Fault Tree Analysis of Degradation Mechanisms in a Low-Temperature PEMFC System under Two Different Anode Circulation Modes

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Abstract— **This study investigates the impact of hydrogen supply subsystem configurations on the durability of Low Temperature Proton Exchange Membrane Fuel Cells in vehicles. Four configurations are analyzed: flow-through, dead-end anode, recirculation with pump, and with ejector. Using Fault Tree Analysis, the paper identifies degradation pathways leading to potential failures in two configurations: dead-end anode and hydrogen recirculation. Nitrogen and water accumulation at the anode is a key focus, with the aim of assessing their impact on membrane and anode compartment degradation. While these configurations improve hydrogen utilization, they also introduce risks that may reduce fuel cell system lifetime**

Keywords: Low Temperature Proton Exchange Membrane Fuel Cell, Fault detection, Hydrogen recirculation loop, Nitrogen gas crossover, Degradation, Durability

I. Introduction

The electricity supply by a Low-Temperature Proton Exchange Membrane Fuel Cell (LT-PEMFC) within a vehicle requires the implementation of a sophisticated system [1]. A large number of elements must be considered during system design, notably the interrelated processes of gas circulation, humidification, and heat regulation, which are essential to maintaining optimal conditions within the membrane [2]. PEMFCs are highly sensitive to operating conditions. As a result, various phenomena may affect the stack's power output and lifespan. These include flooding due to excess humidity or, conversely, drying out [3]. To ensure reliable operation, the fuel cell (FC) system must perform key tasks, including electricity generation and the dynamic regulation of internal flows. These functions are handled by a set of subsystems, each composed of components known as "auxiliaries". Figure 1 shows a schematic overview of a generic FC system, composed of multiple subsystems and their respective auxiliaries. It is important to note that this diagram is not exhaustive. The auxiliary configuration can be adapted depending on the selected operating mode. For instance, active humidifiers (which consume additional energy) can be replaced with passive solutions, with or without auxiliaries and no extra energy consumption [4]. The system can generally be divided into five subsystems: (i) air supply, (ii) hydrogen supply, (iii) water and gas humidification, (iv) temperature control, and (v) electrical load management [5,6,7].

Among these, the hydrogen supply subsystem plays a key role and can be configured in different ways depending on the application [8]. Four hydrogen circulation modes are typically found: flow-through anode, Dead-End Anode (DEA), recirculated mode with a hydrogen pump, and recirculated mode with a hydrogen ejector [9]. The effects of the DEA or recirculated modes are often not considered in experimental test benches due to their complexity. For this reason, an analytical study of degradation mechanisms associated with both modes has been conducted using a Fault Tree (FT) approach. The aim is to identify potential system faults during operation and to support the implementation of preventive and safety measures, contributing to a better understanding of FC degradation and a more accurate estimation of lifetime.

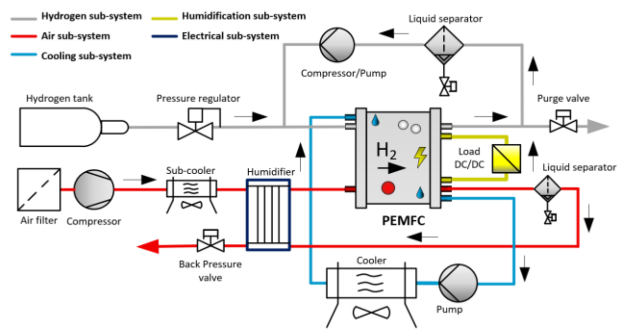

Figure 1. Generic representation of a typical fuel cell system

Before addressing degradation analysis, it is important to provide a clear overview of the hydrogen circulation modes currently used in PEMFC systems. These modes are not always well defined, which can hinder experimental design and interpretation of system behavior. Establishing this state of the art and graphically representing each configuration helps visualize potential degradation points and understand their physical origins. Although widely used in real applications, the anode hydrogen recirculation mode has received limited scientific attention, especially regarding its degradation risks. Experimental test benches are often simplified and may not reflect real-world conditions, raising scientific challenges such as identifying specific degradation mechanisms and developing a systematic approach to analyze them. This study addresses that gap by building a comprehensive FT to map degradation progressions and failure pathways. The methodology starts with the well-documented DEA mode, then extends to the recirculated mode—a novel contribution. The resulting FT supports fault

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diagnosis and root cause analysis in this underexplored configuration.

