FAULT TREE ANALYSIS OF FAILURE MODES RELATED TO WATER MANAGEMENT IN A PEM FUEL CELL SYSTEM FOR AEROSPACE APPLICATIONS

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Abstract

Alternative all-electric propulsion concepts, for example based on proton-exchange membrane fuel cells, must comply with the established safety and reliability requirements of the aviation industry. Hence, failure analysis have to be conducted in early system design phases. One potential method for such analysis are fault trees. The complexity of fuel cell propulsion systems make the development of fault trees an extensive task. In this work, the fault tree analysis is especially applied to failure conditions connected to the intrinsically important water management of the fuel cells. Close physical relations of multiple parameters linked to the failure conditions complicate the development of respective fault trees. Therefore, an approach with three dedicated fault tree layers is proposed in this work, including a physical-level resolving the correlations of the influencing physical parameters. This method increases the structure, the completeness and the modularity of the fault trees. Furthermore, the physical-level can be a valuable input for future developments of failure detection, and mitigation mechanisms. The developed fault trees can thus be used as an input in the design phase of a fuel cell based aircraft propulsion system as well as a basis for preparatory certification activities.

Keywords

aircraft propulsion; hydrogen; PEM fuel cell; water management; fault tree

NOMENCLATURE

Symbols

a	water activity	-
λ	membrane water content	-
p	pressure	Pa
φ	relative humidity	-
R	membrane resistance	Ω
σ	membrane conductivity	$\Omega^{-1}\,\mathrm{cm}^{-1}$
T	temperature	K
t	thickness	m

Subscribts

i	placeholder
m	membrane
sat	saturation
w	water

Abbrevations

ACL	anode catalyst layer
BoP	balance of plant
BPP	bipolar plate
CCL	cathode catalyst layer
CL	component-level
FHA	functional hazard analysis
FTA	fault tree analysis
FT	fault tree
GDL	gas diffusion layer
HBV	humidifier bypass valve
HOR	hydrogen oxidation reaction
ORR	oxygen reduction reaction
PEMFC	proton-exchange membrane fuel cell
PEM	proton-exchange membrane
PL	physical-level
TLE	top-level-event
TL	top-level

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1. INTRODUCTION

The aviation sector is aiming for ambitious climate goals [1]. However, the emissions of aviation are projected to increase further in the upcoming decades [2]. Among other measures, it is thus necessary to develop alternative propulsion concepts. Besides the carbon dioxide emissions, it is vital to also tackle nitrogen oxide and contrails with said new developments, as the latter add up to 66 % of the aviations climate impact [2]. Hydrogen-electric propulsion systems, employing fuel cells, are one promising technology, as they offer the potential to entirely eliminate carbon dioxide and nitrogen oxides emissions [3]. Hence, multiple companies and institutions are currently investing in the research and development of such propulsion concepts (see for example [4–8]).

Low temperature proton-exchange membrane fuel cells (PEMFCs) are often considered promising for aviation applications [9, 10]. However, for an efficient operation PEMFCs require multiple subsystems, referred to as balance of plant (BoP). A PEMFC and its BoP form a complex and multidisciplinary system, leading to substantial design challenges when developing a fuel cell propulsion system for aviation applications [11, 12]. Furthermore, their complexity make fuel cell systems prone to numerous different possible failure modes that need to be considered [13, 14].

As safety and reliability are of paramount interest in the aviation sector, it is highly relevant to assess said failure modes already early on in the design process [15, 16]. Accordingly, safety analyses are part of the early stages of the aviation's standard development process for all aircraft and their subsystems [17]. Further standards recommend guidelines and methodologies to conduct said analyses [18], proposing for example the fault tree analysis (FTA). An FTA enables the identification of all lower level failure modes contributing to a specific known failure condition, generating valuable input for architecture design and certification [18, 19].

In this work, failure conditions associated with the water management of an aviation fuel cell propulsion system are investigated using an FTA. The water management is selected as an example to demonstrate the FTA method, as it is especially challenging, intrinsically fundamental for the operation of PEMFCs, and can easily be disrupted [20, 21]. Additionally, water management faults are among the most commonly occurring faults in PEMFCs [13] and are potentially a major failure condition in an aviation propulsion system [22]. The system complexity and close physical correlations make the setup of fault trees (FT) for water management a difficult and extensive task and require a tailored methodology. Thus, to enhance the FT development for water management issues in a fuel cell propulsion system, a three-layered and largely modular approach incorporating a dedicated physical-level, is introduced in this work.

2. BASICS OF PEMFCS, PEMFC WATER MANAGEMENT AND FAULT TREE ANALYSIS

For the general understanding, subsection 2.1 presents the basic working principle of PEMFCs. As the focus of this work is put on failure conditions related to the PEMFC water management, subsection 2.2 introduces respective water management fundamentals. Furthermore, basic principles and the methodology for the conduction of FTAs are explained in subsection 2.3.

2.1. Fundamentals of PEMFCs

The working principle of PEMFCs is explained in many standard works of literature, like Barbir et al. [23] or Larminie and Dicks [24]. If not indicated differently, this section is based on information from the aforementioned literature. A simplified depiction of a single fuel cell is shown in figure 1.

Inside a PEMFC, a reaction of hydrogen (H_2) and oxygen (O_2) takes place. This electrochemical reaction is split into two sub-reactions (indicated with ① and ② in figure 1) by the fuel cell. To prevent the direct reaction, the cell is split by a proton-exchange membrane (PEM) into an anode and a cathode side. In the anode side of the cell, the supplied hydrogen is oxidized at the interface of the PEM and the anode catalyst layer (ACL) forming protons and electrons (see ①). The protons (H^+) resulting from the hydrogen oxidation reaction (HOR) in the anode can directly transfer through the PEM to the cathode side, while the electrons (e^-) are forced to travel through the gas diffusion layer (GDL), the bipolar plates (BPP), and an external electric circuit to the cathode side. In the external electric circuit the electrons can conduct usable electric work. In the cathode, the protons, the electrons, and the supplied oxygen (often supplied in the form of ambient air) form water (H_2O) in the oxygen reduction reaction (ORR) at the interface of cathode catalyst layer (CCL) and the PEM (see ②). Besides water, also heat is released in the process, which needs to be dissipated to avoid an overheating of the PEMFC, usually working in a temperature range below 100°C.

