HYBRID ELECTRIC PROPULSION SYSTEMS FOR MEDIUM-RANGE AIRCRAFT FROM A MAINTENANCE POINT OF VIEW

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Abstract

The use of a hybrid electric propulsion system for aircraft offers the potential to increase aircraft efficiency, reduce fuel consumption and thus reduce emissions. Design concepts, emission analysis and aircraft performance are being studied extensively. However, how future hybrid electric propulsion systems will change the maintenance, repair and overhaul (MRO) of an aircraft is also an important consideration. This paper examines the effects of hybridisation on a parallel hybrid electric propulsion system of a medium-range aircraft, the Airbus A320, powered by an IAE V2500 engine. The electric motor is powered by a battery and is used to assist the turbofan engine, mainly during the takeoff phase. The additional system components of the chosen hybrid electric propulsion system and their corresponding damage mechanisms are addressed from a maintenance point of view. Challenges for future maintenance are discussed and possible failure modes and failure possibilities are analysed. For this purpose, a Failure Mode and Effects Analysis and a Fault Tree Analysis will be carried out. The results of this analysis can be used to determine how the additional components need to be designed to maintain the overall safety of the propulsion system at the current level. This will also provide needs and ideas for a future design for maintenance.

Keywords
Hybrid electric aircraft; Failure modes, Maintenance; FMEA; FTA; Design for Maintenance

NOMENCLATURE

Symbols

P_{EM}	Power of the electric machine	MW
Δ SVR	Delta shop visit rate	%
Δ TIT	Delta turbine inlet temperature	K

Abbreviations

AC	Alternate Current
BMS	Battery Management System
D4M	Design for Maintenance
DC	Direct Current
DfM	Design for Maintenance
EASA	Electrical Apparatus Service Association
EGT	Exhaust Gas Temperature
EMI	Electromagnetic Interference
EWIS	Electrical Wiring Interconnect System
FADEC	Full Authority Digital Engine Control Machine
FMEA	Failure Mode and Effects Analysis
FTA	Fault Tree Analysis
GaN HEMT	Gallium Nitride High-Electron-Mobility Transistor
IGBT	Insulated Gate Bipolar Transistor
LLP	Life-Limited Part
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
MRO	Maintenance, Repair and Overhaul
PCB	Printed Circuit Board
PMSM	Permanent Magnet Synchronous Machine
RPN	Risk Priority Number
SoC	State-of-Charge

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SoH	State-of-Health
SVR	Shop Visit Rate
TIT	Turbine Inlet Temperature
VDA	Verband der Automobilindustrie e.V.

1. INTRODUCTION

Minimising the impact of climate change and reducing the use of fossil resources is a focus of current research and development. The European Union declared environmental targets in its Flightpath 2050 to reduce CO_2 emissions by 75 % per passenger-kilometre, to reduce NO_x emissions by 90 %, and achieve emission free taxiing as well as recyclable aircraft [1].

A technological revolution is therefore needed in aviation, with increased use of electrical energy. There are already a number of concepts, ranging from more electric aircraft (MEA) to all electric aircraft (AEA). This paper focuses on a parallel hybrid electric propulsion system for the Airbus A320 medium-range aircraft powered by an IAE V2500 engine.

This work considers the individual components of the electric drive train in more detail in order to provide an overview and introduction to the various and extensive disciplines from a maintenance perspective. A technology assessment of the key components and a description of their damage types and mechanisms provides information on necessary maintenance measures. Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) are performed to identify system critical components following the procedure of [2]. The results of all sections are incorporated into a Design for Maintenance (D4M) discussion.

2. HYBRID ELECTRIC PROPULSION SYSTEMS FOR MEDIUM-RANGE TURBOFAN AIRCRAFT

To provide a comparability, the following section regards concepts which include turbofan propulsion systems that are supported, complemented or extended by an electric drive train and thus by an additional type of energy source. In this case, the energy sources are a conventional kerosene (chemical energy) powered turbofan and a battery (electrochemical energy) powered electric motor. As more than one energy source is involved in the propulsion system, it is called a hybrid system [3]. The way the two energy sources are coupled together determines whether the system is serial, parallel or mixed, compare with fig. 1 and the following sections.

2.1. Serial propulsion systems

In serial propulsion systems, thrust is generated solely by an electric motor-driven fan or propeller. The electrical energy is provided by batteries charged by a gas turbine driven generator [3–5]. In this configuration, the gas turbine can be operated independently of the fan speed and thus at its maximum efficiency [3, 6]. Because the fans or propellers are electrically driven, they are flexible in shape, size and position [6]. On the other hand, the components of the electric drive train have to be configured for maximum thrust, resulting in a higher weight of the electric motor and power electronics [7]. An example of a serial propulsion system is the N3-X hybrid-wing-body aircraft concept. 14 distributed fan propulsors are driven by electric motors. The electrical power comes from generators driven by turboshaft engines [8, 9].

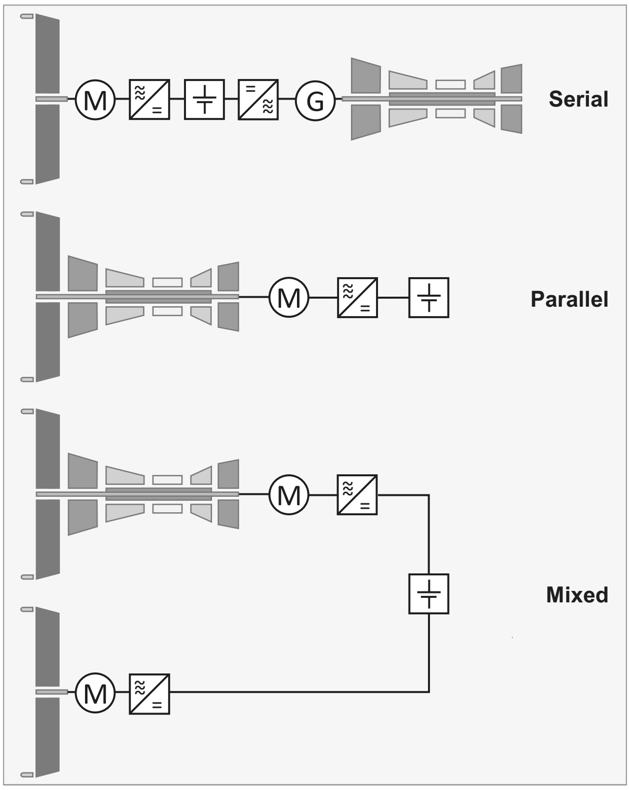

FIG 1. Hybrid electric propulsion system concepts for turbofan aircraft.

2.2. Parallel propulsion systems

In parallel propulsion systems, thrust is generated by parallel power paths that are mechanically coupled. In the parallel hybrid turbofan engine, a conventional turbofan engine is complemented by an electric motor mechanically coupled to the low-pressure shaft [3–6, 10]. In this configuration, the turbofan engine can be optimised for cruise flight. Additional thrust required for take-off or flight manoeuvres is generated by the electric motor, which is powered by a battery. A major disadvantage of this hybrid concept is that the electric motor is coupled to the engine shaft and therefore the gas turbine engine is directly influenced. This can lead to inefficient partial load operation of the gas turbine engine [7].