This article begins with an overview of common anode hydrogen circulation configurations in PEMFC systems. It then presents a detailed FT-based analysis of degradation mechanisms in two key modes: Dead-End Anode and recirculated anode. The objective is to identify the main degradation pathways that can lead to failures and to propose a structured method for anticipating faults under realistic operating conditions.

II. ANODIC CIRCULATION CONFIGURATIONS

The management of the hydrogen supply is supervised by a complex subsystem. Depending on the application and the selected operating mode, the configuration can vary, with alterations to the auxiliaries being utilized. The following study provides a comprehensive review of the four predominant operating modes.

A. Flow-Through Anode

This mode is both simple and cost-effective to implement. It continuously circulates hydrogen in controlled proportions, but unreacted hydrogen is vented to the environment, reducing utilization efficiency, increasing costs, and raising safety concerns. As a consequence, this configuration was therefore quickly forgotten for vehicles [10]. To prevent membrane drying, a substantial humidification system is needed to moisten the incoming hydrogen. The Flow-Through Anode configuration is shown in Fig. 2: the desired flow rate is set by a mass-flow controller, humidification is provided by an active humidifier, and downstream pressure is regulated by a back pressure valve at the outlet.

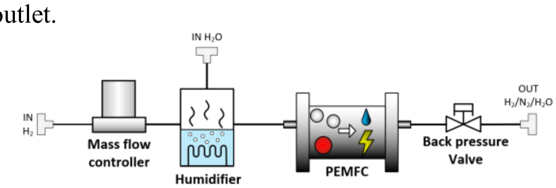

Figure 2. Hydrogen sub-system in flow-through anode configuration

Nevertheless, due to its uncomplicated setup and the guaranteed suitability of the supplied hydrogen, it is still the preferred configuration on laboratory test bench. This raises questions about the reliability of certain durability assessments, given that the configuration of test bench is not fully representative of real-road applications.

B. Dead-End Anode

The DEA configuration is presented in the same way as the Flow-Through mode, but a solenoid valve placed at the end of the hydrogen line is used to stop the flow outlet. This configuration requires a small volume of gas and low energy consumption, which reduces the FC system cost [10]. The solenoid valve is controlled in order to carry out specific purges that are optimized according to the system. The purge process is instrumental in the removal of excess liquid water, impurities, and nitrogen which have been transferred from the cathode to the anode [8]. As illustrated in Fig. 3, the DEA design is shown. The outlet pressure is controlled upstream by a pressure regulator. The purge valve is periodically opened for purging operations.

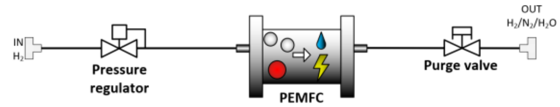

Figure 3. Hydrogen sub-system in dead-end anode configuration

C. Hydrogen recirculated

It is well established that hydrogen utilization in PEMFCs typically ranges from 80 to 95%, depending on the FC design [11]. The recirculation mode returns excess hydrogen from the anode outlet to the inlet, allowing it to participate again in the electrochemical reaction while promoting forced convection within the channels. This flow aids in removing excess liquid water via a pressure-driven gas stream that carries droplets out of the distribution channels. Simultaneously, the process recovers unused hydrogen and water vapor, improving humidity management in the FC [12]. It also enhances hydrogen utilization and facilitates the removal of water and gaseous impurities through a purge system. The water vapor in the recycled stream helps regulate membrane hydration [11]. Moreover, as most hydrogen is reused in the closed circuit, the process poses no environmental risk. Currently, hydrogen recirculation is the most widely adopted approach in PEMFC vehicles [8]. The following modes are based on this principle but use different components.

