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Development of a Controls Approach for Fuel Cell-Powered All-Electric Aero Engines based on an FHA

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Abstract

Given the development of climate change in the past decades and its anticipated effects, the aviation industry is undergoing a growing momentum towards developing a future generation of electrified propulsion systems. Hence, sustainable key technologies, such as fuel cells, batteries and electric motors, must be integrated into the powertrain of commercial aircraft. While these technologies are already being applied in other transportation sectors, the feasibility of their integration still ought to be investigated for aviation. Various challenges in terms of weight and efficiency must be overcome to introduce these technologies into aircraft propulsion systems. However, significant influence is owed to the controls of these powertrains to ensure effective power output, handling quality, reliability and safety of the aircraft.

From the control's perspective the integration of fuel cell-based powertrains presents several challenges for three reasons. Firstly, more media of control are being introduced, such as hydrogen and high voltage. Secondly, the different media display highly-nonlinear interactions with each other and cannot be treated separately. Thirdly, these individual components entail numerous additional challenges with regards to durability and lifetime. Specific in-flight health monitoring is therefore crucial to the application of these technologies in aviation.

An electrically powered aero engine topology using a low-temperature polymer electrolyte membrane fuel cell (LT-PEMFC) is being considered in this work. The specific control tasks that result from both performance and safety requirements are being analysed and compared to those of conventional gas turbine aero engines using functional structures. An analysis of the degrees of freedom present in both conventional and electrically powered aero engines is being performed - indicating a growth in complexity, which can arise with the electrification of aero engines. The comparison showed an almost 100 % increase in the number of control variables required for the electric propulsion system.

The results of this work shed light on the challenges imposed on powertrain controls by the fuel cell technology of today, in general, and the LT-PEMFC, in particular, to comply with the demanding performance and safety requirements of aviation. Based on control tasks derived for the fuel cell powered aero engines, a potential controls approach was developed addressing the challenges identified for integrating an LT-PEMFC into a passenger aircraft. This way, the introduction of sustainable electrified aero engines can be enabled.

Keywords: Electric Aircraft Propulsion, PEM Fuel Cell, Controls Strategy, All-Electric Aircraft, Future Aviation

1. Introduction

The goals set by the European Commission in Flightpath 2050 [2] demand for rapid advances in electrification of the aviation industry. A growing momentum towards developing a future generation of turbo-electric, hybrid-electric and all-electric propulsion systems has prompted exploratory studies to be conducted and small-scale demonstrators to be built. Key sustainable technologies, such as fuel cells, batteries and electric motors, are already being applied in other transportation sectors. In order to enable their integration into the powertrain of a commercial aircraft, they have to comply with the strict performance and safety requirements in aviation. Various challenges in terms of weight and efficiency will also need to be overcome to introduce these technologies into a propulsion system. However, significant influence is owed to the controls of these powertrains in terms of effective power output, handling quality, reliability and safety of an aircraft. From the control's perspective the integration of fuel cell-based powertrains presents several challenges as well. The necessary performance and safety requirements have to be understood and well-defined to develop new controls approaches and concepts suitable for these electrified propulsion systems. For this work, an electrically powered aero engine topology using a low-temperature polymer electrolyte membrane fuel cell (LT-PEMFC) system was chosen as primary source of electrical energy. The LT-PEMFC is supplemented with a buffer battery for boost and to allow for improved dynamic response required during critical manoeuvres – for example during take-off and landing.

In the following section the selected powertrain topology is outlined and the subsystems of the LT-PEMFC-powered electric propulsion system (EPS) are introduced. Therein the functionality and the design of an LT-PEMFC is explained and its interfaces to other subsystems and the aircraft are defined. The methods applied in this work including the control task analysis, the safety assessment process in aviation according to Aerospace Recommended Practices (ARP) 4754A [3] as well as selected methods in accordance with ARP 4761 [4] are introduced in Section 3. In Section 4 the aviation-specific requirements are being evaluated by applying these methods for FC-powered propulsion systems. Subsequently, a holistic analysis of the control tasks required for an LT-PEMFC-powered EPS is possible. These control tasks are compared to those of conventional gas turbine aero engines and an analysis of the degrees of freedom is performed. Based on the results, a potential controls approach is developed addressing the challenges identified for integrating an LT-PEMFC into a passenger aircraft.

2. LT-PEMFC-Powered EPS

Electrified powertrain topologies can be categorised in turbo-electric, all-electric and hybrid-electric topologies [5]. Turbo-electric topologies utilise a generator, which is driven by a gas turbine, to provide electrical energy to electric motors. In full turbo-electric topologies all propulsors are driven by electric motors, while in partial turbo-electric concepts at least one propulsor is also driven by a gas turbine. All-electric concepts rely completely on galvanic cells, such as batteries and fuel cells, for energy supply to the electrically driven propulsors. These topologies can be solely battery-based or fuel cell-based, where the fuel cell system is supported by a battery. Such a fuel cell-based approach has been applied in the HY4, the first hydrogen fuel cell-powered four seater passenger aircraft [6]. In this case, 80 kW of electric power are provided by LT-PEMFCs. Hybrid-electric topologies are a combination of the former topologies and include gas turbines as well as galvanic cells to provide energy to the propulsors. Here, fuel cells can also be included and synergies with the gas turbine compressor and turbine system could be utilised.

Numerous electrified powertrain topologies have been identified for different passenger capacities and flight range requirements [7, 8], some of which include different types of fuel cell systems (FCSs). These FCSs are intended to consume hydrogen to provide electric power to electric motors, which drive the propulsor. To comply with the strict requirements in aviation, for instance concerning reliability, safety and weight, many challenges concerning air, fuel, water and thermal management of FCSs have to be solved. Hence, FCSs have not been applied in commercial aviation yet.

A simplified version of the all-electric topology chosen for his work is shown in Figure 1. It represents one independent propulsion unit of which there can be multiple integrated into an aircraft depending on the aircraft design and the propulsion system distribution strategy. Many conceptual studies show promising results for distributed propulsion architectures – referring to more than one propulsor per wing. For example the X-57 Maxwell [9, 10] is designed to have 12 small high-lift propellers and large wingtip propellers. However, the number of propulsion units will add to the complexity of the controls problem due to the additional synchronisation efforts as well as the accommodation of aerodynamic and acoustic interference effects. For the purpose of this study a single independent propulsion unit will be considered. In this unit the FCS is the main source of power, while additional power can be supplied by batteries during peak load demand and to compensate for the lack of dynamic flexibility displayed by FCSs.

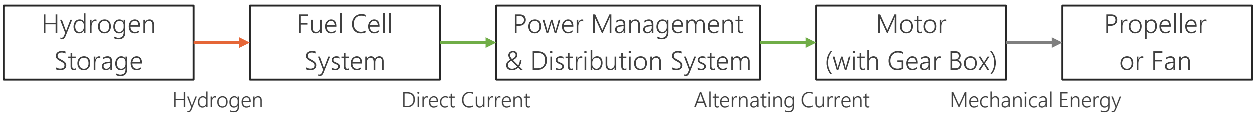


Figure 1 – Architecture of the selected fuel cell-powered electric propulsion system unit

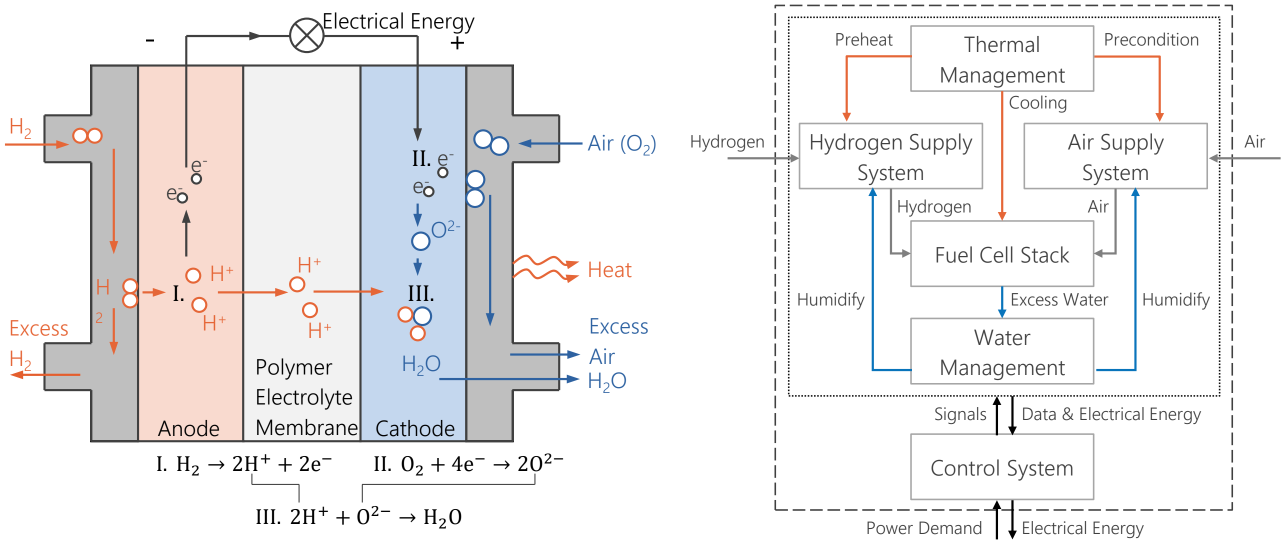
On the EPS level a power management and distribution system (PMDS) in the form of inverters, converters and cables is required to ensure reliable operation of the electric motors controlling the voltage and current levels [11]. This concerns all subsystems involved in the power supply chain. In the selected topology this includes both the fuel cell system (FCS) and the battery system, which is included in the PMDS. These and all other EPS subsystems involved are briefly described in the following sections.

