Journal of Physics: Conference Series

PAPER • **OPEN ACCESS**

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To cite this article: Stefan Kazula *et al* 2023 *J. Phys.: Conf. Ser.* **2526** 012063

Functional and Safety Challenges of Hydrogen Fuel Cell Systems for Application in Electrified Regional Aircraft

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Abstract. This paper identifies potential weaknesses and challenges of hydrogen fuel cell systems as main energy provider for electrified aircraft propulsion and presents potential solutions. The general design, operating principles and main characteristics of hydrogen-fuelled low-temperature polymer electrolyte membrane fuel cell systems (PEMFCSs) are described. The safety assessment process in aviation according to Aerospace Recommended Practices ARP4754A and selected methods according to ARP4761 are introduced. The functions of fuel cell systems in electrified aircraft powertrains are analysed in functional structure trees on aircraft, powertrain and fuel cell system level. By means of a Functional Hazard Analysis (FHA), potential malfunctions and their effects are investigated and their severity is evaluated. Critical failure modes are identified and requirements for acceptable failure probabilities are stipulated. Solution options to mitigate failure effects are stated. The results of the mentioned analyses reveal design challenges associated with the application of fuel cell systems in electrified aircraft propulsion, for instance, concerning functional independence as well as solutions for cold start conditions, heat transfer and lightweight design. Furthermore, safety challenges arise due to the utilisation of cryogenic hydrogen as fuel and the high amount of electric energy.

1. Introduction

The aviation industry has to contribute to limiting the effects of climate change. Hence, the European Commission published the Flightpath 2050 [1] and the commercial aviation industry prepared the ATAG Waypoint 2050 [2] to reduce carbon dioxide CO_2 emissions of aircraft. As a consequence, sustainable and regenerative energy sources, such as green hydrogen, are being investigated for utilisation in aviation. Hence, the aircraft powertrain topology needs to evolve.

A variety of electrified powertrain topologies have been identified for different passenger capacity and flight range requirements [3], some of them including hydrogen fuel cell systems (FCSs). These FCSs are intended to provide electric power to electrically-driven propulsors. In this regard, numerous challenges concerning air, fuel, water and thermal management still have to be solved to comply with the strict reliability, safety and weight requirements in aviation. Hence, FCSs have not found their way as primary energy source of the propulsion system in commercial aviation industry yet.

This paper presents a functional and safety analysis of hydrogen PEMFCSs for electrified propulsion systems. First, selected electrified powertrain topologies and PEMFCSs are described. Then, the safety assessment process in aviation according to ARP4754A [4], as well as selected methods according to ARP4761 [5] are explained. Subsequently, functional structure trees of FCSs are established and a Functional Hazard Analysis (FHA) is conducted. Based on these activities, design challenges for application of PEMFCSs in aircraft propulsion and potential solutions are identified.

2. Electrified Aircraft Propulsion

The electrification of the aircraft propulsion system can entail the introduction of various new components to the aircraft powertrain, e.g.

- electric motors and gear boxes,
- electrical power conversion, typically by power electronics,
- high power electrical wiring,
- electric generators, batteries and fuel cells as well as
- different types of hydrogen storage.

Furthermore, additional thermal management systems such as heat exchangers, cooling and heating systems will be required. The components of electrified powertrains can be partially integrated into the fuselage, wing or into a traditional nacelle, as shown in Figure 1. Hereby, partially fuselage-integrated concepts could improve the wing aerodynamics, while introducing challenges concerning heat transfer.

The topologies of electrified powertrains can be categorised in turbo-electric, all-electric and hybrid-electric architectures [6]. Turbo-electric architectures utilise generators, which are driven by respective gas turbines, to provide electrical energy to electric motors. All-electric architectures rely completely on galvanic cells, such as batteries and FCSs, for energy supply to the electrically driven propulsors. These architectures can be solely battery-based or fuel cell-based, where the FCS is supported by a battery, see Figure 2. Such a fuel cell-based approach has been applied in the HY4, the first hydrogen fuel cell-powered four seater passenger aircraft [7]. Hybrid-electric architectures are a combination of the former topologies and include gas turbines as well as galvanic cells to provide energy to the propulsors. There, potential synergies of the combination of FCSs with gas turbine compressor and turbine systems are being investigated.