1) Active recirculation with a hydrogen pump

Active recirculation uses a hydrogen pump connected to the gas/water separator, which is itself connected to the H_2 anode outlet. The anode outlet must pass through a purge separator to remove liquid water, which could damage the pump and affect the quality of the reactant. The inlet flow is regulated by a pressure regulator upstream of the FC. The pump pressurizes the anode exhaust gas—composed of hydrogen, water vapor, nitrogen, and impurities—and sends it back to the anode inlet, where it mixes with pure hydrogen before being reintroduced into the cell. This method is described as 'active' due to its electrical energy consumption and is illustrated in Fig. 4.

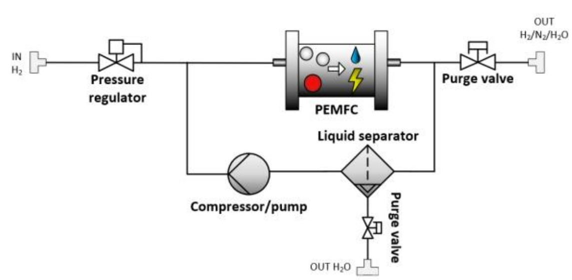

Figure 4. Hydrogen sub-system in active recirculation configuration

2) Passive recirculation with an ejector

The hydrogen ejector operates as a suction system, using high-pressure gas to create a venturi effect that induces suction of a secondary flow. It recirculates hydrogen from the anode outlet back to the inlet. The ejector has a dual-nozzle design: the primary nozzle supplies pure hydrogen, while the secondary recycles hydrogen from the anode outlet. These flows mix in the ejector's mixing zone. As the gas moves toward the diffusion zone, velocity decreases and pressure rises. The resulting pressurized mixture is directed to the anode inlet [13]. As shown in Fig. 5 [14], this recirculation mode is considered 'passive' since the ejector consumes no electrical energy, improving system stability and efficiency. A purge valve is also installed at the outlet to periodically remove accumulated species from the anode loop, as further discussed in Section III. In mechanical engineering, ejectors offer greater reliability than pumps but operate passively, with performance highly dependent on geometry and operating conditions. Without additional components, ejectors often show instability during start-up, shutdown, or load changes, especially under low-flow, low-current conditions, causing fluctuations in the recirculation line [11]. Water in the reactant stream further degrades ejector performance [13], making precise control of operating conditions both complex and crucial.

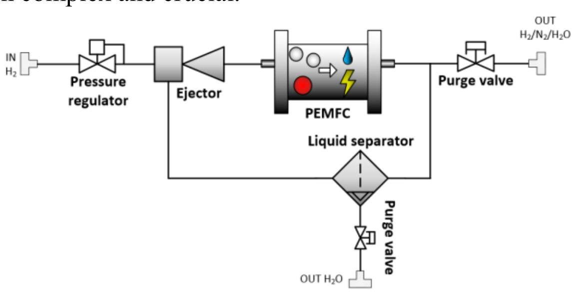

Figure 5. Hydrogen sub-system in passive recirculation configuration

However, it should be noted that alternative recirculation methods do exist, and these will not be the focus of this study. Other methods include pressure oscillation recirculation [15,16], recirculation fans, and series of pumps and ejectors [13].

It has been established that both DEA mode and recirculation mode with a pump improve the efficiency of hydrogen use. Nevertheless, it should be noted that these modes also impose higher demands on system quality, control, and diagnostics. A review of the extant literature studies the failures associated with DEA mode [16,17], but little research has been carried out on failures linked to recirculation mode.

III. Degradations Related to Dead-End Anode and Recirculated Modes

This section focuses on the possible degradations caused by the H_2 supply subsystem in DEA and recirculated modes within the FC system. These degradation mechanisms are analyzed using a FT, a graphical tool that identifies potential failure causes through deductive reasoning. It also helps analyze combinations of events that are necessary and sufficient for a failure to occur. The structure of an FT is described as follows:

- Main event: Represents the failure or risk to be analyzed;
- Intermediate events: Contributing sub-events;
- Basic events: Root causes requiring no further analysis;
- Logic gates: Symbols (AND, OR, XOR) used to link events and define their relationships.

In this case, the failure is characterized by the presence of degradation signs in the membrane or in the anode compartment, which results in a loss of overall stack performance.

