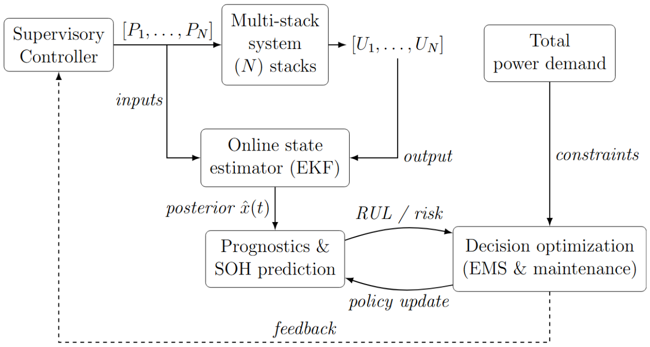


Figure 1. PHM framework for multi-stack PEMFC systems: online state estimation and mission-conditioned prognostics provide the information required to coordinate energy management and maintenance decisions, with feedback to the supervisory controller.

3.1. Load-dependent degradation–performance model

A reduced-order, physics-based model has been formulated to capture the dominant degradation mechanisms of PEMFCs, namely (i) catalyst degradation through the loss of electrochemically active surface area (ECSA), and (ii) membrane aging through membrane thinning and conductivity loss. The degradation dynamics are load-dependent, while uncertainty is introduced through stack-to-stack parameter variability and a stochastic formulation of membrane damage.

A compact representation of the coupled degradation model is

$$\dot{x}_{\text{deg}}(t) = f\big(x_{\text{deg}}(t), u(t)\big), \tag{1}$$

where $x_{\text{deg}} = [S,\ L_{\text{mem}},\ \sigma_{\text{mem}}]^\top$ denotes the dominant degradation states, with S the normalized ECSA, L_{mem} the membrane thickness, and σ_{mem} the membrane proton conductivity. The input vector $u(t)$ groups the operating conditions, including the load and the measured environmental and operating variables, such as temperature T, relative humidity RH, and gas partial pressures p_{H_2} and p_{O_2}.

3.2. Health index and EOL definition

To link the degradation state x_{deg} to performance, a polarization model is established to map the operating conditions and degradation state to the PEMFC output voltage,

$$V(t) = V\big(x_{\text{deg}}(t), u(t)\big). \tag{2}$$

The health index (HI) is defined as the normalized rated voltage. It depends only on the degradation state and therefore reflects only the state of health:

$$\text{HI}(t) = \frac{V(x_{\text{deg}}(t), u_{\text{rated}})}{V\left(x_{\text{deg}}^{\text{BoL}}, u_{\text{rated}}\right)}, \qquad \text{EOL} \Longleftrightarrow \text{HI}(t) \le \text{HI}_{\text{th}}, \tag{3}$$

where $x_{\mathrm{deg}}^{\mathrm{BoL}}$ denotes the beginning-of-life (BoL) degradation state. The EOL criterion is defined directly from a normalized loss of rated performance.

3.3. Online state estimation and mission-aware RUL

The coupled degradation–performance model is embedded in an extended Kalman filter (EKF) to estimate online, from voltage measurements under dynamic operation, the dominant degradation states in x_{deg} together with selected effective degradation parameters. These parameters are modeled as random-walk variables to enable online adaptation.

For prognostics, the EKF posterior at the end of the estimation phase is sampled and each sample is propagated forward under a projected future load profile using the stochastic degradation model through Monte Carlo simulation. The resulting RUL prediction is therefore mission-aware, since it is conditioned on the assumed future load scenario, and yields an RUL distribution that reflects both posterior estimation uncertainty and stochastic variability in the degradation process.

3.4. Validation highlights

The approach was validated on long-term dynamic durability data with periodic polarization-curve characterizations. Model/estimator outputs were assessed by reconstructing the polarization test curves.