The voltage that can realistically be achieved by a single fuel cell in operation is usually below 1 V [27]. Hence, to achieve useful voltage levels, multiple single cells are connected in series via the bipolar plates, forming a so-called fuel cell stack [27]. The bipolar plates thereby provide channels for reactant supply and act as electrical connection. Additionally,

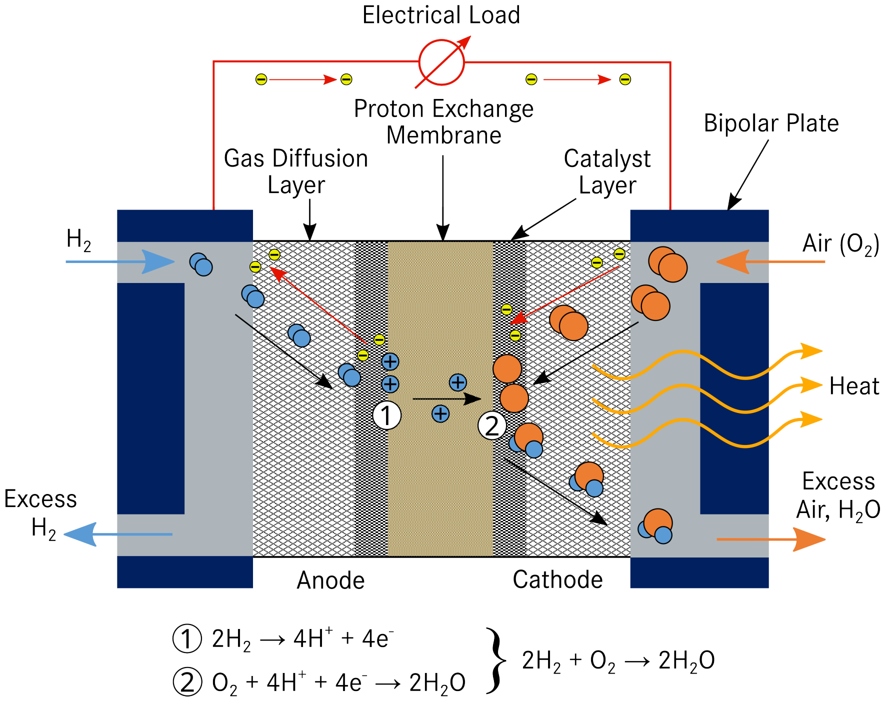

FIG 1. Schematic depiction of the working principle of a PEMFC, its main parts and the electrochemical reactions, based on and adapted from Siemer [25] and Kazula et al. [26]

they can be used to integrate fluid cooling channels for temperature control [27].

For the operation of a PEMFC stack, additional subsystems are necessary. These subsystems (or the BoP) are responsible for the conditioning of the reactant gases before entering the stack (set temperature, humidity, etc.) and the removal of the reaction products (water and heat). Furthermore, an electrical subsystem is required to handle the generated electrical power and distribute it to the consumers, for example the electric motors. Finally, a control system is required to actuate the components of the subsystems according to the power demand. To fulfill the corresponding functions, the BoP can incorporate a multitude of different components, like pipes, valves, heat exchangers, and others, forming a complex system altogether.

The maximum power, which can be achieved with a single stack system, is limited due to limitations in the fuel cell stack size and other reasons [28]. However, aviation applications demand high power levels up to multiple mega watts. Hence, multi-stack fuel cell systems are required [28]. A large amount of different system architecture variants with a varying complexity are generally possible for mutli-stack fuel cell systems [29].

2.2. PEMFC Water Management

The water management inside a PEMFC is essential for an efficient operation [21, 30, 31]. The water management comes down to maintaining a balance between a well hydrated PEM and the avoidance of excess liquid water accumulation inside the electrodes, the GDLs, or the channels [20, 21, 31].

Generally, the PEM material (often Nafion) can absorb water, either gaseous or liquid, from its surrounding environment [32]. The water content $\lambda_{\mathrm{m,i}}$ of the PEM at its surface is thereby linked to the water activity $a_{\mathrm{w,i}}$ at the respective surface [33], as described with a non-linear fit by Kulikovsky [34]:

$$\begin{aligned}\lambda_{\mathrm{m,i}} &= 0.3 + 6 \cdot a_{\mathrm{w,i}} \cdot (1 - \tanh(a_{\mathrm{w,i}} - 0.5)) \\ &\quad + 3.9 \cdot \sqrt{a_{\mathrm{w,i}}} \cdot \left[1 + \tanh\left(\frac{a_{\mathrm{w,i}} - 0.89}{0.23}\right)\right]. \end{aligned} \tag{1}$$

When considering gases, the water activity $a_{\mathrm{w,i}}$ is equal to the relative humidity φ_{i} at the PEM surface [35], with the latter being the ratio between partial pressure of water $p_{\mathrm{w,i}}$ and water saturation pressure $p_{\mathrm{w,sat,i}}$:

$$a_{\mathrm{w,ACL}} \hat{=} \varphi_{\mathrm{ACL}} = \frac{p_{\mathrm{w,ACL}}}{p_{\mathrm{w,sat,ACL}}} \quad \text{and} \tag{2}$$

$$a_{\mathrm{w,CCL}} \hat{=} \varphi_{\mathrm{CCL}} = \frac{p_{\mathrm{w,ACL}}}{p_{\mathrm{w,sat,CCL}}}. \tag{3}$$

Generally, the partial pressure of water is a function of the absolute gas pressure and the water saturation pressure is linked to the temperature. Following equations (1) to (3) and assuming the absence of liquid water, the water content of the PEM material is directly coupled to the partial pressure of water and the water saturation pressure of the gas in contact with the PEM [33, 35]. The PEM water content can thus be controlled by regulating the amount of water in the electrodes. Depending on the PEM material and the fuel cell design, the PEM hydration can either be achieved internally or assisted by external measures [20, 21]. Internal humidification is solely based on the water produced by the ORR in the cathode [20,21]. This, however, might be insufficient for larger fuel cell stacks or in certain operating points (high temperature, low current density, etc.) [20]. Hence, additional water can for example be supplied to the electrodes by an external humidification of the reaction gases upstream of the fuel cell inlet [20].