An example of a parallel hybrid system is the Boeing SUGAR Volt concept: Two turbofan engines are electrically assisted by battery-powered electric motors coupled to the low-pressure shafts of the turbofan engines [8].

2.3. Mixed propulsion systems

Mixed propulsion systems include serial as well as parallel propulsion system configurations. This allows for several possible configurations and further opportunities to optimise engine performance in different operating segments [3, 5]. Fig. 1 shows only one possible configuration. An example of a mixed propulsion system is the E-Fan X project: In a test aircraft, one of four existing turbofan engines is replaced by a 2 MW electric motor [11]. In another conceptual study, a mixed propulsion system was selected as a retrofit for an Airbus A320-200 aircraft [12].

3. NEW CHALLENGES FOR MRO

The addition of an electric drive train to a medium-range aircraft can serve to augment the takeoff and climb phases, resulting in fuel savings and less jet engine load. The required batteries can be recharged on the ground and in flight, or exchanged during the ground phase. It is predicted that, under certain conditions, the use of hybrid electric propulsion systems can reduce turnaround time due to an optimised battery exchange process and reduce refuelling time due to a reduced amount of kerosene required [13]. Further fuel savings are possible during the taxi phase of the aircraft if the landing gear is electrified [13, 14]. However, new aircraft propulsion concepts lead to new requirements in aircraft operation, airport infrastructure, ground handling, increased electrical power demand, turnaround time, etc. Aircraft operations, for example, are affected by the need for new cockpit concepts, crew training or safety instructions. Airport infrastructure and ground handling are considered in [13].

In addition, the use of hybrid electric propulsion systems brings new challenges for maintenance, repair and overhaul (MRO). An overview of the most essential affected fields is given in fig. 2. A further overview with a focus on mapping the needs of a design for maintenance in electric aviation is given in [15]. The introduction of new systems requires new inspection and repair methods, or rather processes, supported by quality management. Thus new certified equipment, tools, maintenance manuals and instructions are required. To repair or replace parts, additional spare parts and storage capacity is required. These, and the need for additional shop areas place demands on the facility's infrastructure. Finally, suitable and trained staff must be available. Additional training and adapted certification procedures for aircraft mechanics are mandatory [16], especially for work on high-power propulsion components. Detailed regulations can be found in EASA Part-145.

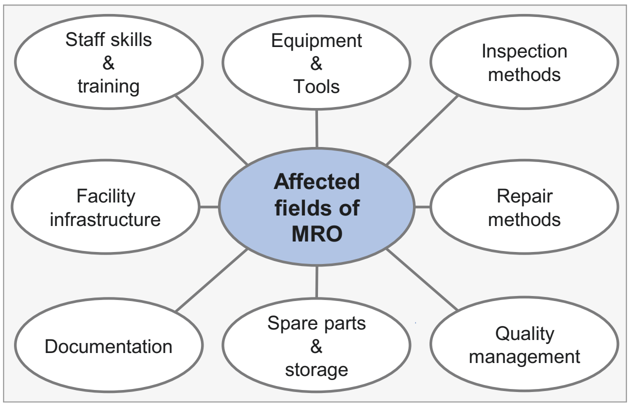

FIG 2. Affected fields of MRO as a result of aircraft electrification.

4. IMPACT ON ENGINE LOADS

Aircraft engines are subject to gradual wear during operation. Mechanical stresses, thermal loads, erosion, fouling and corrosion lead to increased clearances, changes in aerodynamic geometries and ultimately to an overall reduction in engine performance as measured by an increase in exhaust gas temperature (EGT). As the degradation rate is highly dependent on operational factors various models exist for the correlation of MRO-metrics to utilisation. Typically, degradation effects show a distinct correlation with the number of engine flight cycles rather than flight hours, as the highest loads occur during take-off at maximum thrust setting and atmospheric pollutants such as particulate matter, salt or chemical concentrations are particularly pronounced at low altitudes [17].

One parameter that has a certain degree of freedom is the actual thrust at take-off and during climb by using thrust reductions. This is possible whenever the combination of take-off weight, runway length and ambient conditions do not demand maximum thrust. This is a common practice for extending service time. By applying thrust reductions, peak temperatures are decreased and operating time in critical corrosive temperature regimes can be reduced. This increases service life and reduces maintenance costs and can be quantified by empirical models from the evaluation of engine fleets.

A similar trend is observable in parallel propulsion systems. Due to the electric assistance of the low-pressure shaft, the core engine is less loaded, leading to reduced thermal stress. Fig. 3 (left) shows the reduction in peak turbine inlet temperature (TIT) at take-off at various power settings of the electric machine. The results are obtained from an in-house thermodynamic performance calculation tool of a V2500 turbofan engine, which is adapted to a parallel hybrid-electric propulsion system [18]. With an electric assistance of 1, 2 and 3 MW TIT can be reduced by 9, 18 and 34 K, respectively. Furthermore, the variation in TIT can be correlated to changes in shop visit rate (SVR) of conventional turbofan engines operated at different thrust settings. The SVR expresses the total number of engine removals experienced for every 1000 hours of engine operation. Here, data of CFM56-3 engines is used, which are operated at similar thrust levels as the reference engine [19]. The results are shown in fig. 3 (right). The analysis suggests, that SVR can be decreased by 4 to 13 %, based on the reference value of a conventional turbofan engine in short-haul operation on a narrow-body aircraft. Secondary effects, such as higher thrust demand due to weight penalties of the electric components, as well as service life of the electric components themselves are so far missing and have to be included in future studies.

Nevertheless, without further adaptations to the turbofan engine, the service life of the turbomachinery is probably increased due to hybridisation [20]. In this constellation, the turbofan engine would contribute to the system's resiliency as the turbofan keeps the ability of generating full rated thrust without any electric assistance. Another possible scenario is the adaptation of the turbofan engine to hybridised operation, where the thermodynamic cycle is increased to higher temperatures in order to exploit higher thermal efficiencies. In this case, the maintenance intervals could be similar to those of conventional aircraft engines, with a less pronounced influence of the take-off phase due to the electric assistance at high loads.

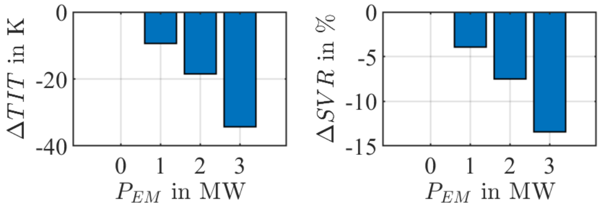

FIG 3. Influence of hybridisation on turbine inlet temperature (left) and shop visit rate (right).

5. ELECTRIC DRIVE TRAIN - DAMAGES AND FAILURES

The addition of an electric drive train unavoidably increases system complexity, which can lead to an increased risk of failure. Therefore, the added components are discussed below in terms of their types of damage or failure mechanisms.

The electric drive train consists primarily of an electric motor, power electronics and a battery. In terms of maintenance, the wiring and connectors, mechanical coupling, control systems and sensors also need to be examined.