Although there are many concepts, electrified aircraft propulsion systems have not been introduced to commercial aviation yet, as they need to comply with the strict reliability, safety and weight requirements. High potential for application has been identified for PEMFCSs. However, safety challenges related to air, fuel, water and thermal management still have to be solved. In this paper challenges are being analysed with the help of a functional and safety analysis of the FCS and presents potential solutions. Therefore, a fundamental understanding of the fuel cell and the FCS is required first.

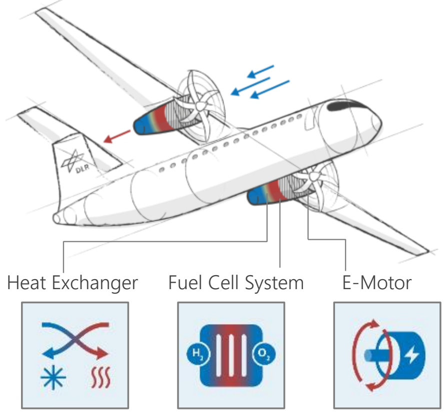


Figure 1. Fuel cell-powered aircraft

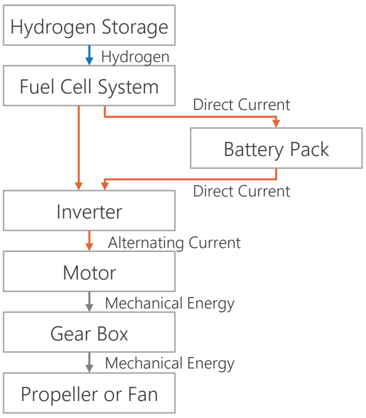


Figure 2. Fuel cell-based propulsion

2.1. Fuel Cells

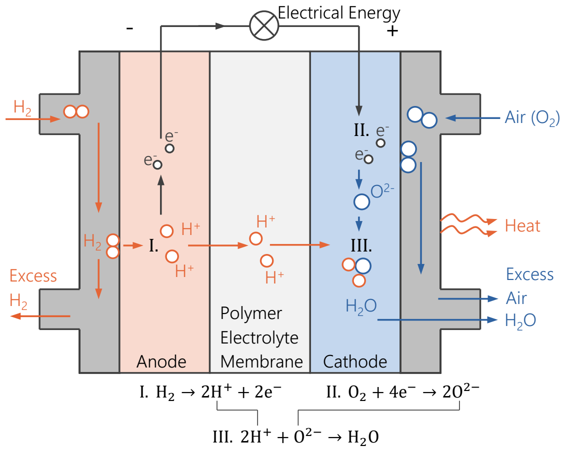
A fuel cell (FC) is an electrochemical cell, in which electrical energy is produced from the chemical potential of the fuel by encouraging a pair of redox reactions: a reduction and an oxidation reaction. All fuel cells consist of two electrodes, which are separated by an ion-conduction medium, an electrolyte. In order to eliminate CO_2 emissions, the fuel of choice ought to be hydrogen H_2 even though other hydrocarbon fuels can be consumed by certain fuel cell types. The PEMFC is the most commonly used fuel cell type, because of its high power density and its advanced technology readiness level (TRL) [8].

In low-temperature PEMFC (LT-PEMFC) applications, a sulfonated polymer membrane, typically Nafion^{TM}, is used as electrolyte. Fuel in the form of H_2 and air as oxidiser are continuously provided to the respective electrodes, the anode and the cathode. The electrodes must each be coated with a catalyst to initiate the chemical reactions as illustrated in Figure 3. Thereby, the oxidation reaction (I) is encouraged at the anode. Protons H^+ are created by liberating electrons e^- from the hydrogen. The electrons are then transported to the cathode with an electrical conductor and can be consumed as electrical energy [9]. The protons H^+ pass through the electrolyte to the cathode. On the cathode side the reduction reaction (II) occurs. During the subsequent redox reaction (III), water H_2O is produced as a by-product. About 40 to 60% of the chemical energy of the hydrogen is converted into electrical energy – the remainder being predominantly heat. The released heat energy of 237 kJ/mol is equal to the Gibbs free energy ΔG of the hydrogen consumed [10].
At 25° C the maximum reversible cell voltage is 1.23 V. This value is reduced due to activation, ohmic and gas transport losses [11]. The electrical efficiency η_{el} of a fuel cell is defined by the ratio of the actual cell voltage to its maximum reversible voltage. The voltage of an FCS can be increased by arranging multiple cells in series to form a fuel cell stack. The neighbouring FCs in a stack must be structurally and electrically connected to each other, while their respective reaction gases need to be separated. Bipolar plates with a positive cathode-side pole and a negative anode-side pole are used for this purpose. They also contain gas diffusion, gas separation and cooling layers.