2.1 Fuel Cell System (FCS)

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) [12].

In LT-PEMFCs a sulfonated polymer membrane, typically Nafion™, is used as electrolyte [13]. Core to the functionality of the FC is the characteristic of the electrolyte to be conductive only for ions of certain molecules but not for electrons. Thereby allowing for the electrons to be used in a consumer. The so-called membrane electrode assembly (MEA) is made up of the electrolyte and two electrodes, which are each coated with a catalyst to initiate the chemical reactions as illustrated in Figure 2 (a). Thereby, the oxidation reaction (I) is encouraged at this electrode, the anode. Fuel in the form of H_2 is continuously provided to the anode, while its counterpart, the cathode, is supplied with air as oxidiser. Protons H^+ are created at the three-phase contact between catalyst, electrolyte and fuel by liberating electrons e^- from hydrogen H_2. Electrical energy can be used via an electrical conductor as the electrons are then transported from the anode to the cathode [14]. Simultaneously the protons H^+ pass through the electrolyte to the cathode, where the reduction reaction (II) occurs. During the subsequent redox reaction (III) water H_2O is produced as a by-product.

The 237 kJ/mol of energy released during this conversion is equal to the Gibbs free energy ΔG of the hydrogen consumed [15]. About 40 to 60 % of the chemical energy of the hydrogen is converted into electrical energy – the remainder being mostly heat. At 25° C the maximum reversible cell voltage is 1.23 V. This value is only a theoretical maximum. In reality it is lower due to activation, ohmic and gas transport losses [16]. The voltage of an FCS can be increased by arranging multiple cells in series to form a fuel cell stack. Within a stack the neighbouring FCs 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 [17].



(a) Working principle of LT-PEMFC (b) FCS including BoP components

Figure 2 – Illustration of LT-PEMFC and FCS

Additional mechanical, thermal and electrical components and subsystems (Balance of Plant, BoP) are required for automated and optimised operation of an LT-PEMFC [18]. These subsystems and selected necessary functions are illustrated in Figure 2 (b). In particular, air and fuel supply, water and thermal management systems as well as controls and sensors are necessary [19–21]. The hydrogen storage and distribution system is not part of the FCS.

LT-PEMFCs are highly sensitive to carbon monoxide CO contamination and fuel impurities [14]. This demands for fuel and air filters. Additionally, the supplied reactants have to be preconditioned concerning pressure, temperature and humidity [22]. 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 [23]. Thus, complex cold start and water management systems can become necessary. During operation, the electrical energy generated by the FC has to be controlled, conditioned and distributed to the consumers. Also, large amounts of heat need to be removed. Particularly for LT-PEMFCs with an operating temperature of about 80°C, large heat exchanger units are required.

2.2 Power Management and Distribution System (PMDS)

The main purpose of the PMDS is to ensure the reliable and safe operation of the electrical motor powering the propeller by controlling the voltage levels and electric current in all components included in the PMDS. Additionally, all accessory actuators as well as the avionics of the aircraft, which communicate the demands of the pilot need to be powered by electricity. Therefore, the PMDS is responsible for communicating the power demand to the FCS, which in turn controls its BoP components to provide the necessary power output, and also for compensating for insufficient power supply by drawing from other sources of electrical energy. Figure 3 shows the simplified architecture of the PMDS and its interfaces. Included in the PMDS are not only the inverters, converters and cables, but also the buffer battery and a supercapacitor to ensure the necessary system dynamics. Furthermore, the PMDS ought to include means of controlling components and subsystems connected to the PMDS in handing failure modes or unusual operating conditions. This includes for example wind milling or short circuits in the windings of the electrical motor.

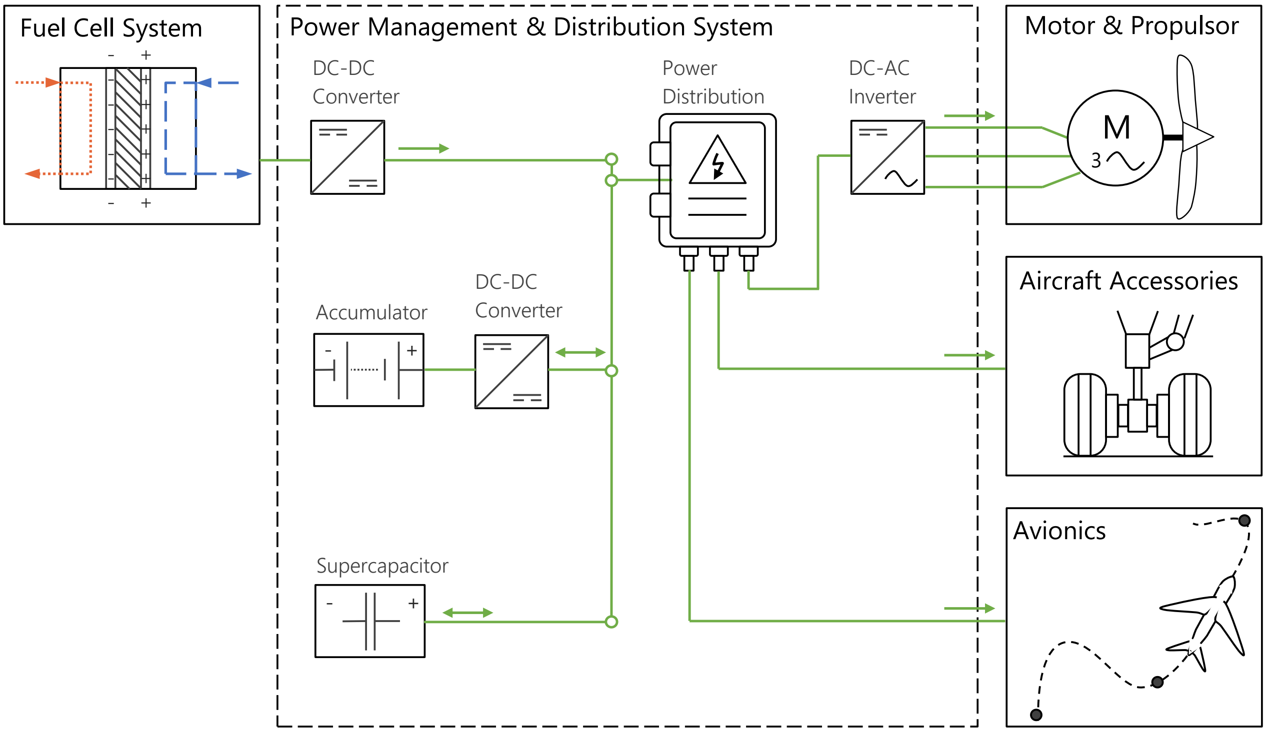


Figure 3 – Power management and distribution system architecture

As the buffer battery has some limitations to the electric current during charge and discharge, using a supercapacitor can compensate for any dynamic changes in load demands. This is particularly important here since it powers also the avionics and the accessory components. Means of overcharge protection ought to be included in the PDMS architecture as well. The DC-DC converter of the accumulator unit is a bidirectional converter able to boost or buck the voltage level depending on whether it is being charged or discharged. The accumulator unit also includes the batterie management systems. As for the FC current supplied, only boost conversion is assumed here. It is feasible to consider a single multiport converter to address all conversion tasks for FCS as well as accumulators and supercapacitor in one central unit. While this may improve the power density of the overall PMDS, it will cause disadvantages in terms of reliability as one failure point is prone to shut down the entire direct current system [24].

For the PMDS concept suggested here, conventional electric components are chosen to reflect the current state of the art in industry. However, much potential for future development and technological advances lies within this subsystem, for instance in terms of improving the power density by using alternative materials, cooling systems or functional synergies, while maintaining reliability and safety.

The use of batteries as sole energy source for a passenger aircraft is not feasible with the current state of the technology in terms of gravimetric energy density. Current Lithium-Ion (Li-Ion) batteries only achieve up to 0.3 kWh/kg [25]. One main disadvantage of batteries as electrochemical energy storage is that their mass does not decrease during flight. This would be the case for a conventional or FC-powered aircraft due to the consumption of the respective fuel. To determine whether a battery-powered EPS is feasible for a specific mission and use case, both the power-to-energy ratio and the lifetime cycle of the battery system have to be considered [26]. The power-to-energy ratio is defined as the peak battery power to the according energy capacity. Potential alternatives to the Li-Ion batteries used for electric vehicles today are Lithium-Sulphur (Li-Si) and Metal-Air batteries [27]. However, they are not commercially available yet.

Studies [26, 28] show that the use of high temperature superconducting materials in power electronics promise significant power density improvement of up to 26 kW/kg with efficiencies of 98 to 99.5 %. The secondary weight owed to cables on the maximum current that is conducted and on the cable length rather than the power rating [26]. A nickel-plated aluminium cable already tested in an aircraft context is chosen with 0.00324 kg/A·m and an efficiency of 98.5 % [29]. While electrical components such as the cables and power electronics may seem secondary in the technological advancements currently being pursued, their design points are of great importance and require much consideration. Due to the electrification of the aircraft and propulsion system the overall amount of cable length needed is significantly greater than in conventional aero engines and with that the associated losses. Various studies [7, 30] have been conducted to investigate the effects of boosting the voltage level from the current standard of 540 V to achieve higher efficiency and reduce the conductor weight. However, this leads to thicker necessary insulation material in the machines, corona protection mechanisms for power converters and circuit breakers [31]. Another variable in the architecture of the PMDS could be the question of alternating current (AC) versus direct current (DC). While alternating current promises reduced overall mass and increased efficiency according to Jones *et al.* [32] – mostly due to the power conversion efficiency – the controllability and operation of such an architecture remains challenging. In addition to the high voltage bus, there are other DC buses of 28 V, 12 V and/or 5 V present, supplying low power loads to the cabin and cockpit as well as control systems [24]. For the purpose of this work considering the EPS primarily, the architecture of the low voltage circuit is not defined in detail. Altogether, the mission and use case but also the integration of the EPS components in the aircraft are crucial for determining the ideal design points for the PMDS.