A. Dead-End Anode Fault Tree

Our analysis begins with the accumulation of species migrating from the cathode to the anode, potentially triggering various degradation mechanisms. These events are identified by letters and illustrated in the FT shown in Fig. 6. The selected basic events include oxygen crossover through the membrane (E1), back-diffusion of cathode-produced water (E2), and nitrogen crossover from air (E3). These mechanisms, resulting from species transfer across the membrane, are not detailed in this article. The DEA is considered as an operating condition which, combined with these events, contributes to performance loss through membrane and anode compartment degradation.

In blocked mode, water and nitrogen from the cathode can infiltrate the anode side and gradually accumulate in the flow channels before purging (C and E). In the absence of forced convection when the purge valve is closed, several degradation phenomena may occur [18, 19]. These are described below:

- Nitrogen accumulation (E) leads to hydrogen dilution at the anode, causing localized hydrogen starvation (F) [20]. This induces a rise in potential in one region (G) and a corresponding drop in another (H) [21]. The potential increase is a known trigger for carbon oxidation (I), degrading the anode compartment [22]. Carbon deposits can hinder active sites, reducing performance, while platinum catalyst degradation (K) compromises the anode–membrane interface, impairing proton transfer [23].

  Carbon oxidation may also catalyze hydrogen peroxide decomposition, forming highly reactive –OH or –OOH radicals (G) that degrade the membrane [24]. Hydrogen peroxide results from oxygen crossover and water back-diffusion from cathode to anode (A), though DEA mode does not appear to increase its formation at this stage. At the same time, the potential drop causes membrane heating, which contributes to polymer degradation (J) [24].

- Water transported by back-diffusion from the cathode accumulates at the anode outlet when the valve is closed, potentially causing flooding (C) [25]. This fuel starvation can generate a reverse current (D) [26], which may initiate or accelerate carbon corrosion on the catalyst, leading to an irreversible decline in electrochemical active surface area.

Purging involves strategically timed and regular valve openings to prevent gas starvation. This optimization helps recover the reversible voltage drop caused by water and impurity buildup, thereby reducing the risk of irreversible deactivation from carbon corrosion [18, 12].