2.2. Fuel Cell Systems

Additional mechanical, thermal and electrical components and subsystems (Balance of Plant, BoP) are required for the automated and optimal operation of a LT-PEMFCS. These subsystems and selected necessary functions are illustrated in Figure 4. In particular, air and fuel supply, water and thermal management systems as well as controls and sensors are necessary [12], [13]. The primary hydrogen storage is not part of the FCS. However, small secondary energy storage systems, such as buffer batteries or metal hydrides may be included.

LT-PEMFCs are highly sensitive to carbon monoxide CO contamination and fuel impurities [9]. This demands for fuel and air filters. Additionally, the supplied reactants have to be preconditioned concerning pressure, temperature and humidity [14]. The polymer electrolyte membrane requires humidification of around 30% for ideal operation, durability and reliability, as dehydration and humidity cycling can lead to mechanical fatigue or chemical attacks [15]. Thus, complex cold start and water management systems can become necessary. During operation, the electrical energy generated by the FC has to be controlled, converted and distributed to the consumers. Also, large amounts of heat need to be removed. Particularly for LT-PEMFCSs with an operating temperature of about 80°C, large heat exchanger units and coolant tanks are required.



$\mathrm{I.}\ H_2 \rightarrow 2H^+ + 2e^-$ $\quad \mathrm{II.}\ O_2 + 4e^- \rightarrow 2O^{2-}$

$\mathrm{III.}\ 2H^+ + O^{2-} \rightarrow H_2O$

Figure 3. PEM fuel cell working principle

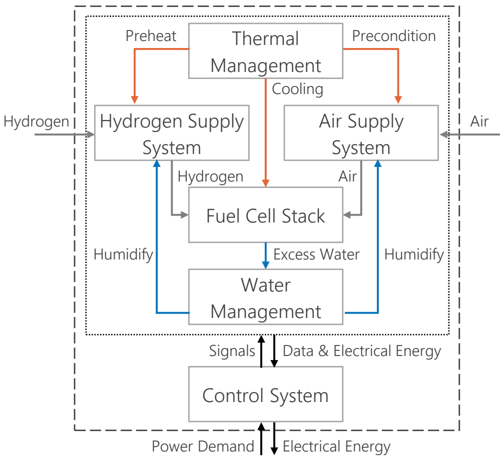


Figure 4. Subsystems of a fuel cell system

3. Methods

In modern industries, the desired products become increasingly complex. Hence, particular efforts are necessary during early phases of the development process to efficiently ensure safety and reliability of a product [16]. This can be achieved by application of a mature design approach and analytical methods, which identify potential risks and weaknesses as well as determine the reliability of the product. The assignment of suitable safety and reliability methods to each phase of the development process can improve the product significantly.

3.1. Safety Assessment Process in Aviation

In Europe, the European Aviation Safety Agency (EASA) constitutes the safety approval regulations for commercial aircraft in the Certification Specifications (CS), e.g. the CS-25 – Large Aeroplanes [17]. During the certification process for obtaining flight approval, compliance with these regulations must be demonstrated. For this purpose, the EASA proposes acceptable means of compliance (AMC), ranging from calculations and analyses to tests.

Paragraph CS-25 AMC 25.1309 describes the safe design process in aviation based on ARP 4754A [4], which has been formulated by a consortium of various aviation companies and authorities. This process is based on the V-model of systems engineering [18]. Here, functions, requirements and architecture of the product are developed, validated and verified at different levels of detail from aircraft to system to element level, as illustrated in Figure 5.