2.3 Remaining Subsystems

The electric motor is directly linked to the PMDS, as it is the main consumer of the electrical energy produced. As indicated in Figure 3 there are a number of subsystems being communicated with by the PMDS, which are part of the EPS or essential to the integration of the EPS into the aircraft. Not only the BoP components of the FCS need to be powered by electricity but also aircraft accessories, such as solenoid valves and the controls of various pumps and hydro-mechanical actuators to perform tasks such as the positioning of slats and flaps. Furthermore, significant amounts of data need to be exchanged with the avionics of the aircraft to control the power supply in accordance with the load demands. This information needs to further be communicated to the control unit responsible for the motor-propulsor system (MPS) to regulate the propeller pitch and the motor speed. Depending on the type of motor chosen the need for a gear box may be eliminated. The load demands will determine the amounts of fuel required by the FCS to supply sufficient amounts of power at all times. As the H_2 storage and distribution is not part of the FCS, it will be referred to as HSDS (hydrogen storage and distribution system).

3. Analysis Methods

In contrast with stationary applications and earth-bound transportation, the propulsion system has to fulfil its tasks during all operating conditions of the aircraft covering altitude differences of about 14 km and ambient temperatures from -70 to 60° C as well as ambient pressure from 100 to 14 kPa. To accommodate these varying operating conditions the reliability and stability of the control system of an aircraft is crucial. In general, the control tasks related to the propulsion system of an aircraft can be summarised as having to guarantee [33]:

- Safety and reliability under all operating conditions including take-off under various on-ground conditions,
- Short response times during changes of operating conditions,
- Economic operation for all mission phases considering the tradeoff between reducing fuel consumption and maximizing thrust as well as durability of the overall propulsion system and
- Consideration of the impact of environmental conditions (high altitude, hottest day, coldest day, wet air ect.).

In modern civil airplanes, little control is left to the pilot directly to minimise the probability of human error. However, this intrinsically demands for a control architecture considering all potential failure modes of the system and an exceedingly high degree of accuracy and reliability of the control system itself. In order to achieve that, the design process illustrated in Figure 4 is being applied to the FC-based EPS described in Section 2. Based on a functional analysis, methods of the system safety assessment such as a functional hazard analysis (FHA) can be applied to allow for a more holistic view on the overall system behaviour and interdependencies, which demand for additional control tasks. After consolidating all control tasks found, they can be analysed and developed into a control strategy. Lastly the controls architecture is being developed.

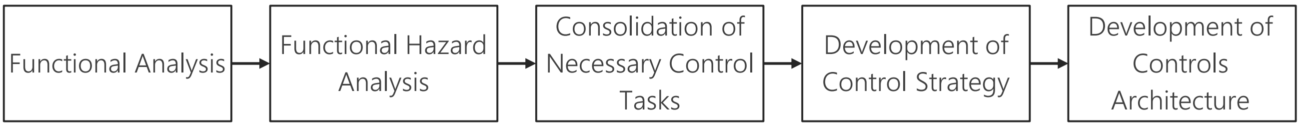


Figure 4 – Proposed control architecture design process

This proposed control architecture design process presents only an excerpt of a complete systems engineering approach, which is utilised to develop a control architecture. The latter is being described in the following section.

3.1 Utilised Systems Engineering Approach

The basis of this systems engineering approach is the safe design process in aviation based on ARP 4754A [3]. This process embodies the V-model of systems engineering, where functions, requirements and architecture of the product are developed, validated and verified on different levels of detail from aircraft to system to element level as illustrated in Figure 5. From the functional requirements given by the aircraft and topology of the propulsion system down to the components themselves control tasks can be derived. By performing safety assessments on different system levels, the requirements can be validated and further control tasks defined.

The following section describes the safety assessment process in aviation, which has been adopted in this work to complete the compilation of control tasks by considering the strict safety requirements for commercial aircraft. From there, control strategies can be developed for individual components to fulfil its control tasks. Alongside the development of the controls architecture the integration into the overall system is designed and the satisfaction of all safety requirements is verified again on different system levels. This work solely focusses on the first half of the control architecture design approach and the comparison with conventional aero engines.

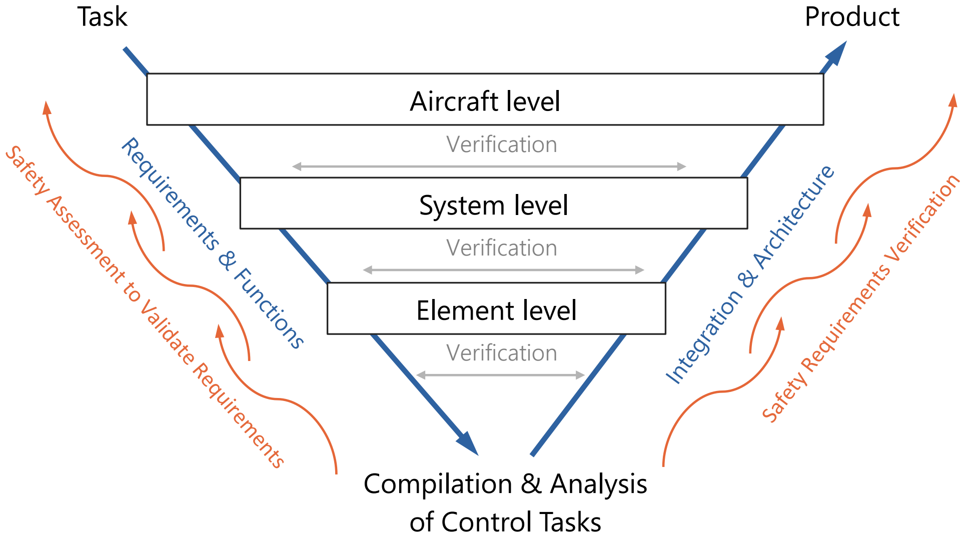


Figure 5 – Control architecture design process

3.1.1 *Safety Assessment Process in Aviation*

From the early phases of the development process onwards the analysis of potential risks and weaknesses is necessary in order to design highly efficient, innovative components suitable for electrified aero engines. 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 [34]. As part of 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 AMC 25.1309 of CS-25 describes the safe design process in aviation based on ARP 4754A [35], which has been formulated by SAE International, a consortium of various aviation companies and authorities. The according methods of this process are described in ARP 4761 for each development phase [36]. In this work, the top-down method Functional Hazard Assessment (FHA) is being applied to the EPS and in particular the FCS integrated in the EPS. The FHA is one of the most relevant safety and reliability methods during the preliminary design phase, along with Fault Tree Analysis as part of a Preliminary System Safety Assessment (PSSA). The latter ought to be performed in the next iteration of the control architecture design process. Other important safety methods are the System Safety Assessment (SSA), the Failure Mode and Effects Analysis (FMEA) and the Common Cause Analysis (CCA). Also, design reviews are suggested at least after each phase of the design process [37], [38].

3.1.2 *Functional Analysis*

The basis of the FHA is a functional analysis of a system or component. A function is defined as the conversion of input material, energy or data into desired output [39]. Function structure trees (FSTs) are particularly suitable as input for an FHA and are therefore the method of choice in this work [40].

In an FST 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 [41]. The level of detail should be chosen in accordance with the purpose of the analysis [42].

By first establishing a function structure before designing a physical architecture, more potential solutions can be found and synergetic effects utilised. The more detailed the function structure can be defined, the more accurately the final solutions will fit the problem. However, it is important to start out with a simple functional structure that can iteratively evolve into a more detailed and complex structure throughout the development process to avoid limiting the design space too early.

3.1.3 Functional Hazard Analysis (FHA)

The main goal of the Functional Hazard Analysis (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, requirements for acceptable failure occurrence probabilities are derived with up to less than 10^{-9} events per flight hour [43].

An FHA can be conducted on aircraft, system and subsystem level [36]. In this work, the FHA is performed on the EPS and the FCS level. Failure conditions associated with EPS and FCS malfunctions and their effects are determined. A distinction is made regarding the effects of different degrees of malfunction, the number of affected engines and the flight phase. The results obtained from the FHA serve as ideal top-level events in the FTA of a PSSA. Carrying out an FHA early on in the design process, allows for a more complete analysis of all control tasks at hand.

3.2 Control Task Analysis

Figure 6 shows a regulator control loop. Contrary to a positioner it includes a disturbance d, which interferes with the plant operation such that the control variable is altered. In order to correct the current state of the control variable, the actual value c, it is being measured by a sensor and processed to the sensor output b. By comparing this value to a desired value r, the error e is determined. Inside the controller the error information gets processed in a way that a command u can be sent to the actuator, which acts upon the plant with the force f to correct for the disturbance.