To enable the electrochemical reaction inside a PEMFC, an efficient proton conduction across the PEM from the anode to the cathode side has to be ensured [23, 24]. However, the resistance R_m of the PEM against proton transport is dependent on its water content λ_m, as it can be derived from the following equations [33,36,37]:

$$R_\mathrm{m} = \frac{t_\mathrm{m}}{\sigma_\mathrm{m}}, \tag{4}$$

with t_m being the PEM thickness and σ_m the PEM conductivity [36]:

$$\sigma_\mathrm{m} = \sigma_{30} \exp\left[1268\,\mathrm{K}\left(\frac{1}{303\,\mathrm{K}} - \frac{1}{T}\right)\right], \tag{5}$$

with

$$\sigma_{30} = 0.005139\,\tfrac{1}{\Omega\,\mathrm{cm}} \cdot \lambda_\mathrm{m} - 0.00326\,\tfrac{1}{\Omega\,\mathrm{cm}}, \tag{6}$$

where T is the temperature. Thus, based on the equations (4) to (6), the proton conduction resistance of the PEM increases for low humidification levels [21,31]. To avoid voltage losses due to such an increase, it is hence vital to keep the PEM sufficiently hydrated in the entire operating range by respective measures [21, 31]. The scenario of a too low PEM water content is typically called drying.

Although sufficient humidification is required to maintain the PEM water content, the amount of water inside the fuel cell should not be too high. Otherwise, condensation and thus the formation of liquid water droplets can occur [20, 21]. In the case of an accumulation of liquid water inside the electrodes, also referred to as flooding, the transport of the reaction gases towards the reaction sides is hindered [21,31]. This can reduce the reaction gas concentration at the reaction site, resulting in increasing voltage losses [21,31].

The problem of maintaining the water balance is further complicated by the fact, that various physical parameters impact the water balance (e.g. temperature, operational pressure, current density, etc.). As a result of the various influencing parameters, a multitude of different subsystems and components will impact the water balance [21]. This can also be the case, if the general function of a certain subsystem or component is not primarily connected to the water management (e.g. pressure control valves, heat exchangers, etc.). Additionally, variations of the local operating conditions make proper water management challenging. Within a single cell, temperature, relative humidity, and current density can vary over the cell area. Variations can also appear along the mass flow direction inside a stack, forming local zones with too dry or too wet conditions [20].

2.3. Basic principles of Fault Tree Analysis

To fulfill the strict certification requirements of the aviation industry, the development processes of aircraft and their subsystems follow defined standards like the SAE ARP 4754B [17]. Failure modes are therein addressed early on in the design process. As the engine can be accounted as a subsystem of the aircraft, a preliminary system safety analysis (PSSA) needs to be conducted while developing the engine requirements and architecture [17]. In the course of the PSSA, FTAs are one of the recommended methodologies for a structured and methodical failure analysis [17]. FTs help to reveal failure chains and root causes of undesired top-level-events (TLE) [18, 19]. The TLEs usually represent critical failure conditions previously identified by a functional hazard analysis (FHA) [18].

The SAE ARP 4761A [18] describes, how an FTA shall be conducted. Generally, FTs represent a top-down approach [18, 19]. The FT starts with an undesired TLE, which shall be investigated. Subsequently, all failure events and failure combinations leading to the TLE in the next lower level (e.g. subsystem level) are identified [18,19]. This procedure is then successively repeated, uncovering further lower level failure events and failure combinations. The procedure is either ended, if a sufficient level of details is reached or if basic failure events are uncovered, which can not be developed further [18,19].

An FT is usually depicted in a graphical form [19]. A selection of the most frequently used FT elements and their graphical symbols are shown in figure 2. The symbols can generally be categorized in either events or boolean logical gates [18]. The logical gates are used to depict the links between the events in the FT [18], enabling the modeling of failure combinations. As an example, if an event only occurs when multiple sub-events occur at the same time, an AND-gate can be used to represent this logic [18,19]. Using the combination of events and boolean logic, the FT can be built up step by step, until no further development is possible or a suitable level of detail for the scope of the analysis is reached.

Symbol	Name	Definition
Description	Description Box	Description of output of a logic symbol or event.
ID	OR-Gate	Boolean Logic Gate Event occurs, if at least one of the underlying event. occurs. Box can include event ID if required.
ID	AND-Gate	Boolean Logic Gate Event occurs, if all underlying events occur. Box can include event ID if required.
ID	Transfer-Gate	Representation of information transfer. Box can include event ID if required.
ID	Basic Event	Event internal to system under analysis, no further developmend. End of fault tree. Box can include event ID if required.
ID	Conditional Event	Condition necessary for another event to occur. Box can include event ID.
ID	Undeveloped Event	Event is not developed further. Box can include event ID.

FIG 2. Frequently used elements in FTs for the representation of events and logical gates based on SAE ARP4761A [18] using the graphical representation of Isograph Reliability Workbench Software [38]

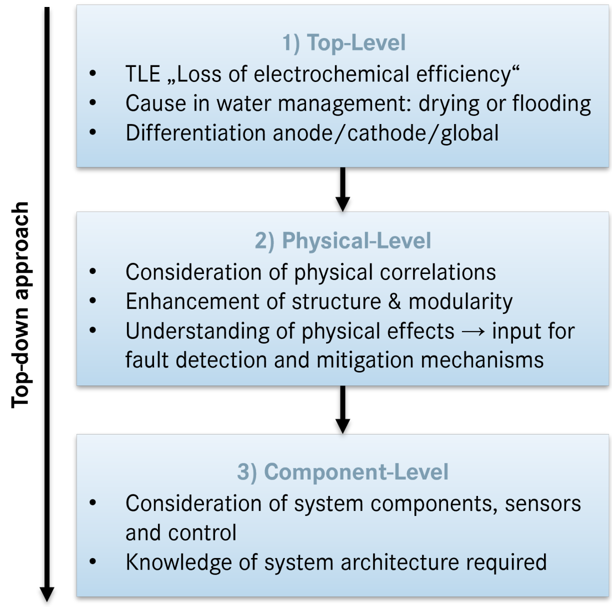

FIG 3. Top-down approach for fault tree development highlighting the three different levels developed in this work

3. METHOD FOR FAULT TREE DEVELOPMENT

The scope of the FTs developed here is to investigate water management failure conditions in a PEMFC aviation propulsion system. Using the FTs, relevant failure chains can be uncovered. Thereby, the general understanding for water management issues can be enhanced and components, whose failure modes impact the water management, can systematically be identified.