Technological considerations are made and damage and failure modes are surveyed for each component of the electric drive train. Based on this, possible maintenance measures for MRO are derived. Task intervals and required maintenance man hours are not considered in this work. Finally, the failure rates of the components are estimated based on the literature.

General assumptions or simplifications to determine failure rates for the basic failure events are:

- All failure rates are assumed as constant.
- All failure rates are taken from literature and data banks.
- The turbofan engine, the full authority digital engine control machine (FADEC) and the cooling of the electric machine are regarded as a single component.
- Due to the early concept phase, simplification takes place throughout the safety analysis.
- The topology of power electrics is not specified yet. Due to the early concept phase a conservative approach is followed.

The failure rates are listed during this work. All researched failure rates including references can be found in the appendix.

5.1. Electric machine

At the top level, electric machines can be classified into direct current (DC) and alternate current (AC) machines. The latter can be classified according to the number of phases or according to synchronous and asynchronous machines. In order to select the most promising machine, main requirements for an electric machine for aviation purposes have to be satisfied: High efficiency, thermal robustness and high power density. A detailed analysis of different technologies for very light, high performance electric drives has been published in [21]. The conclusion was that a permanent magnet synchronous machine (PMSM) or an induction machine with a squirrel cage rotor are the most promising types. A conceptual study results in a 2 MW inner rotor PMSM [22].

An example of a future electric motor is the Siemens SP2000D, which is designated to the E-Fan X project [23]. It provides a power of 2 MW and a power density of 7.7 W/kg. The machine is directly liquid-cooled, which is required for high power density [6, 21].

It is conceivable to integrate the required control units of the electric machine into the existing FADEC unit of the turbofan engine.

5.1.1. Electric machine failure

Failures in electric machines can be classified according to the generating stress mechanism (electrical or mechanical) or according to the location of the fault (bearing, stator or rotor). The latter classification is used in several publications to show the fault distribution in more detail. In [24] a relationship between the fault distribution and the type of electric machine is shown. The used data is based on [25–28]. While low voltage machine failures are mostly caused by mechanical stress inside the bearings, high voltage machine failures are mostly caused by defects inside the stator, see fig. 4. This is due to the change from sleeve bearings to roller bearings, which results in a reduced degradation process.

Bearing failures result in increased vibration and noise levels or, in the worst case, can cause the rotor to lock.

Bearing failures are caused by contamination and corrosion, improper lubrication or improper installation, see [29].

Failed stators and rotors are mostly due to winding failures. An illustrated overview of winding failures is given in [30]. The causes of winding failure can be manifold, ranging from winding connections, phase damage, failed insulation, locked rotor, which in turn can be caused by poor connections, broken power lines, contaminants, abrasion, vibration, voltage surge, unbalanced voltage and overload.

Furthermore, cooling has a special importance for the motor. If it fails, the motor will overheat. Due to the moving parts in the pumps of the cooling systems, it is prone to failure mechanisms such as fatigue and wear [2].

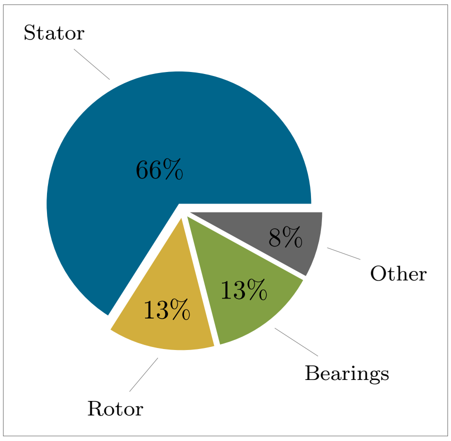

FIG 4. Failure distribution in high voltage electric machines following [24]

5.1.2. Electric machine failure rates

It is reasonable to specify the failure rates according to the type of failure mechanism. Electric machine failures are mainly caused by windings, bearings and cooling. The failure rates used in the FTA are given in tab. 1.

TAB 1. Failure rates of the electric machine for the FTA

Component	Failure rate λ [1/h]
Winding	6,25E-07 [31]
Bearing	1,70E-06 [31]
Cooling	6,04E-05 [32]

5.1.3. Electric machine maintenance measures

During operation, monitoring the condition of a system is a requirement for condition based or predictive maintenance. The following surveys provide an overview of current technologies for condition monitoring of electric motors [24–26, 29].

The Electrical Apparatus Service Association (EASA) has published a standard [33] which gives recommended practices for the repair of rotating electrical apparatus. According to these standards a condition monitoring or replacement at regular intervals for high-speed bearings was recommended by technicians in an interview [16]. In addition, a visual inspection at regular intervals is required and maintenance tasks such as lubrication of the bearings, inspection and cleaning of the coolant air ducts, runout checks, dynamic balancing and disassembly of the motor unit were mentioned. After removal, the motor has to be overhauled in a dedicated accessory shop.

5.2. Power electronics

Power electronics serve to control and convert electric energy efficiently and reliably to the consumer needs. This is enabled by the conversion of electrical energy in terms of the voltage form, the level of voltage and current, and the frequency. The main functions of power electronic systems can be rectification, conversion, inversion and variable frequency inversion. Various components such as MOSFET (Metal Oxide Semiconductor Field Effect Transistor), GaN HEMT (Gallium Nitride High-Electron-Mobility Transistor) or IGBT (Insulated Gate Bipolar Transistor) are used as electrical valves. These components are then combined with passive elements such as resistors, inductors and capacitors to perform specific functions [34]. In contrast to the parallel hybrid system in fig. 1, the electric drive train presented here uses an inverter to supply the electric motor with energy from the connected battery.

Due to weight and space constraints in aircraft, high power density is required for the power electronics. To achieve this, the inverter needs to work at high switching frequencies. If the power electronics are installed close to the engine, they must also be highly temperature resistant. The specified requirements can potentially be fulfilled by SiC MOSFET technology [3, 35, 36]. A comparison of the potentials of different SiC MOSFET topologies for AEA is presented in [37]. However, SiC MOSFETs pose special demands on the layout and electromagnetic interference (EMI) filter due to higher harmonic frequencies. In addition, SiC MOSFETs have a lower short circuit withstand capability and increased sensitivity to long cables between the inverter and the load, as this can lead to overvoltages due to the short rise time of the SiC MOSFET [36].

5.2.1. Power electronic failure

Failures of power semiconductors, which are the main components of power electronics, are classified into either chip level or package level failures [38]. The basic failure modes are open circuit, short circuit and parameter drift [2]. Open and short circuits are difficult to predict and lead to spontaneous failure. Parameter drift occurs from long-term degradation, a so-called wear-out failure. But all have the same failure mechanisms. Most common are bond wire lift-off, baseplate solder joints cracking or chip solder joints cracking [39]. These failures are caused by (cyclic) thermal loads, mechanical loads, EMI, cosmic

radiation, pollution, humidity or overstress (e.g. overvoltage, lightning) [38, 39].
A survey [38] shows that thermal stressors are considered the most critical for power electronics. Mechanical stressors such as vibration or shock are also critical for electric vehicle and drive train applications. In particular, the combination of thermal and mechanical stresses increases solder crack propagation on printed circuit boards (PCBs).
Cosmic radiation, which is a concern for space or aviation applications, can cause single event burnouts in power semiconductors [38, 40]. Detailed failure mechanisms and test procedures are described in [41] and [42].
According to [43], the failure distribution of power electronic components can be seen in fig. 5. According to the survey in [38], capacitors, PCBs and semiconductors are considered to be the most vulnerable components.