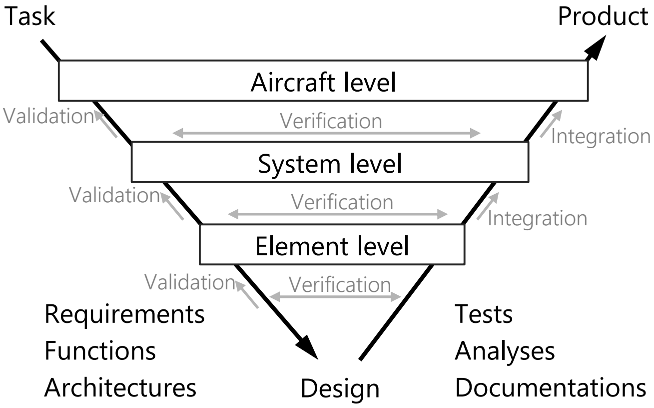


Figure 5. V-model of systems engineering

The according methods of this process are described in ARP 4761 for each development phase [5]. In this work, the top down method Functional Hazard Assessment (FHA) is applied to FCSs. Along with the Preliminary System Safety Assessment (PSSA) in the form of a Fault Tree Analysis (FTA) this is the most relevant method during the early stage of the preliminary design phase. Other important safety methods are the System Safety Assessment (SSA), the Failure Mode and Effects Analysis (FMEA) and the Common Cause Analysis (CCA), which comprises the Zonal Safety Analysis (ZSA), the Particular Risk Analysis (PRA) and the Common Mode Analysis (CMA). Also, design reviews are suggested at least after each phase of the design process [19].

3.2. Function Structure Trees

The basis of the FHA is a functional analysis of a product. A function is defined as the conversion of input material, energy or data into desired output. Function structure trees are particularly suitable as input for an FHA and are therefore the method of choice for the functional analysis in this work [20].

In a function structure tree the main task of the product is described as the main function, which is then broken down into various subfunctions revealing further degrees of detail respectively [21]. The level of detail should be chosen in accordance with the purpose of the analysis.

3.3. Functional Hazard Analysis (FHA)

The main goal of the FHA is to systematically identify potential system malfunctions, their causes and effects. Therein, failure effects are classified according to CS-25 AMC 25.1309 depending on their severity for aircraft, crew and occupants into ‘catastrophic’, ‘hazardous’, ‘major’, ‘minor’ and ‘no safety effect’. This way, the requirements for acceptable failure occurrence probabilities are derived with up to less than 10^{-9} events per flight hour (FH) [22].

An FHA can be conducted on aircraft, system and subsystem level [5]. In this work, the FHA is performed on the FCS level. Failure conditions associated with FCS malfunctions and their effects are determined. A distinction is made regarding the effects of different degrees or severity of a malfunction, the number of engines affected and the phase of flight.

4. Selected Results

In the following, the functions of FCSs in an FC-based electric propulsion system are analysed on different architecture levels and potential synergies as well as challenges are identified. This allows for an evaluation of existing concepts of electrified aircraft propulsion system topologies and the recommendation of design adaptations as well as required novel solutions.

4.1. Function Structure Trees

The aircraft has to fulfil different top level functions, one of them being ‘control thrust’ [4], [18]. Thrust control is mainly achieved through the propulsion system by generating, adjusting, ensuring and determining thrust [22]. In the case of hydrogen FC-powered propulsion systems all of these functions are governed by FCSs as sources for electrical energy to drive propulsors generating thrust.

Apart from thrust control, a traditional propulsion system has to fulfil several secondary functions. For example, hot bleed air must be provided to anti-icing systems of aerodynamic surfaces and pressurised air must be supplied to the cabin air conditioning system. Additionally, the electricity for board electronics, aircraft avionics and many accessories is traditionally provided by generators integrated in the gas turbine propulsion system. Furthermore, the propulsion system can assist wheel brakes and brake flaps in decelerating the aircraft by generating reverse thrust. A potential FC-based propulsion system must reliably contribute to these functions.

The main function of an FCS in an all-electric aircraft is to provide the electrical energy demanded for the sum of the required functions of a propulsion system. A function structure tree of a PEMFCS is shown in Figure 6. Some essential functions of a PEMFCS, such as the transfer of ions, the sealing and the purging of the cell as well as the structural integrity of the FC housing have not been listed explicitly to maintain a clear structure of the tree.