The FTs in this work focus on failure modes occurring during the operation of the fuel cell system. It is assumed that the system is correctly controlled during healthy state operation. Design or manufacturing issues are not considered in the FTs. Furthermore, also the spatial effects of the water management over the cell area and on stack level are not considered in the first place. To handle the complexity and the close physical interconnections described in section 2, a tailored three layered approach is proposed for the FTs, which is explained in the following.

Figure 3 shows the basic principle of the proposed methodology and summarizes key elements. The approach separates the FT into the following three sub-levels: a top-level, a physical-level, and a component-level. From top to bottom, a top-level (TL) is used first. Besides the definition of the top-level-event (TLE), also the main failure conditions leading to the TLE (mainly drying and flooding) and variants of said failure conditions are included in the TL. To account for the complex physical interdependencies in PEMFCs, a physical-level (PL) is proposed to assist the modularity, structure, and completeness of the developed FT below the TL. Finally, the component-level (CL) is introduced. The CL incorporates the identified basic failure modes inherent to specific system components contributing to the upper levels of the FT. Each of the three sub-levels are described in detail in the upcoming subsections 3.1, 3.2, and 3.3.

3.1. Development of Top-Level

From top to bottom, the first sub-level of the FTs is the TL. The corresponding part of an FT developed for an exemplary single PEMFC stack is shown in figure 4. As TLE, "Loss of electrochemical efficiency due to water management issues" is defined. The elctrochemical efficiency is chosen in the TLE instead of power or thrust, as a PEMFC system, which is power controlled, could potentially change its operating point as a consequence of an occurring failure and still deliver the demanded power. However, this would result in a reduced efficiency.

A "Loss of electrochemical efficiency" could have multiple causes. Due to the focus of this work on the water management, the TLE is defined as "Loss of electrochemical efficiency due to water management issues". As explained in subsection 2.2, a water management issue or disturbance can either lead to drying or flooding inside the PEMFC. Hence, an OR-gate is used below the TLE with "Drying of membrane" and "Flooding in electrodes" identified as contributing factors to the TLE.

A flooding scenario can either happen in the anode or the cathode or in both electrodes at the same time. This is represented in the FT by an OR-gate and three corresponding events for the failure conditions

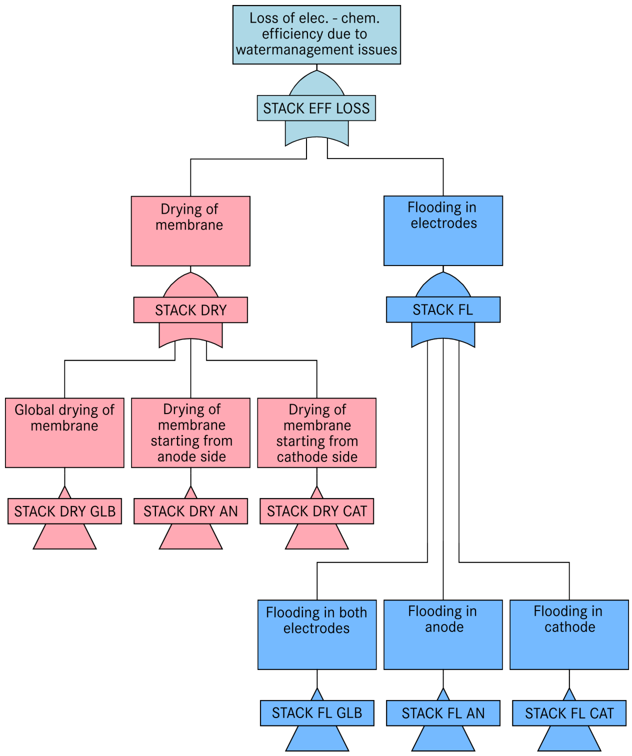

FIG 4. Development of the top-level-event into six failure conditions

(see figure 4). Below "Drying of membrane", causes for a drying of the PEM, which are not connected to one of the electrodes especially, are summarized with the event "Global drying of membrane". Furthermore, events exist, which can specifically be assigned to the anode or the cathode side or the respective reactant supplies in a first place. However, even if according intermediate or basic events can be assigned to one electrode, the resulting drying event will ultimately also affect the side of the PEM in contact with the other electrode. To reflect this phenomenon in the FTs, the formulation "starting from anode/cathode" is added, compared to the flooding side of the TL. Again, similar to said flooding part of the TL, an OR-gate can be used to logically connect the resulting three events below "Drying of membrane". This leads to a total of six failure conditions associated with the water management of a single stack.

The TL of the FT shown in figure 4 is exemplary for a single fuel cell stack. As explained in subsection 2.1, fuel cell systems for aviation applications usually consist of multiple stacks. The TL developed for a single stack here, can be applied to each of the stacks in a multi-stack system. If required, the TLEs of each stack could be connected in an upper system level FT, reflecting the respective multi-stack architecture.

3.2. Development of Physical-Level

The TL has identified six high level failure conditions for a fuel cell stack, with respect to the water management. However, the complexity of fuel cell systems and their subsystems makes it challenging to directly identify all underlying potential root causes or component failure modes. Additionally, many of the physical parameters relevant for an efficient water management are interdependent. As an example, the PEM water content is proportional to the partial pressure of water in the electrodes (see subsection 2.2), which again can be influenced by the absolute pressure, the temperature or other parameters. Hence, as also stated in Qi et al. [21], failures in all subsystems and their respective components may impact the water balance. This is also the case, even if their primary function is not connected to the water management in the first place. To ensure that all relevant failure modes in the system are considered properly by the FTs, the PL is proposed in this work.

The structured approach incorporating the PL as an intermediate step in the development of FTs helps to reduce the risk of missing relevant failure modes and improves the FT completeness. In the PL, the complex couplings of physical parameters are resolved first and all basic physical changes leading to drying or flooding scenarios are identified. In the following, it is then easier to assign specific component failure modes to the identified basic physical events, as it would be to directly connect them with one of the failure conditions from the TL. Additionally, the general physical phenomena behind said scenarios are equivalent for all PEMFC stacks, independent of the system architecture being analyzed. Thus, most of the PL is modular, making it possible to apply it to different stacks in various system architectures. Particularly in early system design phases, this helps to speed up iterations of the FT development. Hence, a PL to resolve the strongly coupled physical processes is a useful method to enhance the structure and modularity of the FTs.