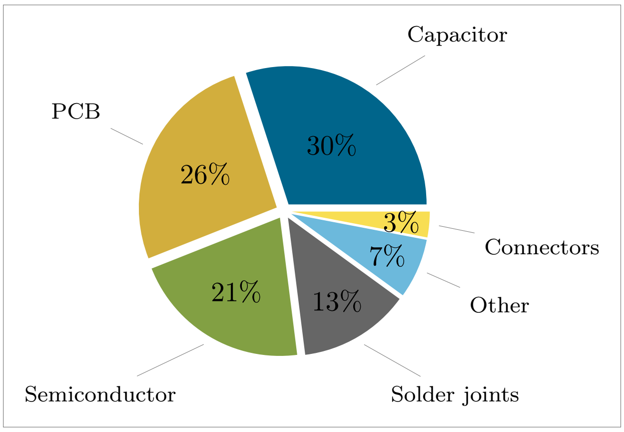

FIG 5. Failure distribution in power electronic components following [43]

5.2.2. Failure rates of power electronics

Although [39] points out that the use of constant failure rates is considered inappropriate from today's point of view, because there are more accurate methods available in the meantime, constant failure rates are still used in this work due to a lack of data. The failure rates used for the FTA are listed in 2.

TAB 2. Failure rates of the power electronics for the FTA

Component	Failure rate λ [1/h]
Semiconductor	4,16E-08 [44]
Capacitor	3,49E-07 [44]

5.2.3. Power electronic maintenance measures

To avoid catastrophic failures such as open and short circuits, power electronic components should be operated within their load limits. In addition, condition monitoring methods should be used to predict the onset of failures due to degradation. It also serves to increase the reliability and to schedule maintenance measures [38]. Scientific contributions from the field of photovoltaic systems show possible methods for determining reliability [45] and for maintenance planning based on wear-out failures of power electronic converters [46].
Since repairs of electronic components are very complex, it does not seem practical to perform an on-wing repair. Instead, the device should be replaced to evaluate its reparability in the shop. In addition, replacement is more cost effective and the aircraft has less downtime. The IPC-7711C/7721C [47] standards can be used to guide the repair process.
In the following, some options to increase the reliability of power electronics are given. Thermal loads, and especially cyclic thermal loads, are critical to power electronics, so active thermal control is necessary. Devices should be protected from humidity, as this can cause corrosion and leakage currents. To avoid EMI, the density of electrical devices must be reduced and adequate protection provided [38].

5.3. Battery

The most important battery parameters for mobility applications are the gravimetric and volumetric energy density as well as the power density, which define the range and the maximum available power of the vehicle. Further relevant parameters are the number of charging cycles, which is related to the performance degradation over the battery lifetime, and maximum charging rates. An important conceptual difference in electrified aircraft designs is the charging procedure. While in some concepts batteries are charged at the gate [48–50], in others they are exchanged between flights [13, 51] to mitigate the problem of insufficient charging rates and to reduce turnaround times.
The majority of electrified aircraft concepts use lithium-ion technology for carbon free energy storage. The main drawback of using advanced lithium ion batteries in the propulsion system is their relatively low gravimetric and volumetric energy density compared to kerosene. In addition, current lithium ion technology is likely to soon reach its theoretical limits in terms of energy density. A promising alternative for future aviation is lithium sulphur batteries, which potentially offer higher energy densities [52]. However, they are still at a low level of maturity and suffer from low battery lifetime and charging rates. An emerging area of research is also the development of all-solid-state batteries, which are non-flammable and therefore provide a much higher level of safety [52].

5.3.1. Battery failure

Relevant failure mechanisms for lithium ion batteries in aircraft applications have been studied by many authors, see e.g. [53–55]. Sripad et al. [53] categorise safety concerns into thermal and functional issues. One of the most important hazards is thermal runaway, which is a self-sustaining increase in temperature and pressure within the battery cells that can lead to fire. Thermal runaway can be caused by overcharging, undercharging or internal short circuits. The task of ensuring charging and discharging processes and operation within the limits of the operating parameters belongs to the battery management system (BMS). Functional issues, which can also lead to immediate critical loss of power supply are caused e.g. by loss of contact within a cell or between cells or by failures within the state-of-health (SoH) and state-of-charge (SoC) monitoring. Slow chemical or electrochemical effects lead to a gradual loss of power in the long term [53]. Thermal hazards could be strongly mitigated by all-solid-state batteries [52].

5.3.2. Battery failure rates

The data are taken from the automotive industry [56], as they have more experience with batteries than aviation. Due to the high safety requirements in aviation, a conservative approach is assumed. It is expected that the BMS will be integrated into the FADEC or meet similar safety standards. To this end, the same failure rate as the FADEC is used. It follows the conservative approach of Schild et al. [2]. The failure rates for the sensors are based on Schild et al. [56], because the failure rates from Quanterion [57] apparently don't consider the different sensor mechanisms. The failure rates used in the FTA are listed in 3.

TAB 3. Failure rates of the battery used in the FTA

Component	Failure rate λ [1/h]
Battery cell	2,40E-06 [56]
Connector	2,96E-07 [56]
Fastening Screw	1,02E-06 [57]
Signal connector	4,39E-07 [56]
BMS	1,00E-06 [2]
Power device	4,09E-06 [57]
Curent sensor	2,00E-06 [31,58]
Voltage sensor	1,80E-06 [31,58]
Temperature sensor	1,70E-06 [31,58]

5.3.3. Battery maintenance measures

Regarding maintenance measures, the implementation of SoH and SoC monitoring is mandatory. Naru and German [16] have identified additional expected challenges associated with batteries from a maintenance point-of-view. Although they focus on urban air mobility, many aspects are also applicable to commercial aircraft. New inspection and repair protocols, as well as specific training, will be required for the safe operation of high-voltage batteries. Inspection and possible replacement of individual battery cells is expected to be labour intensive and may only be possible in specialised shops. Removal or installation of batteries results in wear-out of contacts and involves the risk of damages due to shocks or accidental fouling of connectors. An additional aspect regarding maintenance is the substantial mass of the batteries, which in some concepts significantly exceeds the 10-ton mark and therefore requires special gear for handling [13].

5.4. Electric grid

The installation of an electric drive train inevitably requires the use of additional electric wires, connectors, switches, etc., which have to be integrated into the existing Electrical Wiring Interconnect System (EWIS) of the aircraft.
A look at the Siemens SP2000D electric motor proposed by the E-Fan X project already indicates increased demands on the power supply system, as the motor requires 3,000 VDC [23]. Analyses in [50, 59] concluded that the high energy demand can only be met by switching from a conventional AC system to a high-voltage DC system to achieve higher power transfers. Among others, an important component of the EWIS is the circuit breaker, whose function is to prevent damage by disconnecting the circuit in case of malfunction. Requirements for circuit breakers and a comparison of technologies are given in [50]. The most promising technology for high-voltage DC systems is the hybrid circuit breaker.