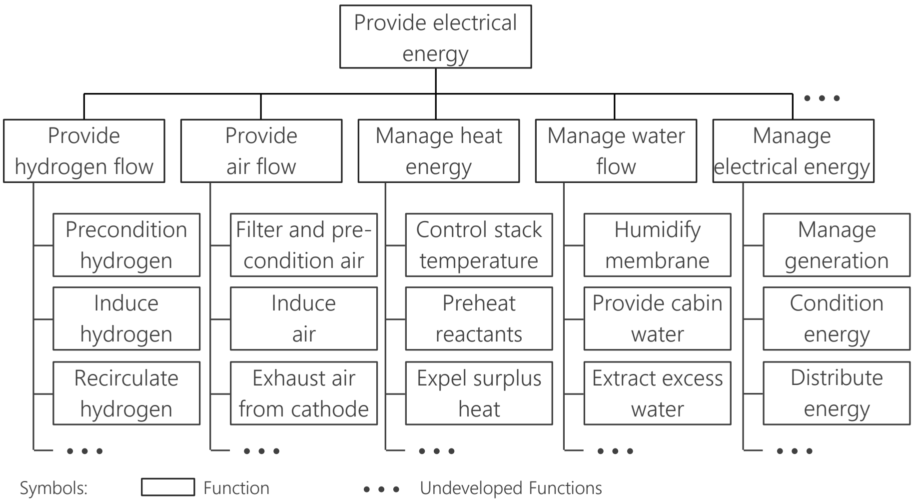


Figure 6. Function structure tree of a PEM fuel cell system

First of all, an acceptable temperature must be achieved to enable the operation of the FC. Especially to initiate the operation during freezing conditions, cold start systems are required. Secondly, sufficient humidification of the electrolyte membrane has to be provided for the transport of ions. The reactant mass flows must be filtered and preconditioned before being induced into the fuel cell. Excess air and water must be exhausted, hydrogen recirculated and the ideal operation temperature of the FC maintained and controlled. Subsequently, the FC continuously generates electrical energy, which has to be conditioned and provided to BoP subsystems, FC electronics, buffer batteries and all remaining components of the propulsion system. While providing the electrical energy for the propulsors in a FC-based electric aircraft, the FCS would also need to supply electrical energy to fulfil the propulsion system functions traditionally taken on by a gas turbine-powered generator. This includes providing energy to onboard electronics and accessories, e.g. the actuators of thrust reverser units.

Additionally, heat exchanger units are necessary to cool the FCS. Due to the ability of fluid flows to transfer heat, many synergies can be used in this context, e.g. for preconditioning the FC reactants or for supplying the ice protection or the air conditioning system of the aircraft.

The integration of further functions into the FCS could reduce the effective system mass, e.g. by including acoustic treatment or by taking up structural loads in the aircraft. Furthermore, cabin water could be produced on board and oxygen-deficient cathode exhaust gas could be used to supress fires.

4.2. Functional Hazard Analysis

The FCS function structure provides the input for the FHA. The main function of the FCS is to ‘provide electrical energy’. A failure of this very functionality can lead to different effects on aircraft level depending on the number of affected engines, the magnitude of the malfunction and its duration. If the malfunction only affects a single engine for a short time period with small performance limitation, buffer batteries can compensate for this malfunction and there is no safety effect. In case the malfunction affects the engine for a longer duration and with a large deficit in power, buffer batteries may not be able to compensate for this malfunction, resulting in ‘reduced thrust’ or ‘loss of thrust’ of one engine. However, commercial aircraft must be designed such that it is possible to safely continue flight with one engine inoperative [17]. Hence, this failure mode only leads to a slight reduction of the aircraft’s functional capability and a slightly increased flight crew workload during certain flight phases such as take-off. Thus, it is categorised as minor effect with a probability requirement of less than 10^{-3} events per FH. The above described malfunction affecting more than one engine could lead to the event ‘loss of thrust’ on multiple engines, potentially resulting in a rejected take-off (RTO). This is classified as hazardous with a probability requirement of less than 10^{-7} events per FH [17].

Further potential hazardous malfunctions and failure modes of FCSs are electromagnetic interferences with other systems as well as fire and explosions, e.g. due to undetected hydrogen leakage. If the FCS is to fulfil secondary functions, additional potential safety-critical events can occur. This applies to the following secondary functions: ‘provide ice protection’, ‘provide pressurised cabin air’, ‘provide electrical energy to board electronics’, ‘condition cabin air temperature’, ‘generate reverse thrust’ and ‘extinguish fire’. For instance, the loss of ice protection capability can lead to wing and empennage icing, potentially causing a ‘loss of aircraft control’.