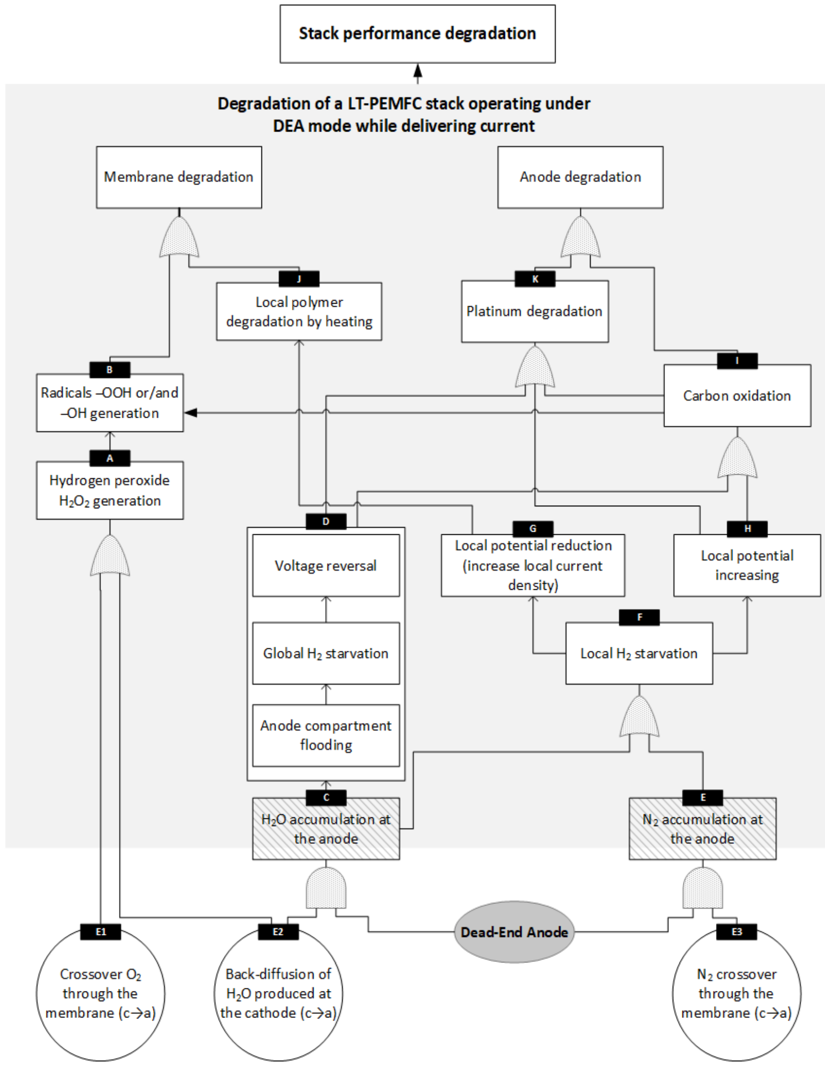

Figure 6. Fault Tree of a fuel cell system in Dead-End Anode configuration

B. *Recirculated Fault Tree*

The active hydrogen recirculation mode (mechanical pump) has been selected for the FT analysis, as shown in Fig. 7, with each phenomenon identified by a corresponding letter referenced throughout the article. Mechanical recirculation pumps are currently the most commonly used by manufacturers [4]. For the DEA mode analysis, the basic events selected for the FC system with H_2 recirculation remain the same: E1, E2, and E3. To avoid redundancy, previously described phenomena will not be repeated here. However, the recirculated mode introduces new intermediate issues due to the reuse of outlet gas at the system inlet. Additionally, using a mechanical pump contributes to new failure modes [4]. The following section details these issues.

- In the event of the system operating in recirculated mode, the proportion of nitrogen already accumulated at the anode (D, see III.A) will increase due to the re-injection of outlet gases from the anode circuit to the inlet (R3) [27]. Consequently, the nitrogen accumulation will result in the same degradation as observed in DEA mode (F, I, K), albeit with an increased probability.
- The secondary flow is already at the temperature and humidity of the stack, and when combined with the primary flow, these operating conditions (temperature and humidity) are therefore higher than the initial parameters and more difficult to control (R2) [28]. Increasing these parameters will increase the probability of H_2O accumulation at the anode (C).
- The efficiency of water separator upstream of the recirculation pump is not always reliable (R1) [4]. As a result, small amounts of liquid water may enter the recirculation loop, making the pump particularly vulnerable. This can cause corrosion of mechanical components (L), degrade the pump system, and introduce impurities into the anode circuit (M), increasing the risk of membrane or compartment damage.