5.4.1. Electric grid failure

Because all EWIS components are considered as electrochemical devices, they are prone to moving surfaces, wear out, as well as general wear and tear, especially during maintenance actions [60]. Repair measures, if they are not carried out carefully, can result in subsequent faults. They are the reason for 80 % of induced faults in wires [61].
Failures in EWIS are additionally caused by ageing and degradation due to mechanical, electrical, thermal or chemical stress. This can lead to corrosion, degraded insulation, arcing (wet, dry and series), contact fretting, etc. [60, 61].
The consequences are mostly critical and can lead to loss of critical functions in equipment, loss of energy and information transfer, loss of system redundancy and smoke or fire [62]. The failure distribution in the EWIS for ageing aircraft in fig. 6 shows that wires are the most critical component in the EWIS.

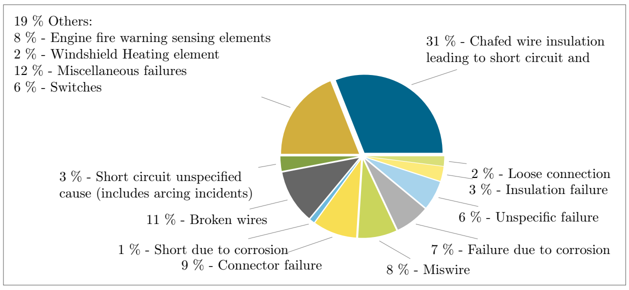

FIG 6. Failure distribution in EWIS for ageing aircrafts in 1997-2001 following [63]

5.4.2. Electric grid failure rates

For the initial consideration under the term EWIS, the wiring, contacts as well as the hybrid circuit breaker are taken into account. For the hybrid circuit breaker, the value of a circuit breaker is used. This serves for the conservative approach. The values of the failure rates used in the FTA are visible in tab. 4.

TAB 4. Failure rates of the electric grid used for the FTA

Component	Failure rate λ [1/h]
Wiring	6,81E-07 [57]
Contacts	4,44E-08 [57]
Hybdrid Circuit breaker	4,94E-09 [57]

5.4.3. Electric grid maintenance measures

The fact that maintenance actions are considered a critical cause of failure in EWIS suggests the need for improved training. This statement also appears in the interview by Naru et al. [16] and the report by [62]. The latter states that improved training should generate increased awareness of potential consequences of drill shavings, metal debris in bundles, nicks, cuts and shaves in wire insulation, etc. on the wire system.

EWIS components are usually difficult to access and repair is extensive, since e.g. the wires are routed through the entire aircraft in tightly bound harnesses. Visual inspection is of particular importance, since even the slightest damage to the wire insulation can result in critical damage when the next stress is applied.

A comprehensive guideline for the inspection of the EWIS can be found, for example, in MIL-HDBK-522 [64]. Standard practices for maintenance of aircraft electrical wiring systems can be found in ASTM F2799-14 [65].

A replacement of EWIS components or subsystems has to be carried out, if their designed lifespan is exceeded [60].

5.5. Mechanical coupling

In current two-shaft engines, mechanical energy transmission from a starter motor (electric motor or air-start motor) to the high-pressure shaft is common practice. The starter motor is connected to the accessory gear box of a turbofan engine. One or more transfer gear boxes transmit the driving force to a radial drive-shaft, which is connected to the high-pressure shaft by a bevel gear. One example where mechanical energy is transmitted between the gearbox and low-pressure shaft is the Rolls-Royce RB163 Spey [66].

An advantage from extending the engine by an electric machine is the possibility of substituting the starter motor whereby the system complexity can be decreased.

A conceptual study carried out by Seitz et al. in [22] comes up with the promising solution of mounting the electric motor inside the fan hub. Therefore, a 2 MW inner rotor PMSM is selected and the rotor is designed to be connected to the low-pressure shaft. The electric motor has to be a tailored body to locate it inside the spinner cone, compare with fig. 7.

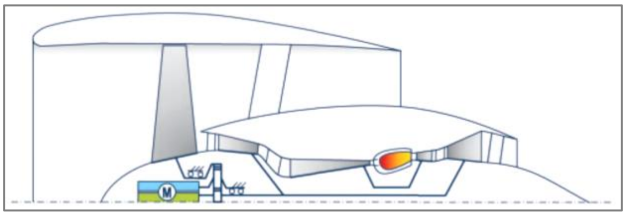

FIG 7. Electric machine (symbol M) integrated in fan hub, rotor connected to low-pressure shaft [22]

Regardless of whether the drive is direct or geared and regardless of whether power transmission has to be carried out in only one or both directions, an implemented clutch must enable mechanical decoupling in the event of a malfunction so that the two drive trains cannot negatively influence each other. The possibility of decoupling (active or passive) of the electric drive machine would increase the safety rating.

5.5.1. Coupling failure

This work focuses on the use of a direct drive so that the damage mechanisms of gearboxes are eliminated. Nevertheless, an overview of failure mechanisms leading to gear wear is given in [67] and a review of monitoring and prediction techniques in [68].

Potential failures are therefore reduced to the mounting and the clutch of the electric machine. These components must then absorb gyroscopic and inertial loads [22] and are therefore prone to fatigue failure.

5.5.2. Coupling failure rates

The failure rate used for the clutch is based oo ground applications in the industry, therefore a conservative approach compared to the aviation industry is assumed. The mounting is assumed to be a bolted connection. The failure rates used in the FTA are shown in the tab. 5.

TAB 5. Failure rates of the coupling used in the FTA

Component	Failure rate λ [1/h]
Safety Clutch	1,22E-06 [69]
Mounting	4,09E-06 [57]

6. SAFETY ANALYSES

The following safety analyses are intended to identify possible system vulnerabilities at an early stage. The system described in this paper is at an early concept phase, any results can therefore only be considered as initial indications. However, the results are sufficient to allow appropriate measures to be considered even well in advance of the design phase in order to increase reliability, maintainability and availability. The Failure Mode and Effects Analysis (FMEA) and the Fault Tree Analysis (FTA) were identified as most promising methods for this purpose. Due to the early concept phase, significant simplifications have been applied to FMEA and FTA. This section defines assumptions that apply to both. The system boundaries involve a single (not both sides of the aircraft) hybrid electric drive. Possible redundancies due to an additional hybrid electric drive are not considered. The aim is to present a complex system in a simplified and tangible way.

In addition, the turbofan engine and the FADEC system are each regarded as a closed system component. In consequence, failure rates for the FTA are given for component level, compared with tab. 6. For the turbofan, the required failure rate given in the Advisory Circular 25.1309-1A [70] has been assumed and for the FADEC the approach of Schild et al. and Hjelmgren is followed [2, 71].

TAB 6. Failure rate of the turbofan engine and FADEC grid used for the FTA

Component	Failure rate λ [1/h]
Turbofan Engine	1,00E-09 [70]
FADEC	1,00E-06 [2, 71]

6.1. Failure mode and effects analysis

The FMEA is based on a template from the VDA (Verband der Automobilindustrie e.V.). After defining the scope of the FMEA, it is necessary to define the system structure. Here, the system is divided into the following main components: Turbofan, FADEC, electric machine (bearing, winding and cooling), inverter (semiconductor and capacitor), the battery (lithium ion battery, thermal management and BMS), EWIS (wiring, contacts and circuit breaker) and mechanical coupling (mounting and safety clutch).