4. FUTURE WORK PLAN

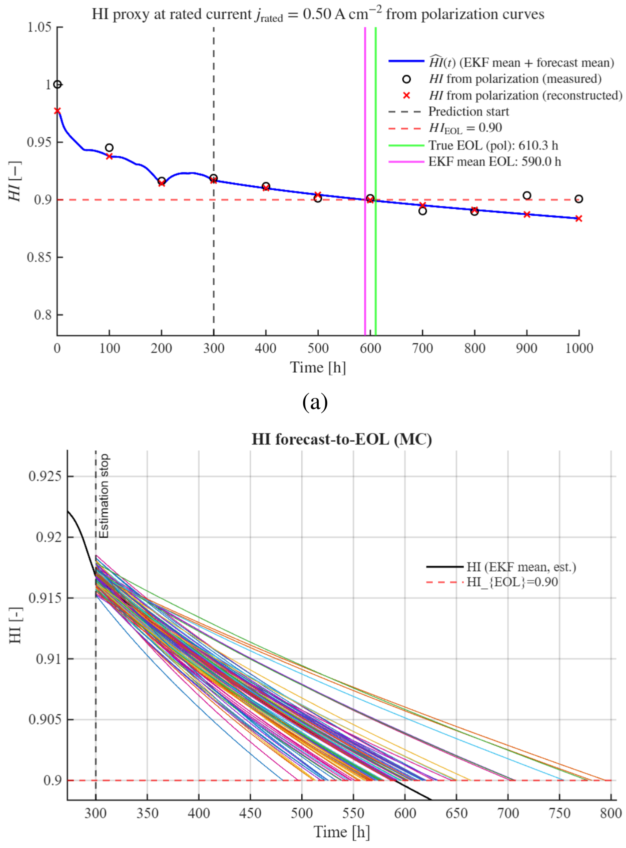
The next research stage focuses on closing the loop by integrating PHM outputs into health-aware EMS and selective maintenance planning for multi-stack systems.

(1) Health-aware EMS formulation. Design load-allocation strategies that exploit redundancy to slow degradation and extend system lifetime under constraints.

(2) Maintenance planning. Develop a maintenance model for actions such as single-stack replacement (effects on health states, cost, and downtime) and define decision rules that use predicted degradation paths and RUL risk to improve availability and reduce lifecycle cost.

(3) Joint EMS–maintenance optimization. Formulate and compare solution approaches for the decision problem. Key steps include defining a consistent lifecycle cost model (fuel/efficiency, degradation/health consumption, maintenance cost, downtime penalties) and realistic operational assumptions (mission statistics and constraints).

(4) Validation Evaluate the proposed strategies against baseline methods (e.g., equal load sharing and corrective maintenance) using synthetic benchmarks—and, when possible, real-system case studies—under realistic duty cycles. Performance will be reported in terms of lifetime extension, lifecycle cost reduction, and availability improvement.



(a)

(b)

Figure 2. (a) HI reconstruction against polarization-derived HI on real dynamic durability data. (b) Monte Carlo simulation trajectories for predicted HI starting from the EKF estimated posterior.

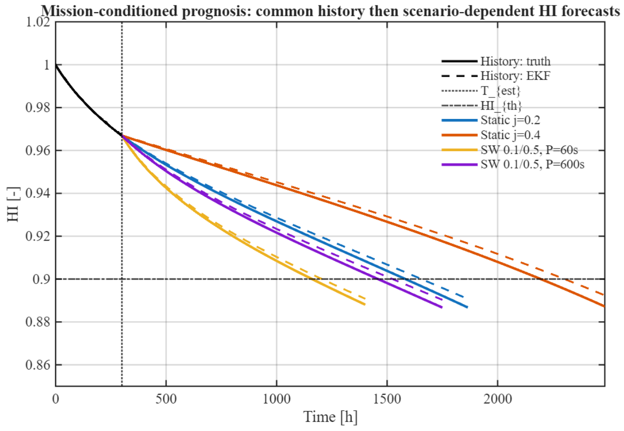


Figure 3. Scenario-dependent HI trajectories under alternative future missions (synthetic benchmark).

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