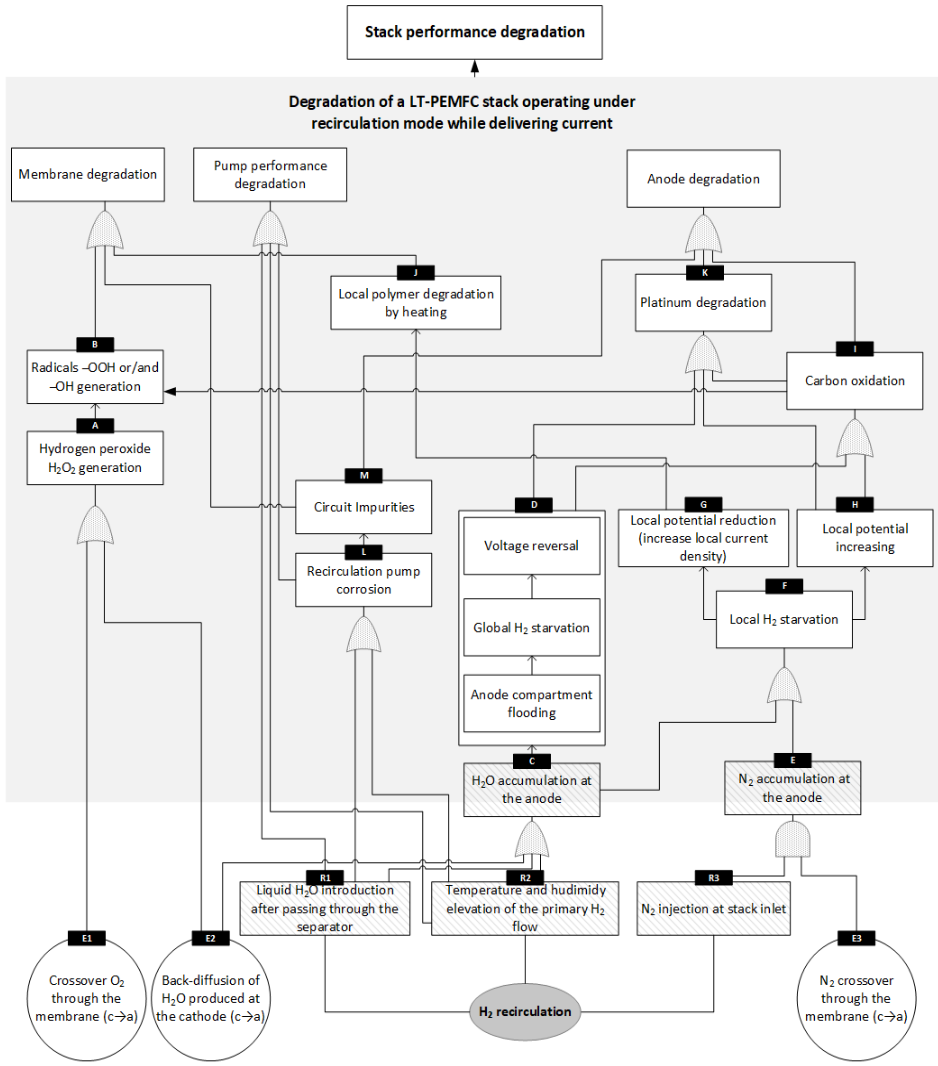

Figure 7. Fault Tree for a fuel cell system in active recirculation configuration

Impurities such as hydrogen, oxygen, nitrogen, and water can degrade FC systems and compromise durability, primarily due to crossover effects enabling their diffusion from the cathode. Thus, gas management and purging strategies remain essential even in recirculation modes.

IV. CONCLUSION

Many studies have investigated fuel supply subsystems and their influence on LT-PEMFC performance, with particular emphasis on the DEA configuration due to its simplicity and cost-effectiveness [29]. However, experimental data concerning hydrogen recirculation modes remain scarce, especially under operating conditions representative of automotive applications. In this context, the contribution of our FT analysis offers added value by shedding light on the potential impact of both DEA and recirculated modes on FC stack durability.

In the present study, the FT was constructed by considering membrane and anode compartment degradation as final events. To obtain a more complete representation of the failure mechanisms, future work should enrich the model by detailing the nature of final degradation phenomena, such as membrane cracking or perforation. Incorporating operating conditions into the FT framework also appears to be a promising direction, as shown in several existing studies. Coupling our FT with those from the literature could help to reveal more specific faults that are influenced by the configuration of the anode subsystem.

The analysis conducted in this study constitutes a first step toward identifying and structuring the degradation issues specific to the recirculation mode, which remains underexplored under realistic operating conditions. This initial FT framework highlights the need for deeper investigation into the effects of this configuration. The next stage should involve advanced system modeling tools, particularly to simulate recirculation dynamics and the transport of species from the cathode to the anode side of the membrane. Additionally, experimental test benches should be adapted to implement or emulate the recirculation mode more accurately. These improvements would enable the collection of realistic operational data, forming a solid basis for the development and validation of fault detection algorithms and supporting predictive maintenance strategies.

Furthermore, as LT-PEMFC technology advances toward higher power densities with increasingly thinner membranes, crossover phenomena between the cathode and the anode compartments become more critical. These effects are particularly significant at high current densities, which often result in non-uniform distributions across the membrane surface, as typically observed in dynamic vehicle operation [30]. It is therefore essential to optimize purging strategies and operating conditions using degradation-focused failure models tailored to each anode circulation mode.

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