In preparation for the FMEA, the functions of each system component are specified. For each function, possible errors, error consequences and error causes are determined. For a subsequent assessment, the significance of the failure sequence, the probability of failure occurrence and the probability of failure detection are rated from one to ten to calculate a Risk Priority Number (RPN) for each failure.

Calculated values of the RPN are visualised in the bar diagram of fig. 8. For reasons of simplicity, the individual functions are not shown in a differentiated manner, but they are represented collectively by the respective components. The highlighted limit value of RPN 100 represents a limit from which the result of the FMEA indicates an increased need for action for the component under consideration.

Although the diagram is simplified, critical components can be identified with the help of the threshold value: The windings of the electric machine, the inverter, the lithium ion battery, BMS as well as wiring and contacts of the EWIS. The windings are critical because of the difficult detectability of possible short circuits. The results for the inverter clearly show the need for action. One possible measure would be to provide redundancies to cover possible failures. The result for the battery is mainly driven by the risk of failure of the charging and discharging capability, as well as circuit interruptions, e.g. due to short circuits. Critical failures in the BMS are the incorrect determination of condition parameters and the disturbed or interrupted communication with other systems. For EWIS, open circuits and interrupted contacts are critical. Failures that may occur as a result of a maintenance procedure being performed are especially relevant.

The focus of the risk prioritisation is to identify potential vulnerabilities, resulting in components and their functions with an RPN > 100. The result of the analysis performed is of a simplified nature and the analysis requires further iteration steps and a more detailed view of failure mechanisms and their severity as the design process progresses. The weakness of FMEA is its subjectivity and level of detail at this early concept phase. However, it shows that critical components can be identified at an early stage to initiate further investigation.

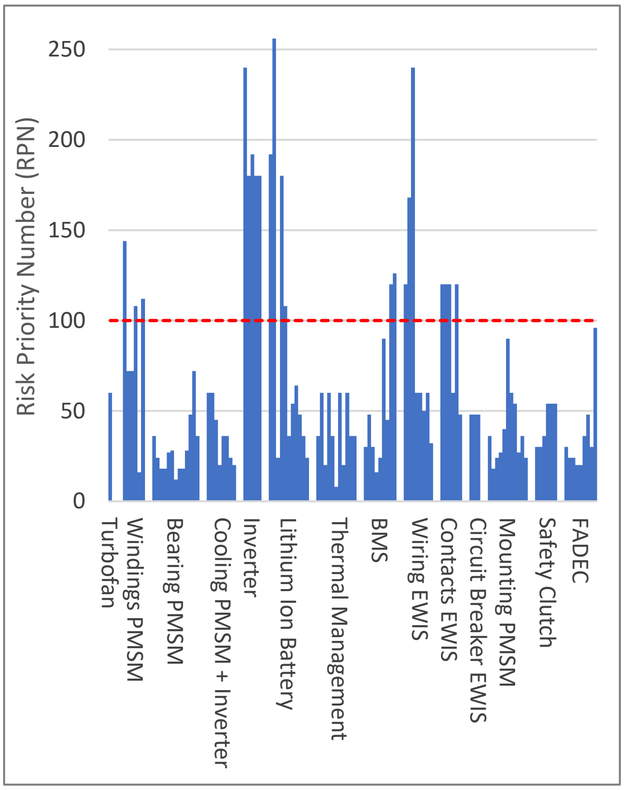

FIG 8. Visualisation of FMEA results, regarding the risk priority number (RPN)

6.2. Fault tree analysis

The FTA takes into account previous investigations. On the one hand, Schild et al. [2] examined an electric drive train in the context of a serial hybrid electric aircraft propulsion system, and on the other hand, Shu et al. [56] carried out a reliability study of a battery in an automotive context. For analysis, the different sub components respectively functions are linked by AND gates and OR gates. In the case of the AND gate, all sub-components must fail for a complete failure of the component. In the case of the OR gate, the failure of a single sub component leads to the complete failure of the component.

The developed scheme of the FTA is shown in the appendix in fig. 9. Due to the complexity of the propulsion system and the early concept phase simplifications are made. The topology of power electronics is unknown, therefore not considered. The cooling is viewed as a complete system and not broken down to the sub-components. The lack of fitting failure rates leads to assumptions and simplifications. All failure rates are taken from literature and databases. All researched failure rates are summarised in the appendix tab. 7.

The total loss of thrust is defined as the main system failure. From top to bottom the structure comprises the turbofan engine, the FADEC as well as the combination of mounting of the electric drive and the electric drive itself. A failure occurring in the FADEC leads to a loss of control in both systems, the turbofan engine and the electric drive train. The latter one is defined as the combination of the safety clutch as well as the loss of thrust by the electric drive, which are linked with an AND gate. This gate was chosen because the top event only occurs if the rotor of the electric machine blocks and the safety clutch fails at the same time. In this case, the output failure can propagate to the turbofan engine. Another case that can lead to a total loss of thrust is the failure of the electric machine's mounting. In any other case, only a partial loss of thrust occurs.

The loss of thrust of the electric drive is defined as the combination of the electrical machine (winding and bearing), the cooling, the inverter (semiconductor and capacitor), battery (battery system, battery module and condition monitoring) and the EWIS (wiring, contacts and hybrid circuit breaker). It can be seen by the OR gate in the FTA that for the loss of thrust of the electric drive train, all sub-components are equal in significance. Comparing the failure probabilities calculated and assigned by means of FTA, the very low failure probability of the electric drive is noticeable. This result is based on the used AND gate, which significantly improves the system reliability.

For the main components of the electric drive train, high failure probabilities can be determined for the cooling system and the battery. The first one is based on the use of mechanically moving parts inside the pumps. The second one is based on the high system complexity, which is accompanied by a large number of possible failure sources.

The result of the FTA primarily represents a recommendation to take a closer look at the future use of a safety clutch (active as fail-safe or passive), as this can counteract a negative influence on the turbofan engine in the event of faults occurring within the electric drive train.

7. DESIGN FOR MAINTENANCE

Design for Maintenance (D4M) summarises efforts to reduce the cost of scheduled and unscheduled maintenance events during the design phases. There is no single definition of D4M, but according to Mulder et al., the term includes the aspects reliability, maintainability and supportability [72]. While more reliable systems increase the maintenance intervals necessary to ensure safe operation and reduce the number of failures, maintainability describes the ease of conducting the checks [72]. Supportability influences how easily logistical resources are available at the right location and timing [72]. Maintenance costs contribute between 10 to 30 % of the aircraft's direct operating costs [73–75]. Even though these costs arise in the operation of an aircraft, 95 % of all life-cycle costs are determined by the end of the design phase [76]. Therefore, it is crucial to include maintenance considerations in design to reduce life-cycle expenditure.