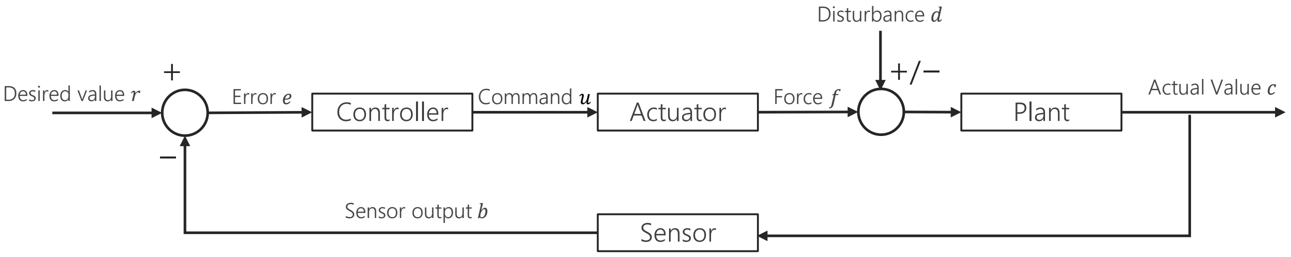


Figure 6 – Basic control loop architecture of a regulator

It is important to note that the variable being influenced by the actuator is different from the variable to be controlled. For instance, in a turbo jet engine the thrust lever is the indicator for the desired value r. The control variable linked to the thrust lever is the engine pressure ratio ($r = EPR$), the fan speed ($r = N_1$) or the turbine inlet temperature ($r = T_{t4}$) depending on the engine manufacturer [33, 44]. However, the actuator variable is the fuel mass flow $\dot{m}_F$ [44]. Additional information needed by the controller to determine the command u are received from other sensors for engine parameters such as: high pressure shaft speed N_2 or compressor exit total pressure p_{t3}. Typical sources for disturbance are variations in ambient air speed and temperature based on weather conditions, altitude changes or geographical location. Additionally, load demands from aircraft accessories and bleed air can cause disturbances in the control loop, which need to be corrected for.

To develop new controls concepts and strategies for electric power trains all requirements have to be understood and well-defined first. This applies to performance requirements as well as safety and reliability requirements. Once that is achieved, a strategy for the overall controls architecture of the EPS can be defined. Each EPS function identified as being safety critical leads to three control tasks as illustrated in Figure 7 [45].

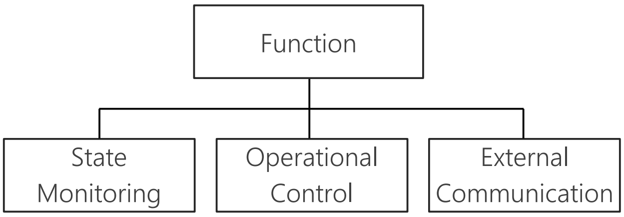


Figure 7 – Types of control tasks associated with each safety critical function

These tasks are associated with the requirements posed on the control system. Operational control is associated with the performance but also avoiding failure. If a failure occurs, it will be detected via state monitoring. This occurrence has to be communicated to other systems and, if required, special safety mechanisms will be activated. Some states will trigger communication with the pilot.

Having carried out FHAs on all hierarchy levels, control tasks can be compiled and analysed. This is the tip point of the V-model in Figure 5 and allows for a preliminary design of the controls architecture and further assessment of its integration. By analysing the degrees of freedom of the entire propulsion system and obtaining a detailed understanding of the physical relationship between all subsystems and quantities to be controlled, decisions can be made with regards to which methods of control ought to be applied. In a subsequent PSSA, including an FTA, the overall probability of system failures could be determined and based on that the list of control tasks may vary and expand to decrease the failure probability of a particular component or subsystem. However, it is possible that the control strategy and controls architecture has to be modified or replaced all together. By including safety analysis early on in the process as is being proposed here, the likelihood of the latter case is intended to be reduced.

4. Safety Assessment for Fuel Cell-Powered Propulsion System

First the functions of the exemplary all-electric aircraft propulsion topology as described in Section 2 will be identified and their relationship on different system levels will be analysed. Thereby synergies can be identified, which may lead to functional integration and additional control tasks.

4.1 Functional Analysis

The functional structure is identical for an aircraft (AC) with conventional aero engines (CAE) and an all-electric aircraft with a FC-powered electric propulsion systems (EPS). Figure 8 illustrates this structure including a selection of the most important functions.

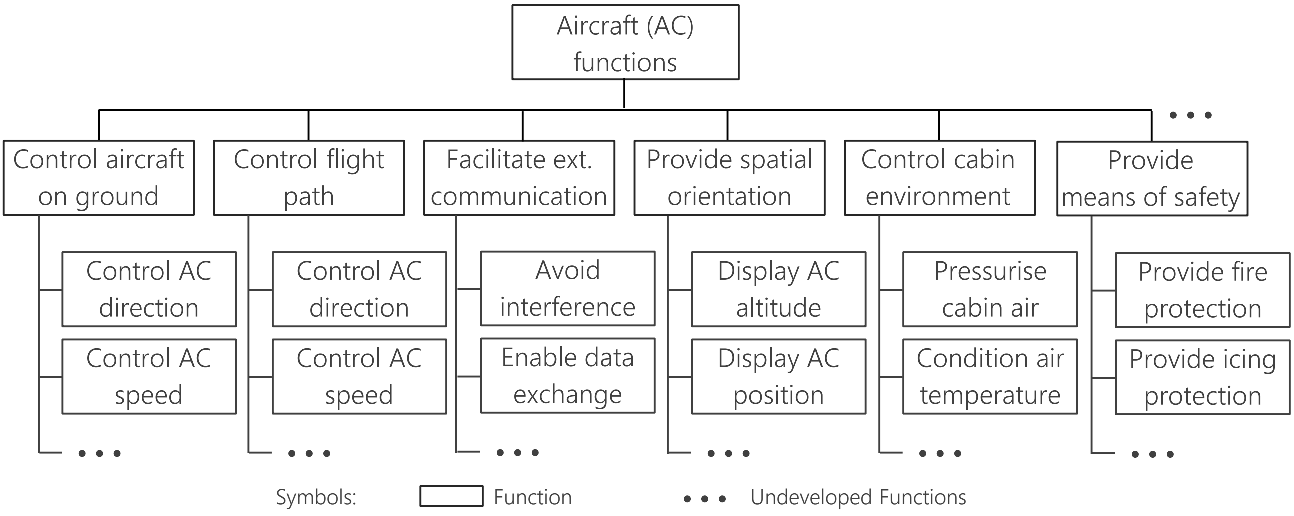


Figure 8 – Function structure tree of aircraft level

The primary link from the aircraft level functionality to the propulsion system is the task of providing a means of control for the AC speed. However, it is not the only one. Providing fire protection is closely related with the propulsion system as well. Hence, it will have to contain sensors to detect fuel leakage, but also mechanisms to prevent fire in areas, where heat sources are present. In the case of an EPS this would be within the FCS, as it uses hydrogen as fuel, which is highly flammable when a source of ignition is present.

Furthermore, functional integration will become increasingly important to reduce the overall system weight, which is key to enabling all-electric flight for passenger aircraft. The various potentials have to be evaluated individually and their benefits considered against the safety risks involved in coupling two systems and creating dependencies between them. To understand the opportunities for this approach all functions of the aircraft need to be considered. As the use of FCs leads to an enormous amount of excess heat, additional tasks such as ‘Condition cabin air’ can be achieved via functional integration with the EPS using heat exchangers to heat the cabin air when needed. Another option might be to utilise the exhaust air of the FCS for fire extinction.

From Figure 8 the high-level control tasks imposed by the aircraft on the propulsion system controller were derived and consolidated: (1) Control AC speed; (2) Pressurise cabin air; (3) Condition air temperature. These tasks are handed down to the propulsion system respectively: (1) Provide thrust; (2) Pressurise cabin air; (3) Condition air temperature. These can be found amongst other functions in Figure 9 showing the functional structure of the propulsion system. Additionally, the function 'Provide fire protection' could be seen as one optional function of the propulsion system as well, but it can also be allocated to the category of additional safety equipment and components not directly included in the propulsion system.

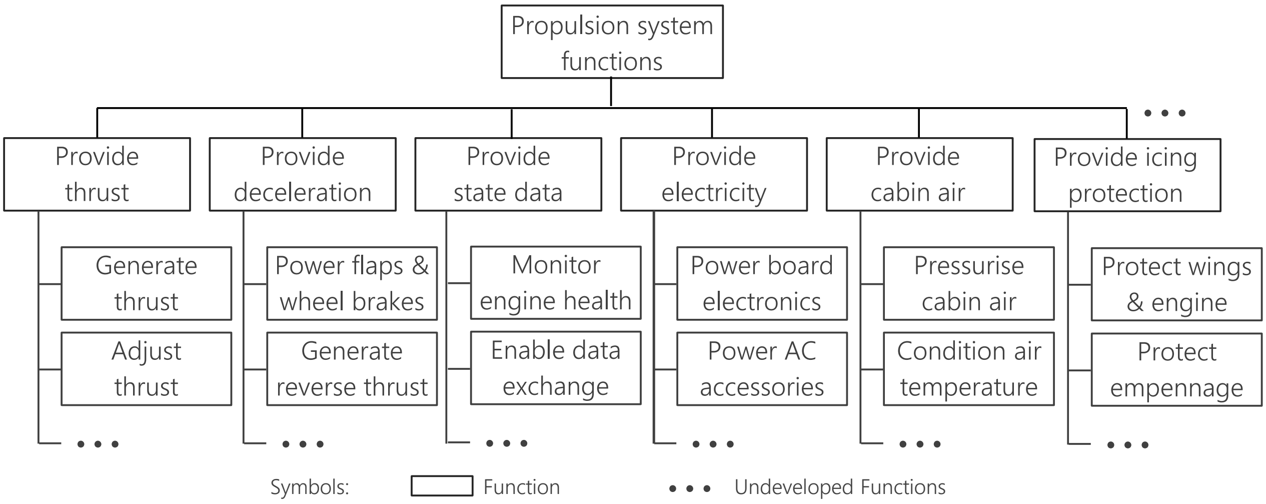


Figure 9 – Function structure tree of propulsion system level

The content of this functional structure tree has been derived from the CAE as propulsion system. With the introduction of FC-based EPSs the retention of all functionalities has to be guaranteed or additional subsystems need to be introduced as a substitute to carry out those functions, which cannot be fulfilled by the EPS. Thus far icing protection of aerodynamic surfaces has traditionally been provided by utilising hot bleed air from the jetwash. The off-gas of an LTPEM-FCS is not hot enough to be the sole provider of heat for evaporative anti-icing operation, but is sufficient for de-icing operation, leaving the risk of runback ice formations [46]. This needs to be evaluated when designing the propulsion system. Additionally, power has to be provided to the board electronics and the avionics unit as well as the AC accessories including those required by the propulsion system itself, e.g. for electromechanical actuators of thrust reverser units or variable nozzles. While in the past the electrical energy required has been provided by the CAE via a generator or an APU, in an EPS this energy can be provided directly but it has to be accounted for in the sizing of the EPS and in the design of the controls architecture.