The basic approach in this work to build the PL to assess flooding and drying scenarios is based on FTs published by Yousfi-Steiner et al. [39]. In their FTs, Yousfi-Steiner et al. [39] reveal simple physical event chains and identify subsequently multiple basic physical parameters (operating parameters of the stack itself) influencing the water management. Additionally, the respective type of change (increase/decrease/unchanged) of physical parameters necessary for the corresponding scenarios to occur, is indicated. Thereby, it is assumed that no change of other physical parameters will counteract the change of the physical parameter being investigated.

The approach by Yousfi-Steiner et al. [39] is adapted and extended. Compared to the FTs by Yousfi-Steiner et al. [39], the TL of the present work introduces an additional differentiation of flooding and drying scenarios based on the electrode being impacted (anode, cathode, global). This spatial differentiation is continued in the PL. Basic physical parameters or intermediate physical events of the PL are assigned to one of the three spatial scenarios (anode, cathode, global), if a clear differentiation is possible. As an example, a changing water production rate as intermediate event can be assigned to cathode scenarios, as the ORR takes place in the cathode. If assuming an equal temperature on the anode and the cathode side, a changing temperature can be assigned to the global scenarios, as this would result in a changing water saturation pressure in both electrodes at the same time. However, some intermediate physical events, like a changing partial pressure of water, can occur independently in both electrodes and a clear differentiation is not possible. Such events can be part of all three spatial scenarios. However, the basic physical events below these intermediate events can again be specific for each spatial scenario (compare subsection 4.2). For example, the causes for a changing partial pressure of water in anode and cathode will differ.

Yousfi-Steiner et al. [39] consider temperature, relative humidity, current, and mass flow as basic influencing physical parameters. However, the absolute pressure, for example, is not considered. Also, some specific intermediate events, like the electro-osmotic drag exceeding the back diffusion, are not considered. Accordingly, the PL in this work is extended to cover a greater range of influencing parameters and to include additional special events.

The PL does not include any component related events and only consists of physical events and event chains. Also the FTs by Yousfi-Steiner et al. [39] are not developed further down towards specific component failure modes. In this work, however, this shall be included. Hence, the CL is introduced beneath the PL as the lowest FT level. The CL is explained in the following subsection.

3.3. Development of Component-Level

The PL discussed in the previous subsection identifies the basic physical events impacting the water management, independent of specific system components. The CL is dedicated to assess, which failure modes of components in the analyzed fuel cell system can result in the physical events identified by the PL. The construction of the CL is simplified by the PL, as it is more straight forward to asses, which component failure modes result in specific physical parameter changes as it would be to directly analyze, which component failure modes impact the TL failure conditions. This reduces at the same time the risk of missing relevant failure modes and enhances the completeness of the FTs.

The CL is dependent on the analyzed system architecture and the subsystems and components used therein. Hence, other than large parts of TL and PL, the CL is not modular and specific to each system architecture. Besides the components themselves, also the respective control system and the sensors acting as input to the control system, can incorporate failure modes. Said failure modes can also impact the function of the system components. Thus, faults therein can also lead to the failure conditions related to water management. Accordingly, they need to be addressed in the CL as well.

To enhance the system safety, different measures can be applied in system design. If the analyzed system architecture incorporates such measures to mitigate specific faults or failure modes, this has to be considered in the CL as well. As an example, redundancies of relevant components need to be reflected in the CL by AND-gates. Also, fault detection mechanisms can be a potential method for mitigation with intrinsic failure modes. These have to be reflected in the CL as well by using dedicated logical elements and events. The level of detail, to which the CL is developed, depends on the FT scope. For some analyses, it can be sufficient that a basic event is, for example, the failure of a valve. For other assessments, the failure of the valve possibly needs to be broken down further.

4. DEVELOPMENT OF EXEMPLARY FAULT TREE BRANCHES

Applying the approach introduced in section 3 to a PEMFC system results in a large amount of FT branches and basic failure modes. Due to this large amount, only two exemplary branches of the developed FTs are shown in more detail in this section, demonstrating the application of the proposed methodology. To develop the CL of the exemplary branches, a respective generic system architecture is assumed. First, subsection 4.1 investigates a drying scenario starting from the cathode side due to a faulty humidifier bypass valve (HBV) position. Then, subsection 4.2 discusses a flooding scenario in the cathode as a result of a single stack failure in a multi-stack system architecture.

4.1. Example Branch for a Drying Failure Condition

A graphical representation of an exemplary FT branch part of the drying side of the TL is shown in figure 5, highlighting the three levels introduced in section 3. A PEMFC stack in a generic fuel cell system for aviation applications is assumed as the basis for the CL. Due to the modularity, the TL introduced in subsection 3.1 and shown in figure 4 can directly be applied to said stack. The branch specifically investigated here is part of the TLE "Drying of membrane starting on the cathode side". For simplification, only this event from the TL is included in figure 5. With the TL being defined, the PL for the investigated TLE can be built up.