Aircraft systems are developed in accordance with SAE ARP 4754A and ARP 4761, which ensure safe design but do not include maintenance considerations [77, 78]. Once the design phase is completed, maintenance tasks and intervals are determined according to the principles of reliability centered maintenance [79]. The process adapted for aviation is the MSG-3 analysis, which provides guidance to an expert board to establish maintenance tasks and intervals in a two-step approach [80].

One challenge is the wide range of different options for implementing D4M, such as whether it is more reasonable to improve maintainability or focus on a more reliable system for longer maintenance-free periods. A further hurdle is the time lag between design and maintenance estimation, which means that system designers do not know how their design decisions will ultimately affect maintenance tasks and the resulting life-cycle costs.

Based on this work and considering the hybrid electric propulsion system, initial demands can be derived for the PMSM, the inverter power electronics and the EWIS.

7.1. D4M - Electric machine

The electric machine must be positioned in such a way that it is protected from external heat input from the turbofan engine (e.g. in front of the compressor section) [7, 81]. Seitz et al. compared different positions of the electrical machine. The most promising solution is to place the machine in the fan hub, where the inner rotor of the electric machine is connected to the low-pressure shaft [22]. From an MRO point of view, it seems reasonable because this solution improves the accessibility of the electric machine [22]. For the cooling system, a direct liquid-cooled winding is intended to avoid overheating. Recommendations for the design parameters to be applied are given in [21] to achieve increased reliability. For further reduction of the general system complexity, the starter motor can be substituted by the electric machine.

7.2. D4M - Power electronics

The result of the FMEA already shows the need for a closer look at this component in terms of reliability, maintainability and supportability. Due to the difficult reparability of power electronics, it is highly recommended to achieve a high level of accessibility and interchangeability. Redundancy is mandatory to increase reliability.

Accessibility is achieved with the electrical machine positioned in the fan hub. Scheduled exchange will probably be the main task in MRO, repairing the power electronics on wing will not be the preferred solution. The power electronics can be mounted on the outer surface of the electric machine, on the one hand to minimise wire lengths for increased effectiveness [22], and on the other hand to share the cooling system with the electric machine for reduced complexity. A technological overview of the thermal management of so-called integrated motor drives is given in [82]. Finally, adequate protection against humidity, corrosion and cosmic radiation is required [38, 50]. In addition, thermal management is required to avoid extensive cyclical thermal loads on the power electronics.

7.3. D4M - Battery

Due to the size, weight and position in the lower fuselage [13], new concepts for MRO have to be developed. Feedback from aircraft maintenance technicians suggests that they prefer battery systems that are modular and hand removable for maintainability [16]. Discussions for complete battery replacement are given in Schmidt et al. and Isikveren et al. [13, 51]. A replacement concept provides the opportunity for regular battery testing for increased safety and reliability. However, regular replacement requires short process times and suitable equipment and tools. The disadvantage of replaceable batteries is the wear of the contacts and the risk of damaging the battery or contaminating the connectors during replacement. On the other hand, charging the batteries during the ground phase requires a charging infrastructure at the airport [50]. For both concepts high accessibility and interchangeability is mandatory. Redundancies are needed due to the importance of the battery. A modular battery concept would preferably take care of this. Due to the cause of thermal runaway, safety and fire concepts need to be considered during the design phase.

7.4. D4M - EWIS

As already mentioned in this work, 80 % of induced faults in wires can be traced back to repair measures [61]. To reduce this rate, improved training of the technicians is required and measures for example to improve maintenance tools, wire routing and accessibility should be considered. The accessibility of the hybrid circuit breaker is mandatory. It must be checked or replaced after the occurrence of a short circuit [50].

8. CONCLUSION AND OUTLOOK

This work was conducted to examine a hybrid electric propulsion system of a medium-range aircraft from a maintenance point of view. Different propulsion systems were presented concisely. It was shown that the electrification of an aircraft propulsion system affects wide fields of MRO. A significant advantage of using a hybrid electric drive to assist the turbofan engine during take-off is a reduction in engine loads, which primarily results in a reduction of turbine inlet temperature.

The existing technologies, failure mechanisms and potential maintenance measures for the main components of the hybrid electric propulsion system were described in detail. Failure rates for the respective components were taken from the literature.

In order to identify critical components with regard to their reliability and maintainability, a FMEA and a FTA were carried out in this work. During the FMEA, the windings of the electric machine, the inverter, the lithium ion battery, battery management system as well as wiring and contacts of the EWIS were identified as critical components. Possible causes for the resulting assessments were explained.

During the FTA, the primary concern is a complete loss of thrust. This can only occur if there is a failure in the turbofan engine, in the FADEC, in the mounting of the electric machine or if the electric machine is blocked in conjunction with a failed safety clutch. In all other cases, there may be a loss of the electric drive train, but only a partial loss of thrust, which can be compensated for by the turbofan engine, unless it has been downscaled due to an adjustment. It is strongly recommended to consider the use of a safety clutch and the implementation of redundancies to increase safety and reliability.

The regarded hybrid electric propulsion system is at an early concept phase, therefore the results can be used as an indication for further research. In the course of further iterative loops, the design must be specified in greater detail. This means that for example the operational parameters are sharpened and the topology of the inverter as well as possible redundancies are defined. The charging concept also needs to be defined. Charging the batteries at the gate or replacing them has a significant impact on MRO. Based on this, the FMEA as well as the FTA can be broken down in more detail and made more complex. Considering the specified design, models to determine failure rates or data sheets can be used. Another way to enhance failure rate data can be accomplished through reliability experiments.

Based on previous aspects, life-limited parts (LLP) can be identified in the further development of the hybrid electric propulsion system. Furthermore the accessibility and maintainability considering the reliability of the components has to be examined.
Economic and ecological considerations should be carried out in further work, especially as there are also arguments against the use of hybrid electric propulsion systems. For example, van Holsteijn et al. [14] raise the question of whether the possible fuel savings can outweigh the disadvantages of the weight increase due to the additional electric components.
The FMEA carried out in this work can be continued and adapted to the needs of maintenance by following the MSG-3 procedure. This also serves to determine maintenance tasks and intervals more precisely, as it was done in the work of Meissner et al. [83]. Therein, the changes compared to the original aircraft configuration are also analysed and evaluated, which can also be useful as a continuation for the present work.

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A. APENDIX

TAB 7. Researched values of the failure rates for the hybrid electric propulsion system. Selected values for the FTA are underlined.