Being able to provide reverse thrust in a CAE is also an optional function. Depending on the physical integration of the EPS components in the aircraft, the deceleration capability will likely be compensated for with new alternative thrust reversing mechanisms. Additionally, movable flaps and wheel brakes are the mandatory deceleration means, which also require actuation energy and control systems.

The major tasks of 'Provide thrust' and 'Adjust thrust' are accomplished by powering a propulsor (a propeller or a fan) with an electric motor – the MPS as previously defined – accordingly. A gear box can be beneficial depending on the chosen electric motor type, propulsor size and the overall design of the powertrain. For the FC-powered EPS this results in the primary task of providing electrical energy to the PMDS as described in Section 2.2. The PMDS is the transmitter of the electrical energy demanded by the MPS and will compensate for any discrepancy between demand and supply with the buffer energy. In order to provide electrical energy, the LTPEM-FCS has to fulfil the functions displayed in the functional structure in Figure 10.

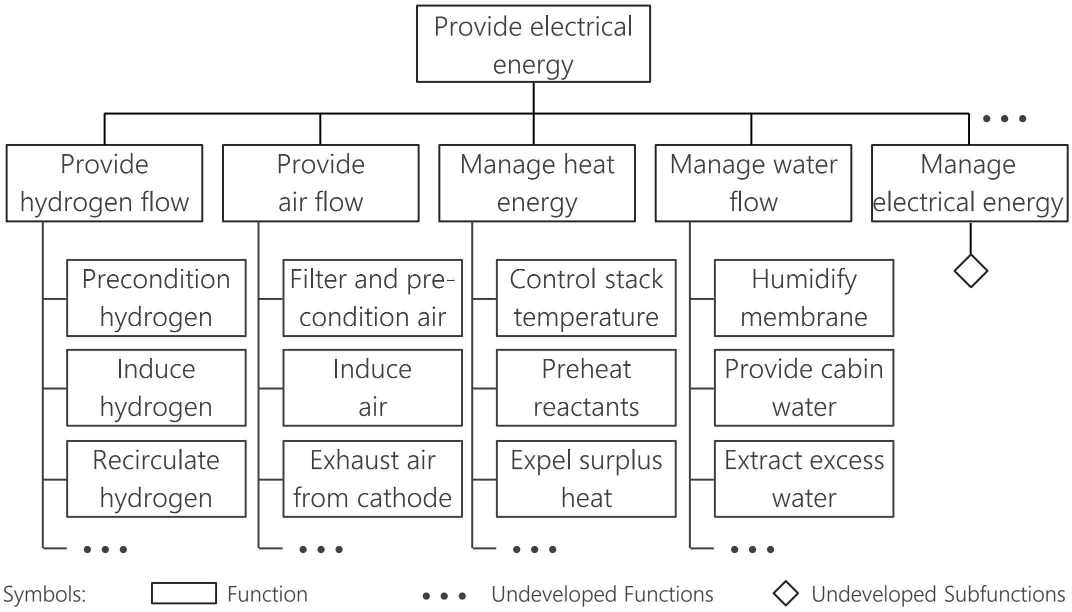


Figure 10 – Function structure tree of LTPEM-FC system

In order to invoke the flow of electrical current between the two electrodes connected to the PMDS, hydrogen flow on the anode side and air flow on the cathode side have to be provided at a given excess ratio, typically between 1.2 and 2.0 [14]. Both media are to be regulated to specific pressure, temperature and relative humidity levels. Proper humidification of the polymeric membrane is necessary to ensure steady ion transport. Air is induced and passed through a filter to avoid contamination which can lead to degradation of the MEA in the FC. Excess air and hydrogen can be recirculated. The amount of water in the cathode flow has to be regulated to avoid flooding. Excess water can be reused for humidification, but also to supply water for onboard use. The ideal operating temperature of the FC has to be maintained and controlled with a coolant. The utilisation of excess heat via functional integration, as previously discussed, has to be regulated as well as ways of expelling surplus heat to the environment.

4.2 FHA Considerations

The FCS function structure provides the input for the FHA. The main function of the FCS is ‘provide electrical energy’. Having this functionality interrupted 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 a small performance limitation, buffer batteries – such as the one included in the topology and shown in Figure 3 – 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 in a way to safely continue flight with one engine inoperative [34]. 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 flight hour (FH). The 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 [34].

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 shall also fulfil secondary functions, additional potential hazardous events can be a result. This applies to the following AC and EPS functions, which could be taken over by the FCS: ‘provide icing protection’, ‘pressurise cabin air’, ‘provide cabin water’, ‘condition cabin air temperature’, ‘generate reverse thrust’ and ‘provide fire protection’. For instance, the loss of icing protection capability can lead to wing and empennage icing, potentially causing a ‘loss of aircraft control’.

In order to ensure low probability of failure in the FCS additional control tasks are of essential importance to be able to ensure overall safety requirements in aircraft operation under all conditions and flight phases. These include but are not limited to:

- A cold start system to preheat induced air in case of freezing conditions,
- Means of purging water that may accumulate on the anode side and
- A pressure difference regulator between anode and cathode to ensure structural integrity.

Considerations for safe system design are vital beyond the FCS. The electrical components are highly susceptible to disruptions caused by electromagnetic interference and can lead to data communication hazards through their own electromagnetic field or electrical components in the vicinity. To prevent a shutdown of the DC a circuit shielding will be required. Furthermore, batteries, the electric motor and power electronics require extensive cooling as well. Fire hazards have to be considered when designing the system integration. For instance, special care has to be taken of the combination of potentially leaking flammable fluids, such as hydrogen, and potential sparks of electric components.

Many further interactions, such as friction, electromagnetic interference or short circuits, between components in the EPS zone can cause fire and other hazardous events. These are to be avoided during regular operation and mitigated during failure operation. To identify these safety hazards a CCA comprising the zonal safety analysis (ZSA) should be conducted in a following design phase.

5. Analysis of Control Tasks

In this section the specific necessary controls tasks that result from the functional analyses in Section 4, as well as the performance and safety requirements are being synthesised and compared to those of a CAE. The main function of the propulsion system is to provide thrust. This is where the EPS significantly deviates from a gas turbine and where the heart of the complexity of the controls problem is situated.

5.1 System Degrees of Freedom Analysis

Table 1 introduces the main control tasks resulting from the FST analysis and the FHA of the exemplary propulsion system. Here the control tasks are categorised using the subsystem definition presented in Section 3. Furthermore, the control variables of the FC-based EPS are listed and, if applicable, an equivalent CAE control variable is provided. The list of control variables is the baseline for developing a potential control strategy for the individual control task, but variations of this solution are possible. From this analysis a total difference in degrees of freedom ΔDoF can be calculated as follows:

$$\Delta DoF = DoF_{EPS} - DoF_{CAE} \,. \tag{1}$$

Excluded from this list are all control tasks, which are clearly identical for both EPS and CAE. This includes those involving the avionics and many accessory components. Control tasks that are no longer applicable, but had previously been important in CAEs, are listed in the last section of the table.

A significant increase in degrees of freedom and therefore control variables relevant in a FC-powered EPS has been demonstrated with this analysis. In the case of this particular topology and the chosen control strategy the use of an all-electric aero engine increases the number of degrees of freedom by fourteen counts, which is equivalent to almost 100%. This is still an estimate based on the simplified topology chosen for this work and the assumptions made. For instance, to control the air temperature multiple actuators may be necessary. The temperature is dependent on the environmental conditions, e.g. cold start or hot start, as well as the power demand through the compression. Controlling the relative humidity of the MEA is another example. It can be done by humidifying both the air and the fuel prior to inducing it into the FC, but depending on the manufacturer and system design it may only be necessary to have a humidifier present on the cathode side because enough water is being recirculated on the anode side.

With the next design phases of defining the control architecture and the system integration, both the details of the topology may vary and additional requirements might be defined.