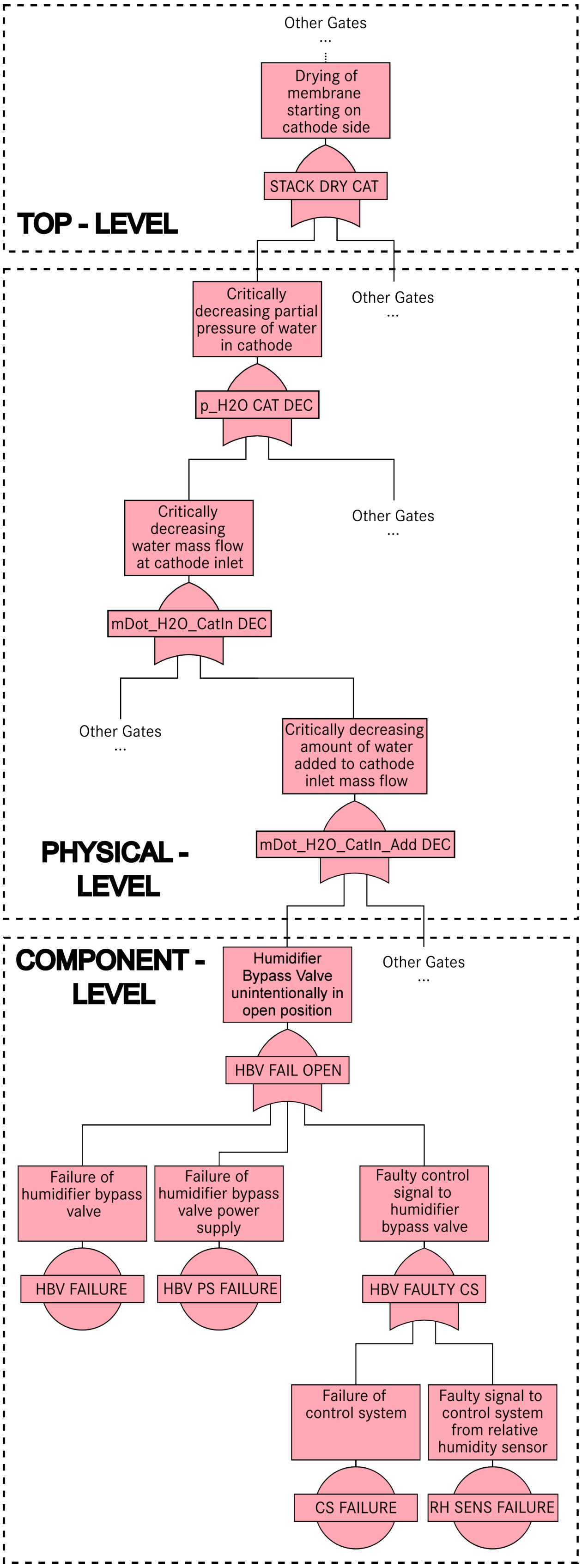

FIG 5. Graphical representation of an exemplary non-exhaustive FT branch for the scenario of a drying membrane starting from the cathode highlighting the different levels proposed in this work

As explained in subsection 2.2, the PEM water content is proportional to the water activity at its surface and thus, in the absence of liquid water, to the relative humidity of the surrounding environment [33]. The investigated TLE is connected to the cathode side. Therefore, the relevant surrounding environment of the PEM is the air inside the cathode. From a physical perspective, the relative humidity in the cathode is driven by multiple parameters, including the partial pressure of water (see subsection 2.2). Hence, a critically decreasing partial pressure of water in the cathode is one potential cause for a drying of the PEM. Following, this physical event is placed in the upper layer of the PL. The other events leading to further FT branches are not specifically shown in figure 5 and summarized by the term "Other Gates ...". Additionally, the condition, that all other physical parameters remain unchanged, while the partial pressure of water decreases, could be reflected by an AND- or INHIBIT-gate and a corresponding event in the FT, if necessary. However, for the sake of simplicity, this is not included in figure 5.

The partial pressure of water inside the cathode is again influenced by different physical parameters, including the mass flow of dry air at the cathode inlet, the produced water by the ORR, or water transported from the anode to the cathode through the PEM. In this example, a critically decreasing mass flow of water at the cathode inlet is selected to be investigated further. Assuming no change of other physical parameters and a constant mass flow of dry air at the cathode inlet, a decreasing water mass flow will result in less water being present in the cathode and thus a decreasing partial pressure of water. Hence, a critically decreasing water mass flow at the cathode inlet is placed as an intermediate event below the previously described event of a critically decreasing partial pressure of water (see figure 5).

As it is the case for most larger fuel cell systems, the water mass flow at the cathode inlet is controlled by some sort of external humidification (compare subsection 2.2). Accordingly, the water mass flow at the cathode inlet can critically decrease, if for example the amount of water added to the dry inlet air mass flow critically decreases and is insufficient to maintain an acceptable level of PEM water content. A respective intermediate event is therefore added to the PL, as can be seen in figure 5. This event is in this case the lowest event of the PL in the analyzed FT branch.

The exemplary FT branch from the TL down to this lowest PL event is still modular and applicable to different system architectures (assuming the usual external humidification). However, in the next step, it shall be investigated why the amount of water added to the dry inlet air mass flow can decrease. This requires the knowledge of the system architecture and respective components. The relevant part of the

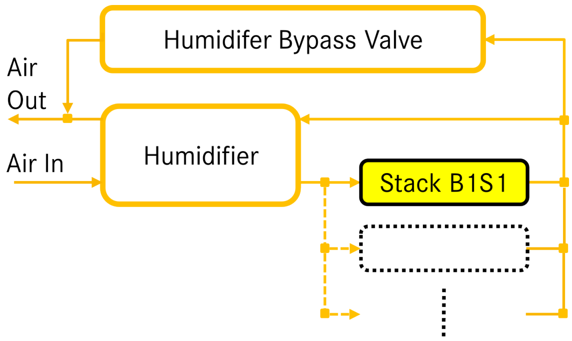

FIG 6. Schematic depiction of a generic multi-stack architecture with external humidification including a humidifier bypass valve in the outlet air mass flow for humidity control

generic system architecture for the branch assessed here is thus shown in figure 6.

Generally, multiple components or subsystems can be used to add water to the dry inlet air mass flow. Here, a membrane humidifier (referred to as "humidifier" in the following) is chosen. In this component, the water is transferred to the dry air mass flow through a membrane. Said membrane is thereby in contact with both the dry inlet air mass flow and the wet outlet air mass flow. Due to the water concentration gradient across the membrane, water is transported and added to the dry inlet air mass flow, while the air is passing through the humidifier. As this is a passive humidification method, a humidifier bypass valve (HBV) is put in parallel to the humidifier on the wet air outlet side (compare figure 6). By opening the HBV, less wet air enters the humidifier. Hence, less water can be transferred to the dry side of the humidifier. Based on this system design assumption, the CL of the FT shown in figure 5 is developed.

Due to its influence on the amount of water added to the cathode inlet mass flow, the HBV must be considered in the CL. If the HBV is in an open position when not required, less water will be added to the dry air inlet mass flow than necessary. As shown in the PL, this will ultimately result in a reduced partial pressure of water in the cathode and thus a potential drying of the PEM starting from the cathode side. An unintentionally opened HBV is accordingly defined as a failure event in the CL (see figure 5).

The HBV unintentionally being in an open position can have multiple causes. One contributing basic failure event is any sort of failure or fault of the HBV itself. For example, such a failure could be a mechanical damage. Furthermore, it is possible that the HBV is in an open position and the power supply fails. If the HBV is required to close afterwards, this is potentially no longer possible and the HBV, depending on its design, can fail in the open position. This scenario could be developed in more details in the FT. However, to keep figure 5 simple, the scenario is summarized in a single basic event. As the HBV is an actively controlled component, a faulty control signal could also result in an undesired opening of the HBV. The root causes of a faulty control signal can either be a failure of the controller itself or a wrong input signal to the controller from the required sensor reading. The corresponding basic events are thus added to the CL, as can be seen in figure 5. The level of detail of the CL in figure 5 is kept very simple. Depending on the target of the FTA, additional levels of detail in the CL should be used. However, for the demonstrative purpose of this section and due to the generic system architecture, the low detail level is sufficient.