Component	Failure rate $\lambda[h]$	Reference	Comment
Turbofan engine	1,00E-09	[70]	Existing requirement
FADEC	9,36E-07	[2]→ [84]	[2]: Max value
	2,85E-06	[2]→ [84]	
	1,37E-07	[2]→ [31]	
	5,00E-08	[2]→ [85]	[2]: Min value
	1,00E-06	[2]	[2]: Estimated value
	7,24E-06	[86]	Calculated by [86] during the FTA
	1,00E-06	[71]	[71]: In comformity with MIL-F-9490D [31]
Winding	1,30E-04	[2]→ [31]	[2]: Seems to be very conservative
	1,40E-08	[2]→ [87]	[2]: Seems to be rather optimistic
	6,25E-07	[2]→ [31]	[2]: Valid only for fractions of a horsepower motors but consider maintenance and service time
Bearing	1,57E-04	[2]→ [32]	[2]: Seems to be very conservative
	6,60E-07	[2]→ [87]	[2]: Seems to be rather optimistic
	1,70E-06	[2]→ [31]	[2]: Valid only for fractions of a horsepower motors but consider maintenance and service time
	4,09E-06	[88]	Describing a ball bearing
Cooling	6,04E-05	[2]→ [32]	Caculated by [2] with values from [32]
	4,09E-06	[89]	Describing a cooling unit
	4,09E-06	[89]	Describing a tube assembly generator cooling
Semiconductor	7,10E-08	[56]	Mosfet value from the automotive field
	4,16E-08	[44]	Mosfet value from F18 flight control/ Seems like the conservative approach
	1,33E-09	[90]	Gate Oxid Reliability SiC MOSFET, 15 V Gate Voltage - estimatedte due the reciprocal of the predictiv lifetime
	1,42E-09	[91]	Gate Oxid Reliability SiC MOSFET, 1200 V, 20 V - estimatedte due the reciprocal of the test time whcih was set as lifetime
	4,10E-09	[92]	Field Relaibility 1200 V MOSFET - C3M MOSFET
Capacitor	3,49E-07	[44]	Describing a plastic metallized film capacitor
	6,00E-08	[93]	Capacitor with a hot spot temperature of 75° C
Connector	2,29E-07	[56]	Value out of the automotive field
	2,96E-07	[94]	Quanterion summarized different values
Battery cell	2,40E-06	[56]	Value out of the automotive field
	1,70E-07	[2]	

TAB 7. Researched values of the failure rates for the hybrid electric propulsion system. Selected values for the FTA are underlined.

Component	Failure rate $\lambda[h]$	Reference	Comment
Signals Connector	4,39E-07	[56]	Value out of the automotive field
	4,43E-09	[95]	Electronic/computer equipment used primarily in ground applications
Fastening Screw	1,02E-06	[57]	Describing the screw assembly
BMS	1,00E-06	-	[2]: As the BMS is an integrated control system comparable to the FADEC
Power Device	4,09E-06	[57]	Describing the battery power supply
Current Sensor	6,45E-07	[56]	Value out of the automotive field
	2,00E-06	[2]→ [31, 58]	[2]: Estimated value
	4,09E-06	[57]	Describing a current sensor
Voltage Sensor	3,63E-08	[56]	Value out of the automotive field
	1,80E-06	[2]→ [31, 58]	[2]: Estimated value
	4,09E-06	[57]	Describing a voltmeter
Temperature Sensor	3,30E-07	[56]	Value out of the automotive field
	1,70E-06	[2]→ [31, 58]	[2]: Estimated value
	4,09E-06	[57]	Describing a temperature sensor
Wiring	1,00E-07	[2]	[2]: Estimated value corresponds to the aviation industry
	6,81E-07	[57]	Describing wiring
Contact	3,12E-09	[2]	
	4,44E-08	[57]	Describing contacts
Hybrid Circuit	4,94E-09	[57]	Describing a circuit brekeaker, not a hybrid circuit breaker
Safety Clutch	9,40E-09	[57]	Describing a coupling assembly
	1,22E-06	[69]	Describing a mecahnical clutch assembly for ground applicationms - industrial part
Mounting	4,09E-06	[57]	Describing a motor mounting

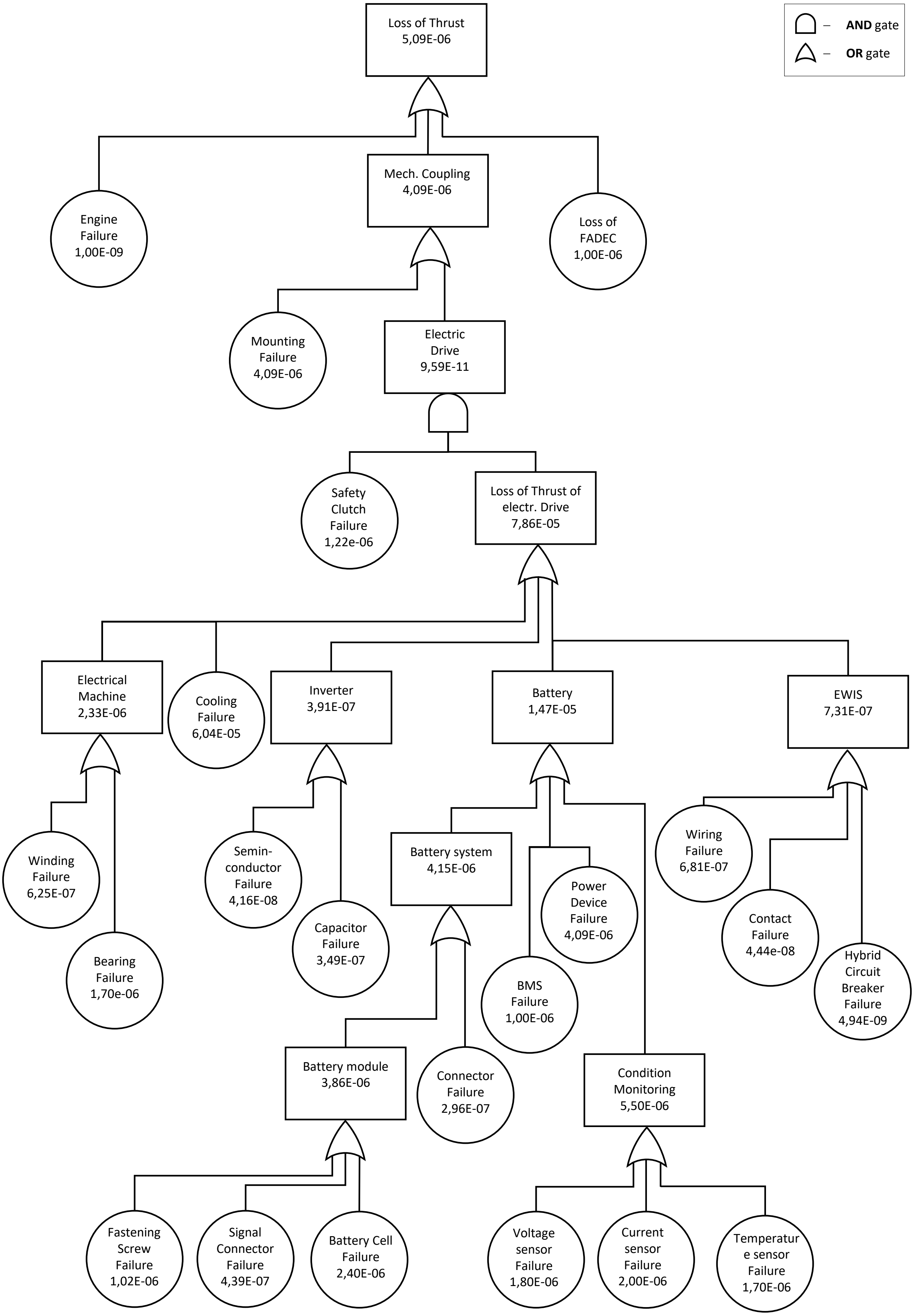

FIG 9. FTA of the hybrid electric propulsion system