Table 1 – Control tasks derived from FST analysis and FHA for FC-based EPS compared to CAE

Subsystem	Control Task	FC-based EPS control variable	CAE equivalent	ΔDoF
FCS	Regulate induced air	$\dot{m}_{air}$, p_{air}, T_{air}	–	3
	Regulate fuel induced	$\dot{m}_{H_2}$, p_{H_2}, T_{H_2}	–	3
	Recirculate excess hydrogen	N_{pump}	–	1
	Control humidity	$RH_{cathode}, RH_{anode}$	–	2
	Limit FC temperature to ideal operating condition	$\dot{m}_{Coolant}$	–	1
	Purge excess water on anode side	$x_{purge\ valve,\ anode}$	–	1
	Provide heat for anti-icing system	$\dot{m}_{icing}$	$\dot{m}_{icing}$	0
PMDS	Provide electrical energy for stack preheating in case of cold start	$I_{preheat}$	–	1
	Delivery of sufficient power supplied based on thrust lever position and stable transition	I_{FC}	–	1
	Deliver electrical power to onboard electronics, avionics and aircraft accessories	$I_{Accessories}$, $I_{Avionics}$	$I_{Accessories}$, $I_{Avionics}$	0
	Deliver boost power for dynamic response	$I_{Battery}$, $I_{Capacitor}$	–	2
	Control battery charge and discharge behaviour	$I_{Battery}$, $U_{Battery}$		2
	Control voltage level on low voltage circuit	$U_{LV\ circuit}$		1
Hydrogen Storage & Distribution	Regulate hydrogen tank conditions	$T_{H_2,tank}$, $p_{H_2,tank}$		2
	Provide hydrogen to FCS	$\dot{m}_{H_2,total}$	$\dot{m}_{fuel}$, T_{fuel}	-1
	Regulate hydrogen supply to cryogenically cooled power electronics	$\dot{m}_{H_2,cooling}$	–	1
Motor & Propulsor	Adjustment of propeller pitch for turbo-prop engines	φ_{pitch}	φ_{pitch}	0
	Regulate lubricant flow in gearbox bearings	$\dot{m}_{lubricant}$	$\dot{m}_{lubricant}$	0
	Control rotational speed of motor and propulsor	N_{motor}	N_2	0
	Adjustment to operation with thrust reversed	$x_{thrust\ reverser}$	$x_{thrust\ reverser}$	0
CAE specific	Management of cooling air for clearance control	–	$\dot{m}_{cooling,HPT}$, $\dot{m}_{cooling,LPT}$	-2
	Automated activation of variable geometry actuation (adjustable guide vanes, bleed valves ect.)	–	$x_{HPC,bleed\ valve}$, $\dot{m}_{HPT,cooling}$, $\dot{m}_{MPT,cooling}$, $\dot{m}_{combustor,cooling}$	-4
Total difference in degrees of freedom (ΔDoF)				**14**

5.2 Fail-Safe Design through Controls

If certain operational parameters exceed their acceptable range, mechanisms to prevent hazardous failure modes can be required. To ensure that a single element, component or connection failure does not lead to a system hazard, fault-tolerant design approaches have to be practiced during system design [47]. These principles of fail-safe design can be:

- Integration of redundant or dissimilar backup system,
- Integration of mechanism to isolate the faulty system, component or element,
- Design failure effect limitations,
- Design failure path and
- Verify fault and error tolerance [41].

For instance, one requirement for a critical value in an FCS can be the pressure both on the anode and cathode side. In order to obtain the desired output of electrical energy from the FCS, a certain pressure has to be provided. On the cathode side, the incoming air is compressed and the mass flow is regulated. To achieve that a plenum might be needed to ensure sufficient air supply during dynamic operation. The first control task would be ‘Provide air at pressure p’. In the control algorithm a state limitation has to be ensured such that the pressure cannot exceed critical values. This is the performance requirement. Additionally, it is necessary to monitor the pressure difference between anode and cathode Δp_{MEA}

$$\Delta p_{MEA} = p_{anode} - p_{cathode} \,. \tag{2}$$

On the one hand, this is necessary to allow for optimal flow through the MEA, but on the other hand, to avoid mechanical stresses in the MEA and with that prevent failure of the FC stack. Therefore, the second control task would be ‘Regulate pressure difference between anode and cathode’. If a fuel cell stack is over-pressurised beyond the tolerance for mechanical integrity, it can affect healthy stacks connected in series or even lead to increased temperatures and with that fire hazards. To prevent these hazardous conditions, the discrepancy needs to be detected and by using a bypass valve the faulty stack can be isolated. If the safety analysis shows that the function from which these two control tasks were derived is safety critical, additional control tasks for monitoring the pressure difference would need to be accounted for, as well as for external communication.

During the shut-down procedure it is necessary to purge the FC in order to avoid having residual water present – in particular during emergency shut down this is important. Under freezing conditions, the formation of icicles might case structural damage to the FC. Furthermore, other safety features need to be incorporated into the system design of the PMDS and the electric motor such as:

- Overload protection and overvoltage protection,
- Short-circuit protection,
- Electric and magnetic hysteresis loop and
- Protection against overheating.

5.3 Monitoring and External Communication

Additional monitoring capability and the need for external communication is therefore required for all safety critical control tasks. These tasks are listed in Table 2 and are only an extension to the list of variables being monitored for performance control purposes.

As previously discussed, synergies between components of different subsystems can be identified offering opportunities for functional integration. However, the more functional integration is applied in the design of the overall system architecture, the more communication between different subsystems may be required.

Figure 11 shows the main communication pathways and examples of entailed information.

Table 2 – Monitoring tasks for safety critical functions

Subsystem	**Monitoring tasks**
FCS	Monitor exhaust gas for signs of production of peroxide radicals – usually caused by insufficient humidification of the cathode side or an oversupply of oxygen
	Detect leakage of hydrogen, water, hot or pressurised air
	Monitor FC temperature – one probe in each stack
	Monitor coolant temperature
	Monitor air, hydrogen filter status
	Monitor inlet pressures
	Monitor pressure difference between anode and cathode – one probe for each stack
PMDS	Monitor battery health – in particular, temperature to avoid fires
	Monitor supercapacitor and battery capacity level
	Monitor moisture, temperature and pressure level within PMDS
	Monitor start-up and shut-down on ground as well as during flight given a state of emergency
Hydrogen Storage & Distribution	Detect leakage of hydrogen
	Monitor hydrogen tank temperature and pressure
Motor & Propulsor	Monitor lubricant temperature (bearings, gear box)
	Monitor rotational speed
	Monitor coolant temperature of electric motor

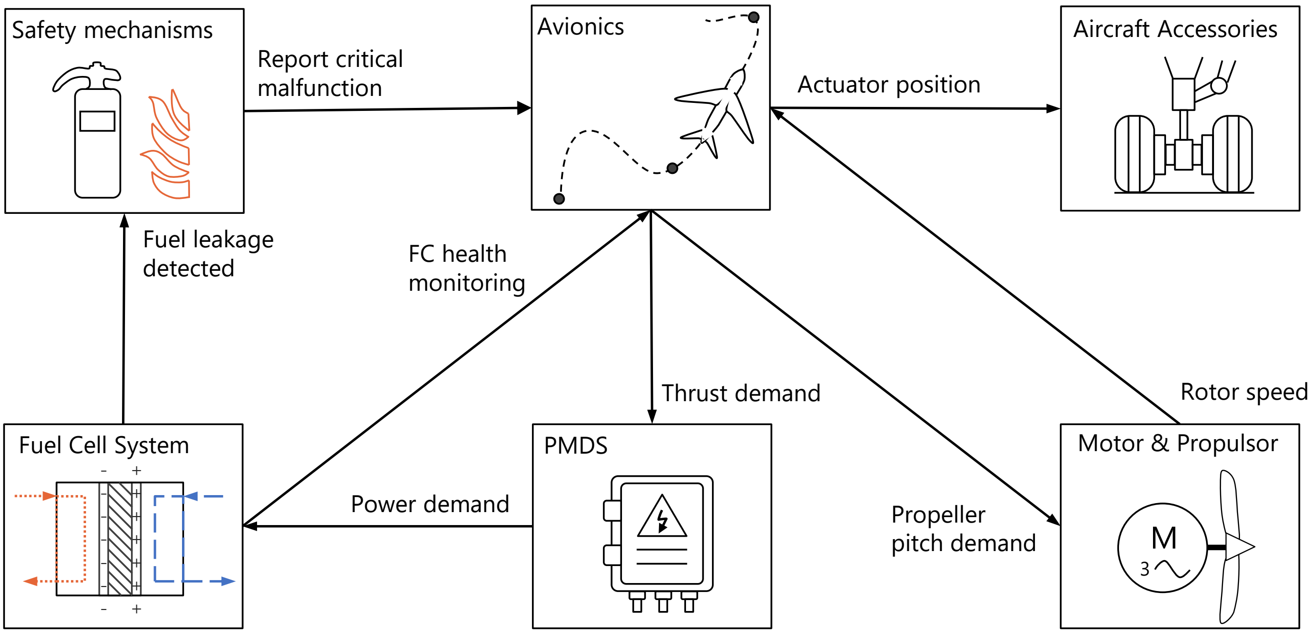


Figure 11 – Communication pathways between subsystems of the aircraft

6. Selected Results and Discussion

From a control's perspective the integration of fuel cell-based powertrains presents significant challenges for three reasons. Firstly, more media of control are being introduced. In traditional turbo engines the air breathed, the fuel, the lubricant, small amounts of coolant and electrical power have to be handled. By contrast, fuel cell powered all-electric engines require additional control of water produced by the fuel cells, larger amounts of coolants to remove the heat from the fuel cells and significantly increased amounts of electrical current.

Secondly, the different media display highly-nonlinear interactions with each other and cannot be treated separately. This is of particular importance when considering fault detection both to prevent or mitigate hazardous effects and also to develop maintenance strategies.