4.3. Evaluation and design challenges

The conducted functional and safety analyses allow for a preliminary evaluation of FCSs in aviation and FC-based propulsion system architectures. The main weaknesses and design challenges of LT-PEMFCSs in aviation arise due to the need to increase their power density, their limited span of operating conditions, the high amounts of heat produced and the use of hydrogen as fuel.

A way to increase the power density of FC-based propulsion systems is by using synergies, e.g. heat exchanger for ice protection, cryogenic hydrogen as coolant for superconductors or metal hydride reactors as hydrogen storage, sensors, filters and cooling systems. Furthermore, synergies can be utilised between the air system of the FCS and the thermal management system.

However, synergies can create functional dependencies in the propulsion system that can lead to hazardous events in case of a malfunction. For this purpose, segregation and redundancy should be provided for the electrical energy supply to the propulsors as well as for potential other essential functions on aircraft level.

To avoid hazardous events due to loss of thrust caused by a malfunction of the FCS, multiple independent FCSs or sufficiently large buffer batteries have to be integrated into FC-based aircraft. This applies to partially fuselage-integrated electrified propulsion system architectures in particular, as nacelle-integrated propulsion systems naturally feature a spatial segregation, and hence, a higher degree of independence. Independence of the respective FCSs has to be achieved for all necessary subfunctions and also the fuel storage. Therefore, at least a small secondary energy storage, such as metal hydrides or buffer batteries may be included for emergency reasons. The additional effective mass of the secondary storages could be reduced by designing them for multiple necessary functions, e.g. for cold start and in-flight restart purposes. Hazardous events, which result from a malfunction of the FCS concerning a secondary function of the propulsion system, can also be avoided by redundancy, e.g. reserve water tanks, secondary ice protection systems or conventional fire extinguishing systems.

Potential secondary energy storages of hybrid electric engines could be smaller than for all-electric solutions, as they include gas turbines. Depending on the coupling of gas turbine and FCS, hybrid-electric solutions can offer a higher level of independence than all electric architectures, and hence, more robustness in case of an FCS malfunction.

While the subsystems of current FCSs ensure most of the necessary functions in an electrified propulsion system, the development of reliable design solutions for cold start, in-flight restart and emergency shutdown is still required.

Furthermore, safety challenges are caused by the fuel and the high amount of electric energy. The utilisation of cryogenic hydrogen as fuel entails multiple risks for fire, explosions, hydrogen embrittlement and condensing humidity. The high amounts of electric energy can result in electromagnetic interference (EMI), overheating and short circuits. The required power electronics and their internal architectures significantly affect the potential for inductive and capacitive coupling with surrounding electrical components. Partially fuselage-integrated propulsion systems in particular cause safety challenges regarding the conductor bound EMI associated with high voltage cables, whereby additionally required shielding increases the overall system weight.

5. Conclusions

To limit extent and effects of climate change, numerous concepts for sustainable electrified aircraft propulsion have been investigated recently, some of them including hydrogen FCSs. As the application of FCSs in aviation entails reliability, safety and weight challenges, they have not been applied in commercial aviation yet. Hence, this paper analyses PEMFCSs as main energy provider for electrified aircraft propulsion, identifies potential weaknesses as well as safety challenges and presents potential solutions. Function structure trees of FCSs have been established, an FHA has been conducted as selected methods according to ARP4761 and with that the safety assessment process in aviation according to ARP4754A was followed.

The results of the conducted analyses reveal design challenges associated with the application of FCSs in electrified aircraft, e.g. concerning functional independence as well as solutions for cold start conditions, heat transfer and lightweight design. Furthermore, safety challenges arise due to the utilisation of cryogenic hydrogen as fuel and the high amount of electric energy. Additionally, the results emphasise the high potential of hybrid-electric nacelle-integrated propulsion system architectures.

In subsequent studies, the conducted analyses should be complemented by an FTA, by the bottom up method FMEA and by a CCA, especially a ZSA to investigate interactions of a fuselage-integrated FCS with components in the vicinity. This way, further potential failure modes of FCSs in electrified aircraft propulsion could be identified and their effects be mitigated by design solutions. Thereby, FCSs could be applied in commercial aviation and enable more sustainable aircraft, while maintaining safety and reliability. As a result, FCSs could contribute to limiting climate change.

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