4.2. Example Branch for a Flooding Failure Condition

Contrary to the exemplary branch in subsection 4.1, the branch investigated in this section is part of the flooding side of the TL (indicated with blue color in figure 4). The entire branch discussed in this section, is illustrated in figure 7. Again, the modularity of the TL (compare figure 4) allows to directly apply it to the generic PEMFC stack and the generic system architecture assumed here. Specifically, an exemplary branch below the TLE of a "Flooding in the cathode" is investigated here. In figure 7, the TL is simplified and only shows said TLE.

Below the TL, the PL is again dedicated to investigate the physical processes resulting in the TLE. From a physical perspective, the sole presence of liquid water is not sufficient for a flooding to occur. A flooding scenario requires liquid water to accumulate in the electrodes (here the cathode). For liquid water to accumulate, it needs to be generally present, but at the same time its removal rate has to be smaller than the liquid water generation- or entry-rate. To reflect this condition, the first gate below the TLE is an AND-gate, connecting the event "Generation of liquid water on cathode side" and the event "Condensation rate greater than liquid water removal rate" (see figure 7). The FT is subsequently split into two subbranches in this part of the PL, which both need to be developed further.

The left subbranch is dedicated to assess the generation or presence of liquid water in the cathode. Generally, liquid water can be present in the cathode either due to condensation in the cathode itself or due to liquid water entering the cathode together with the mass flow at the inlet. The latter can for example be a result of condensation occurring in the inlet piping or the stack manifolds. In the example discussed here, the focus is put on condensation in the cathode itself and an according intermediate event is introduced on the left subbranch of the PL in figure 7. In the next lower level, a generation of liquid water can occur once the partial pressure of water vapor exceeds

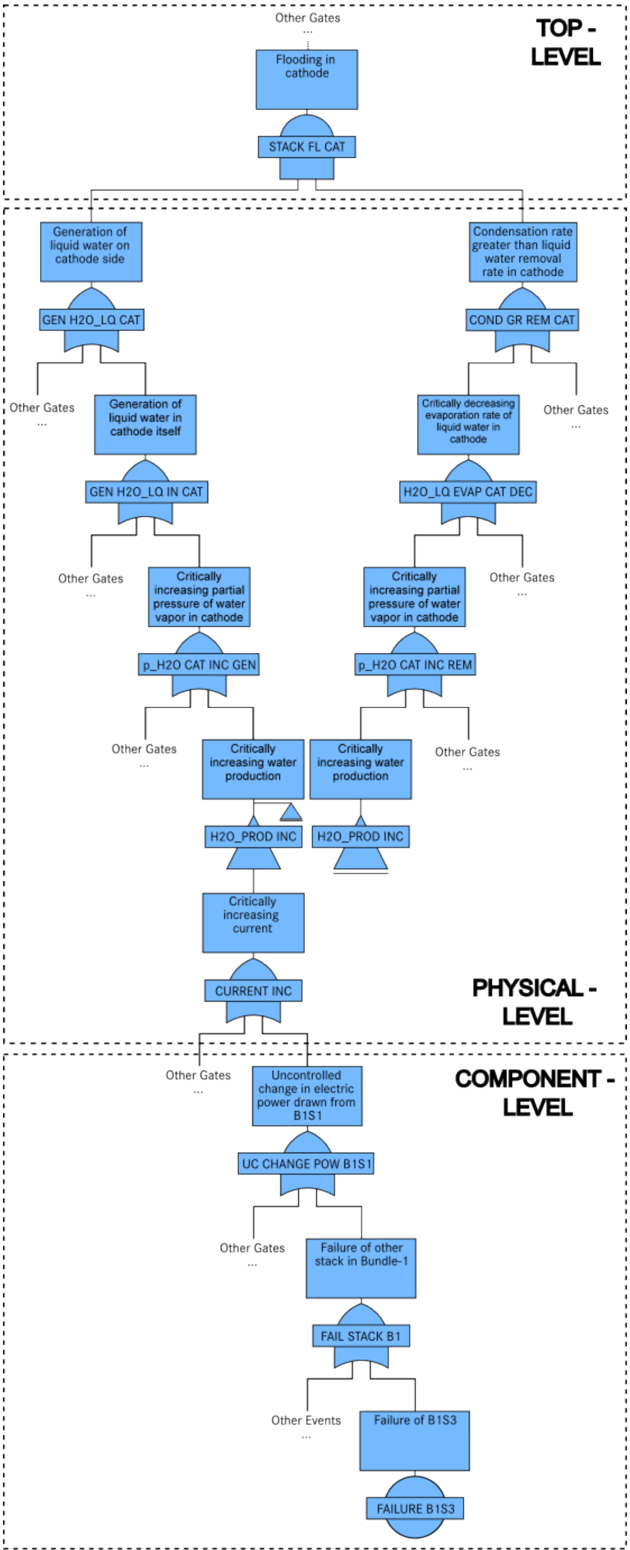

FIG 7. Graphical representation of an exemplary non-exhaustive FT branch for the scenario of a flooding in the cathode highlighting the different levels proposed in this work

the water saturation pressure, causing condensation. Assuming a constant saturation pressure (and thus a constant temperature), a critically increasing partial pressure of water vapor can hence be a potential cause for liquid water formation inside the cathode itself.

On the right subbranch of the PL in figure 7, the event "Condensation rate greater than liquid water removal rate in cathode" is assessed further. Liquid water inside the cathode can either be removed through the outlet in the form of liquid water droplets or by evaporation inside the cathode and following in the form of water vapor. The latter is chosen to be investigated in this example and is accordingly introduced as an intermediate event. The evaporation rate is generally driven by the difference between the partial pressure of water vapor and the water saturation pressure. The larger said difference is, the higher will be the evaporation rate. Once the partial pressure of water vapor equals or exceeds the water saturation pressure (and condensation occurs), the evaporation rate effectively becomes zero. Based on the assumption of a constant water saturation pressure, a critically increasing partial pressure of water vapor inside the cathode will therefore result in a decreasing evaporation rate and a decreasing amount of liquid water being removed. Following, a critically increasing partial pressure of water is placed as a contributing event in the right subbranch.