Thirdly, these individual components entail numerous new challenges with regards to durability and lifetime - from humidification of the membrane electrode assembly MEA of LT-PEM fuel cells to intelligent charging strategies for lithium-ion accumulators, all of which are dependent on the control system. In-flight health monitoring is therefore crucial to the application of these technologies.

Following the design approach for controls architecture proposed in Section 3 of this work control tasks have been compiled and analysed based on the systems boundaries defined in Section 2 and illustrated in Figure 3. However, this does not mean that the controls architecture must follow a cascade approach. It is entirely possible to have a central control unit with all the information about the physical relationship between all components and from there regulate and control the actuators involved. In fact, the increased amount of data exchange required in an EPS might benefit from a holistic controls approach to reduce the amount of data on the bus and improve the overall dynamic behaviour. In order to realise this, control algorithms will become more complex and therefore an increased amount of CPU power and storage capacity would be required to allow for more flexibility and freedom in designing these control algorithms.

In order to evaluate the best architecture for the control of an EPS and its integration in an aircraft the individual subsystems and the implementation of the individual control tasks were assessed. In accordance with the systems engineering approach the controls architecture is being defined with a bottom-up approach – the second half of the V-model – by moving from the components to the subsystems to the aircraft level. As the FCS is the central unit supplying the electrical energy a controls strategy for this subsystem should be defined first before moving on to the other subsystems and further to additional control tasks required for monitoring and external communication between the individual systems up to the aircraft level. Once all the tasks are defined and the physical relationships between all components involved are understood, the global controls architecture and the controls approach should be chosen.

Figure 12 shows a proposed controls architecture for an LTPEM-FCS within the EPS. The individual actuators can either be controlled separately or holistically by a central control unit administering commands and processing sensor data.

The ambient air induced is compressed and thereby heated up before passing through a filter. Additional temperature control may be necessary here or could be achieved with the humidifier and combination with the recirculated air and product water mixture. Furthermore, a cold start system would need to be incorporated to ensure ideal operating conditions under all possible environmental conditions. With a purge valve the amount of recirculated air is being controlled. Excess product water can be expelled or purged into the tank by the dehumidifier unit. Same goes for the anode side, where some water is present as well. All excess fuel is being recirculated and based on the demand additional hydrogen supplied by the hydrogen distribution system – here illustrated simply as H_2 tank. The hydrogen is being preheated using some of the heat bound in the coolant pumped through the FC. Furthermore, the purge valve on the anode side allows for complete purging during a shut-down procedure. Additional monitoring equipment mentioned in Table 2 of Section 5.3 is not illustrated in Figure 12.

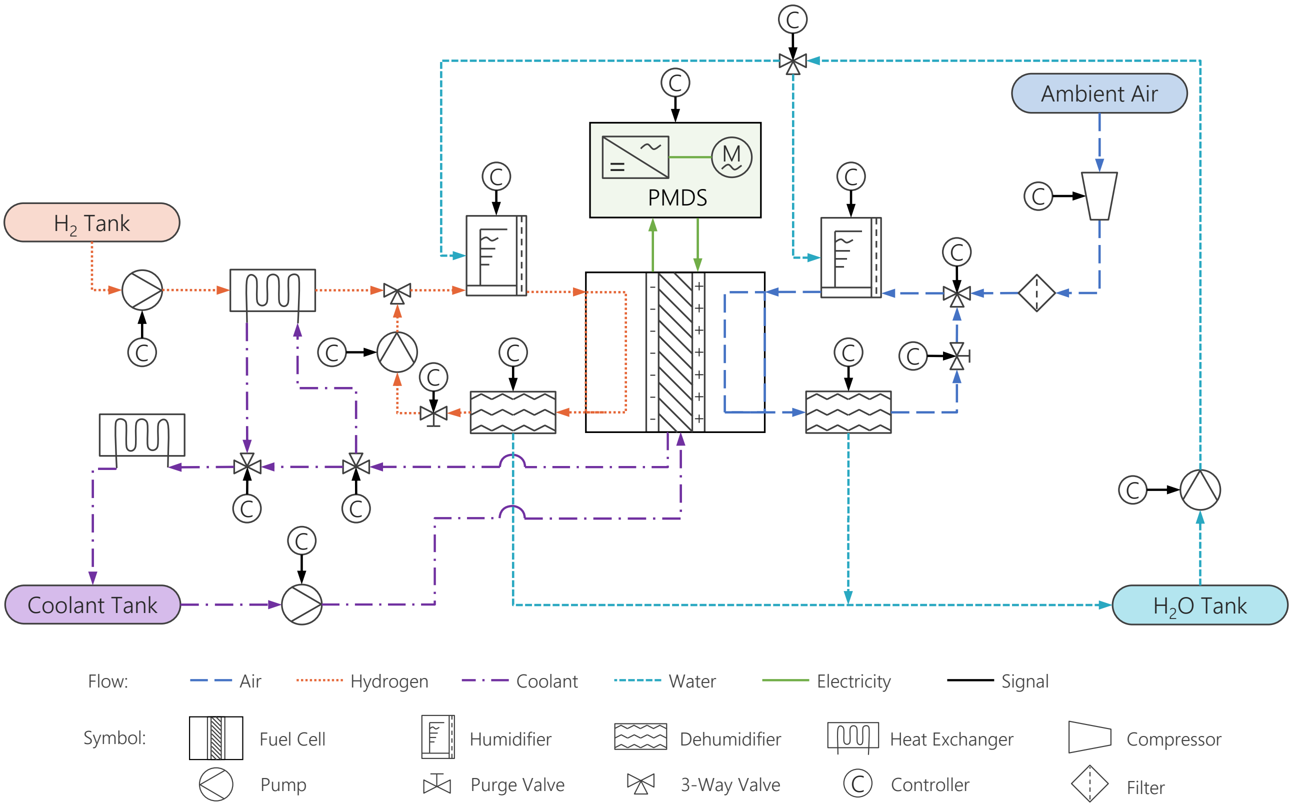


Figure 12 – Controls architecture for low-temperature PEM fuel cell system

The foreseeable, significant increase in the amount of control tasks demonstrated in this work leads to the need for large amounts of computational power required onboard. Digitalisation of the control mechanisms is necessary to adhere to the demands for fast response control. Since the beginning of civil air travel, a growing amount of controls equipment has become digitised. In the avionics sector the era of digitalisation has long begun. However, in aero engines the majority of controls has been maintained at a similar standard as 30 years ago. This is partially due to the fact that hydro-mechanical and pneumatic control components have proven to be reliable and durable but also of course that the development cycles of aircraft and their respective engines is much longer than for instance in the automotive sector. Certifying electrical equivalents has been a challenge as well, but the introduction of more electric aircrafts has brought a large shift. With the latest engine generation, a shift has been seen from Main Engine Control (MEC) units to Electronic Engine Control (EEC) units, as well as hydraulic valves and pneumatic components valves to solenoid valves and electrically operated components. As a result, overall efficiency has been increased and the fuel burn rate reduced, while also reducing maintenance cost and system weight [48, 49]. In the past decades more actuators are designed with necessary controls integrated and hence becoming self-sufficient, while decreasing computing power on the central controller unit [50]. The premise being that these electronic components can be developed successfully and withstand the local environmental conditions associated with such actuators opposed to the usual location near the relatively cool gear box [50]. The introduction of hybrid-electric or all-electric propulsion systems creates another level of complexity in the controls of such aircraft and with that it is questionable whether the engine controls will become significantly more digitalised in the coming new aviation era.

7. Conclusions

The electrification of aircraft propulsion will prompt the introduction of various new components, which have not been developed for and tailored to aviation specific requirements. Great need for further developments of such components can be identified on the one hand but on the other hand great potential for improvement in terms of power density and safety lie therein.

Functional integration can lead to significant weight reduction but also to increased probability of failure due to the additional dependencies between subsystems. If this leads to inacceptable failure probabilities, redundant systems may become necessary and with that additional weight is added to the system. It is therefore crucial to design the control system during the with conceptual design of functional integration to maximise the safety and reliability of the integrated functionality and with that the aircraft.

An analysis of the degrees of freedom present in both conventional and electrically powered aero engines was performed - indicating the growth in complexity, which will arise with the electrification of aero engines. The reasons for that are the increased number of media to be controlled, the highly non-linear relationship between these media and the challenges introduced by using technologies new to the aviation sector such as LTPEM-FCs. In the case of the simplified topology chosen for this work an increase of almost 100 % in the number of control tasks was the result.

Further evaluations in the next design phases of control architecture definition and system integration additional performance and safety requirements may be revealed. These requirements can include the definition of critical values or boundaries for a controlled quantity in order to maintain the necessary performance, which would translate into a state limitation provided by the controller algorithm. Other aspects such as fault detection and in-flight health monitoring to ensure sufficient lifetime will be critical as well. Safety critical control tasks require additional efforts in monitoring and external communication with other subsystems and potentially also the avionics or the pilot. Much effort will be required in the field of controls design to handle the amount of communication while providing stable, reliable and safe transitions between all operating conditions. Some of these additional aspects of consideration have been discussed in this work.

Based on the results of the control task analysis, a potential controls approach was developed addressing the challenges identified for integrating an LT-PEM fuel cell into a passenger aircraft. Thereby, this work sheds light on the challenges imposed on powertrain controls by the fuel cell technology of today, in general, and the LT-PEM fuel cell, in particular. Controls tasks specific to fuel cell-powered aero engines were derived and strategies developed to comply with the demanding performance and safety requirements of aviation and hence enable the introduction of sustainable electrified aero engines.