As can be seen in figure 7, this results in the special case that a critically increasing partial pressure of water vapor in the cathode is part of both branches below the AND-gate. However, as slightly different intermediate gates can be found below the two respective events, they can not be treated as the exact same event and can not receive individual IDs.

In the next step, the potential causes for a critically increasing partial pressure of water vapor are analyzed. As mentioned before, the partial pressure of water vapor in the cathode is influenced by various physical parameters, like absolute pressure or reactant mass flow rate (not shown in figure 7). In the cathode, the water production rate by the ORR is another factor. If all other physical parameters remain unchanged, an increasing water production rate will result in more water molecules in the cathode, increasing the partial pressure of water vapor. Hence, the intermediate event "Critically increasing water production" is introduced as the next development step in both subbranches. As there is no difference in the further development of said events, both receive the same ID and are treated as one event occurring at multiple points of the FT. This is indicated in figure 7 by a small triangle below the event description box on the left subbranch and a horizontal line below the Transfer-gate in the right subbranch. The water production rate is directly proportional to the current of the stack, as can be derived from the working prin-

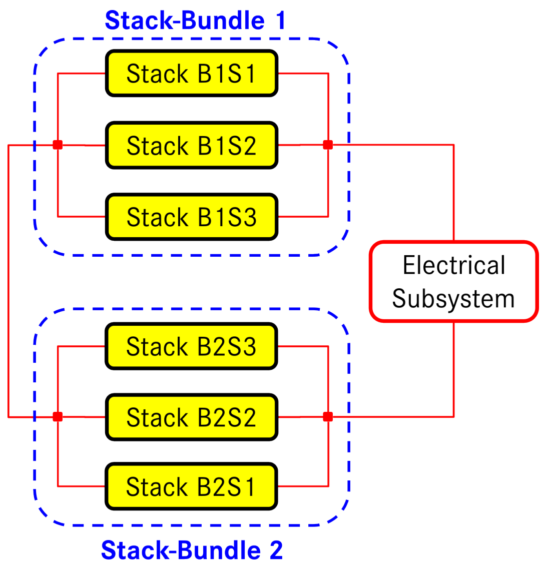

FIG 8. Schematic depiction of a generic multi-stack architecture with electrical parallel-serial connection

ciple and the reaction equations shown in figure 1. Hence, the cause for an increasing water production in the cathode has to be an increasing current. From a physical perspective, this can not be developed further. The causes for an increasing current are therefore subsequently identified in the CL.

Again, the development of the CL requires knowledge about the system architecture. As mentioned in subsection 2.1, fuel cell systems for aviation applications are demanded to deliver high power levels. Thus, a multi-stack fuel cell system, which is controlled based on power demand, is assumed here. The corresponding electrical architecture is shown schematically in figure 8. Three individual stacks are thereby electrically connected in parallel forming a stack bundle. Two of these stack bundles are electrically connected in series. Due to the parallel electrical connection, the three stacks of each stack bundle will operate at the same voltage, while their respective current might differ. However, the serial connection of the two stack bundles results in both bundles operating at an equal total current.

Besides other factors, an increasing current of an individual stack can be the result of an uncontrolled change in the power demanded from said stack. An according event is placed in the upper level of the CL assuming a power demand change for stack one in bundle one (B1S1). In the scenario of a stack failing to produce current in bundle one and the power demand from the system remaining constant in the first place, all remaining stacks are forced to compensate the loss of the one stack. It can be expected that especially the two remaining stacks in bundle one are shifting their operating point towards higher currents, to increase the generated power and to compensate the loss. If no mitigation is initiated, other parameters like the reactant mass flow, remain unchanged and an increasing water production results in an increasing partial pressure of water vapor. Hence, the failure of one of the other stacks in bundle one is added as a possible cause for an uncontrolled change in the demanded power from stack one of bundle one. As an example, a failure of stack three of bundle one (B1S3) is shown in figure 7, as a basic failure event, which is not developed any further. Accordingly, the CL of the exemplary branch investigated in this section is finished.

Whether the basic failure event identified by this exemplary branch of the overall FT is actually resulting in a flooding event is also depending on the operating point and other boundary conditions, like the stack design. For such quantitative assessments, more detailed studies are required in the future, to analyze for example if the failure of a single stack can ultimately lead to an accumulation of liquid water in the remaining stacks.

5. CONCLUSION AND OUTLOOK

To fulfill the strict requirements with regard to system safety and reliability, it is vital to analyze potential failure conditions and failure modes already in the system design phase. One method for such failure analysis is the FTA. The complexity of PEMFC propulsion system make FTAs an extensive and challenging task. The close physical relations with respect to the intrinsically important and sensitive water management of PEMFCs further complicate this. Therefore, this work develops a three layered approach (consisting of TL, PL and CL) to set up FTs for failure conditions associated with the water management. The method helps to improve the structure, completeness, and modularity of the FTs.

The TL and the PL of the proposed method are largely modular and can easily be applied to different system architectures, making them valuable for early system design phases. In the case of design changes of the system architecture, the modularity reduces potential rework in FT iterations. Furthermore, the PL enhances the structure and thus the completeness of the FTs, as basic failure events in the CL can be more easily accounted to a dedicated physical parameter change as directly to a more high-level failure condition. Additionally, the PL can be a valuable input for a future development of failure detection strategies, as it directly resolves the physical parameters impacted by a certain failure mode in the system. With the physical parameters usually being measured by sensors, the PL can thus provide an indication, how certain failure modes can be detected within the system based on the existing measurement equipment. Also, the knowledge and understanding of failure modes and their effects can benefit the development of dedicated and tailored mitigation strategies for said failure modes. In summary, the methodology and the resulting FTs are a valuable input for the system design as well as for the development of controls and operating strategies. Additionally, they can be used as a basis for future analysis required for certification of developed PEMFC based aviation propulsion systems.

However, the FTs presented in this work are of a qualitative nature. Hence, the actual severity of all identified basic failure events or failure modes must be analyzed in the future to quantify their failure effects in the system and ultimately on aircraft level. Simulations or dedicated experiments should be conducted for this purpose. Furthermore, it is necessary to add an analysis of the failure probabilities to the FTs, as the combination of failure probability and failure effect is decisive, whether the certification requirements are satisfied. Depending on the outcome of such analysis, the development of failure detection and mitigation strategies might be necessary, to either reduce certain failure probabilities or to minimize the failure effects on system and aircraft level.

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