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References

1. Kouvaritakis B, Cannon M. *Model predictive control*. Switzerland: Springer; 2016.
2. European Commission. *Flightpath 2050: Europe's vision for aviation*. Luxembourg: Publ. Off. of the Europ. Union; 2011.
3. SAE Aerospace. ARP4754A: Guidelines for Development of Civil Aircraft and Systems. SAE International: Warrendale, PA, United States; 2010. Available at: https://doi.org/10.4271/ARP4754A.
4. SAE Aerospace. ARP4761: GUIDELINES AND METHODS FOR CONDUCTING THE SAFETY ASSESSMENT PROCESS ON CIVIL AIRBORNE SYSTEMS AND EQUIPMENT. SAE International: Warrendale, PA, United States; 1996. Available at: https://doi.org/10.4271/ARP4761.
5. Sahoo S, Zhao X, Kyprianidis K. A Review of Concepts, Benefits, and Challenges for Future Electrical Propulsion-Based Aircraft. *Aerospace*. 2020;7:44.
6. Arat HT, Sürer MG. State of art of hydrogen usage as a fuel on aviation. *European Mechanical Science*. 2017;2:20–30.
7. Jansen R, Bowman C, Jankovsky A, Dyson R, Felder J. Overview of NASA Electrified Aircraft Propulsion (EAP) Research for Large Subsonic Transports. In: *53rd AIAA/SAE/ASEE Joint Propulsion Conference*. Reston, Virginia: American Institute of Aeronautics and Astronautics; 2017.
8. Arzberger M. Overall power train performance estimation from pseudo transient models. In: *AIAA Propulsion and Energy 2021 Forum*. Reston, Virginia: American Institute of Aeronautics and Astronautics; 2021.
9. Hall D, Chin J, Anderson A, Smith A, Edwards R, Duffy KP. Development of a Maxwell X-57 High Lift Motor Reference Design. In: *AIAA Propulsion and Energy 2019*; 4481.
10. Borer NK, Patterson MD, Viken JK, et al. Design and performance of the NASA SCEPTOR distributed electric propulsion flight demonstrator. In: *16th AIAA Aviation Technology, Integration, and Operations Conference*; 2016:3920.
11. Berg Frederick, Palmer Joseph, Miller Paul, Husband Mark, Dodds Graham. HTS Electrical System for a Distributed Propulsion Aircraft. *IEEE Transactions on Applied Superconductivity*. 2015;25:1–5.
12. Stefan Kazula, Stefanie de Graaf, Lars Enghardt. Review of Fuel Cell Technologies and Evaluation of their Potential and Challenges for Electrified Propulsion Systems in Commercial Aviation. *GPPS*. 2022;in print.
13. Schalenbach M, Hoefner T, Paciok P, Carmo M, Lueke W, Stolten D. Gas Permeation through Nafion. Part 1: Measurements. *J. Phys. Chem. C*. 2015;119:25145–25155.
14. O'Hayre R, Cha S-W, Colella W, Prinz FB. *Fuel Cell Fundamentals*. Hoboken, NJ, USA: John Wiley & Sons, Inc; 2016.
15. Carrette L, Friedrich KA, Stimming U. Fuel Cells - Fundamentals and Applications. *Fuel Cells*. 2001;1:5–39.
16. Larminie J, Dicks A. *Fuel Cell Systems Explained*. West Sussex, England: John Wiley & Sons, Ltd; 2003.
17. Töpler J, Lehmann J. *Wasserstoff und Brennstoffzelle*. Berlin, Heidelberg: Springer Berlin Heidelberg; 2017.
18. SAE EUROCAE Fuel Cell Task Group. AS6858. Installation of Fuel Cell Systems in Large Civil Aircraft. 400 Commonwealth Drive, Warrendale, PA, United States: SAE International.
19. Daud W, Rosli RE, Majlan EH, Hamid S, Mohamed R, Husaini T. PEM fuel cell system control: A review. *Renewable Energy*. 2017;113:620–638.
20. Vielstich W, Lamm A, Gasteiger H, eds. *Handbook of fuel cells: Fundamentals, technology and applications*. Chichester: Wiley; 2003.
21. Stefan Kazula, Stefanie de Graaf, Lars Enghardt. Preliminary Safety Assessment of PEM Fuel Cell Systems for Electrified Propulsion Systems in Commercial Aviation. *Proceedings of the 32nd European Safety and Reliability Conference*. 2022;in print.
22. Qi Z. FUEL CELLS – PROTON-EXCHANGE MEMBRANE FUEL CELLS | Systems. In: *Encyclopedia of Electrochemical Power Sources*. Elsevier; 2009:890–900.
23. Lehmann J, Luschtinetz T. *Wasserstoff und Brennstoffzellen*. Berlin, Heidelberg: Springer Berlin Heidelberg; 2014.
24. Swaminathan N, Cao Y. An Overview of High-Conversion High-Voltage DC–DC Converters for Electrified Aviation Power Distribution System. *IEEE Trans. Transp. Electrific.* 2020;6:1740–1754.
25. Kuhn H, Seitz A, Lorenz L, Isikveren AT, Sizmann A, Luftfahrt B. Progress and perspectives of electric air transport. In: *28th International Congress of the Aeronautical Sciences, ICAS, Brisbane, Australia*; 2012.
26. Hoelzen J, Liu Y, Bensmann B, et al. Conceptual Design of Operation Strategies for Hybrid Electric

Aircraft. *Energies*. 2018;11.

27. Hepperle M. Electric Flight - Potential and Limitations. *Proceedings of Energy Efficient Technologies and Concepts of Operation*. 2012.
28. Masson PJ, Luongo CA. HTS machines for applications in all-electric aircraft. In: *2007 IEEE power engineering society general meeting*; 2007:1–6.
29. Teichel SH, Dörbaum M, Misir O, et al. Design considerations for the components of electrically powered active high-lift systems in civil aircraft. *CEAS Aeronautical Journal*. 2015;6:49–67.
30. Sadey DJ, Taylor L, Beach R. Proposal and development of a high voltage variable frequency alternating current power system for hybrid electric aircraft. In: *14th International Energy Conversion Engineering Conference*; 2016:1–10.
31. HECARRUS. WP1:“Efficiency and TRL of each component of the powertrai” D1.1: “State-of-the-art technologies on research and developments underway in the field of alternative propulsion architecture”. In: *Horizon 2020 / Clean Sky JU*.
32. Jones CE, Norman PJ, Galloway SJ, Armstrong MJ, Bollman AM. Comparison of Candidate Architectures for Future Distributed Propulsion Aircraft. *IEEE Transactions on Applied Superconductivity*. 2016;26:1–9.
33. Egon Schesky and Milosch Kral. *Flugzeugtriebwerke*. Berlin: Rhombos-Verlag; 2003.
34. European Aviation Safety Agency. *CS-25: Certification Specifications and Acceptable Means of Compliance for Large Aeroplanes, Amendment 18*; 2016.
35. SAE Aerospace. *ARP4754A. Guidelines for Development of Civil Aircraft and Systems*. Warrendale, PA, United States: SAE International; 2010.
36. SAE Aerospace. *ARP4761. Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment*. Warrendale, PA, United States: SAE International; 1996.
37. Sadraey MH. *Aircraft design: A systems engineering approach*. Chichester, West Sussex, United Kingdom: Wiley; 2013.
38. Moir I, Seabridge A. *Design and development of aircraft systems*. Reston, Va., Chichester: AIAA; Wiley; 2013.
39. Roth K. *Konstruieren mit Konstruktionskatalogen: Band 2: Kataloge*. Berlin: Springer Berlin Heidelberg; 2001.
40. Verein Deutscher Ingenieure, ed. *Sicherheit komplexer Verkehrssysteme*. Düsseldorf: VDI-Verl; 2000.
41. Feldhusen J, Grote K-H. *Pahl/Beitz Konstruktionslehre: Methoden und Anwendung erfolgreicher Produktentwicklung*. Berlin, Heidelberg: Springer Vieweg; 2013.
42. Koller R, Kastrup N. *Prinziplösungen zur Konstruktion technischer Produkte*. Berlin: Springer; 1998.
43. Kritzinger D. *Aircraft system safety: Assessments for initial airworthiness certification*. Duxford, United Kingdom: Woodhead Publishing; 2016.
44. Bräunling WJ. *Flugzeugtriebwerke: Grundlagen, Aero-Thermodynamik, ideale und reale Kreisprozesse, thermische Turbomaschinen, Komponenten, Emissionen und Systeme*. Berlin, Germany: Springer Vieweg; 2015.
45. Moir I, Seabridge A, Jukes M. *Civil avionics systems*. Chichester: Wiley; 2013.
46. Kazula S, Höschler K. Ice detection and protection systems for circular variable nacelle inlet concepts. *CEAS Aeronautical Journal*. 2020;11:229–248.
47. Kritzinger D. *Aircraft System Safety: Assessments for Initial Airworthiness Certification*. Woodhead Publishing; 2016.
48. Tariq M, Maswood AI, Gajanayake CJ, Gupta AK. Modeling and integration of a lithium-ion battery energy storage system with the more electric aircraft 270 V DC power distribution architecture. *Ieee Access*. 2018;6:41785–41802.
49. Buticchi G, Bozhko S, Liserre M, Wheeler P, Al-Haddad K. On-board microgrids for the more electric aircraft—Technology review. *IEEE Trans. Ind. Electron.* 2018;66:5588–5599.
50. Bauerfeind K. *Steuerung und Regelung der Turboflugtriebwerke*. Basel: Springer-Verlag; 2013.