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Review Article

A Review of Certification Compliance Assessment for Nonresettable Protection Devices in eVTOL Applications

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The introduction of electrical vertical take-off and landing (eVTOL) aircraft enables a greener, quieter, and faster method of aerial transportation method than helicopters. Key electrical power technologies are also being developed to enable the realization of these new aircraft types. The Pyrofuse protection device is a nonresettable protection device (NRPD) that offers desirable features for use within small electric aircraft applications. The components used in the Pyrofuse are also currently available at the intended power levels and at low cost. However, the nonresettable aspect of the device represents a challenge in the certification process for its use in eVTOL electrical system protection, although there is a current shortage of published literature on this aspect. Accordingly, this paper provides the first document-based review of certification compliance assessment for the use of NRPDs in an eVTOL environment. This assessment shows that devices such as Pyrofuses can achieve airworthiness in a range of roles as the primary protection for eVTOL electrical power system (EPS). However, this airworthiness is highly dependent on the physical design of the aircraft design, the proposed location of NRPDs, and the immunity to common mode and common cause failures.

Keywords: aircraft; architecture design; eVTOL; hazard assessment; nonresettable; Pyrofuse; UAM

1. Introduction

The introduction of electrical vertical take-off and landing (eVTOL) aircraft enables a greener, quieter, and faster alternative method of transportation to helicopters [1]. EVTOL aircraft are intended for personal urban and intracity transportation applications. Critical to the realization of new aircraft, advances in high power and energy-dense power system technologies are required. Furthermore, to meet airworthiness requirements, the technologies and integrated systems are required to be reliable and failsafe in nature. Electrical power system (EPS) protection is essential to maintain the stability of the system after a fault has occurred. This can be achieved by using dedicated protection devices to isolate any potential faults in the system fast enough to prevent the effects from cascading and damaging healthy systems. In addition, the redundant nature of the EPS architecture ensures that the required power is provided for the aircraft to maintain stability and land safely even after the loss of some equipment during the fault event.

Urban air mobility (UAM) industry experts anticipate eVTOL aircraft to be operational by around 2025–2030 [1, 2]. However, the associated technology development, testing, and demonstration required within this timeframe represents a challenging undertaking, particularly with regard to the availability of lightweight protection devices suitable for eVTOL electrical power and propulsion systems.

Conventional resettable protection devices widely used in multiple industries are electro-mechanical molded circuit breakers (MCCBs) [3], circuit breakers [4], and DC contactors [5]. However, they have a relatively slow operation time for DC systems, are typically bulky and heavy, and are also susceptible to arcing damage resulting in a low contact cycle life [5, 6]

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The recent development in solid-state protection devices addresses the limitations of conventional protection devices, offering fault detection, fast-tripping speed, status, and alert information. They also provide protection against overloads, short circuit faults, and arc faults [5, 7].

Solid-state devices such as solid-state power controllers (SSPCs) have been used and are currently available for aircraft secondary EPS of 28VDC [5]. The on-state losses of solid-state protection devices are significantly greater than conventional circuit breakers [8]. For high voltage systems, the increased on-state and energy losses lead to increased requirements for cooling, which contributes to a significant portion of the devices' weight [8, 9]. Further development is required to reduce the volume and weight of the cooling and packaging of these devices to be used in the primary distribution system for the aircraft.

The automotive industry has recently introduced high-power density Pyrofuses for protection applications. Pyrofuses exhibit advantageous features for eVTOL aircraft applications, such as high-power density, excellent protection sensitivity, fast fault isolation [10, 11], and current commercial availability at the required power levels for emerging eVTOL applications.

The hybrid configuration of the Pyrofuse, which consists of a pyroswitch and a fuse connected in parallel, enabling the tunability of the device to the required application by use of adjustable time-current characteristics, realized through the configuration of component ratings within the Pyrofuse. Existing devices by Mersen [10, 11] are rated for up to 1500 VDC operation, with either external or self-triggering. The self-triggering device consists of two fuses and a pyroswitch; one fuse is used as a sensor connected in series to the pyroswitch, and the other fuse is connected in parallel to the pyroswitch.

A number of published articles present simulation-based and hardware testing of Pyrofuse devices in automotive [10–12] and eVTOL applications [13]. The work in [10–13] is predominantly focused on accurately modeling and demonstrating the operation and coordination of Pyrofuse devices under a range of simulated fault conditions. Sakuraba et al. [10] and Ouida, Palma, and Gonthier [11] have demonstrated that the proposed self-triggered Pyrofuse was able to clear the fault in 1.5 ms and has limited the current to 7 kA under DC conditions of 1000 V with 15.6 kA fault current. Additionally, Sakuraba et al. [10] have performed cycling tests where the self-triggered Pyrofuse has passed for the specific application. Mersen [12] has presented the testing of Mersen's self-triggered Xp series Pyrofuse with a fault level of 11 kA at 500 DC. The results show that the Pyrofuse has successfully protected the circuit, interrupting the fault current at a maximum of 2 kA. Altouq et al. [13] have presented a complete design methodology to transiently model Pyrofuse operation in MATLAB/Simulink. The simulation results have demonstrated the Pyrofuse sensitivity to low impedance faults and the ability to use the Pyrofuse device in a graded protection system. Altouq et al. [13] do consider the concern of Pyrofuse robustness under lightning strike conditions. The literature does not otherwise consider the possibility of device maloperation in an operational environment, nor does it explore device-level or system-level methods to reduce the criticality of the devices for use in the protection of essential-to-flight systems. Similarly, NASA has published functional hazard assessment (FHA) and failure modes and effects analysis (FMEA) studies focused on different eVTOL aircraft configurations in order to abstract safety and reliability requirements [14]. However, these studies do not consider safety requirements specific to the use of nonresettable protection devices (NRPDs) for primary protection, nor do they address the challenges of demonstrating airworthiness at the system/aircraft level. This aspect of using NRPDs for the primary protection of distribution systems has not yet been explored sufficiently in the research literature.

1.1. Outline of Paper. To address this potential issue, this paper presents a first-of-its-kind document-based review of certification compliance assessment for the use of NRPDs, such as Pyrofuses, in eVTOL concept designs. The paper first provides an overview of the US Federal Aviation Administration (FAA) and European Union Aviation Safety Agency (EASA) approaches to eVTOL certification. This is then followed by a summary of key FAA and EASA certification rules, which are specific to the implementation of electrical protection devices in aircraft. Additional requirements and constraints around the use of NRPDs are then derived from FHAs developed by the authors on the basis of logical extension, each one specific to a particular configuration of eVTOL aircraft. These categorize the resultant system behavior and, more specifically, the impact on available thrust arising from a single or series of failure events, with the implications of implementing NRPDs defined. In addition, potential hazards which could lead to common mode failures are explored, drawing from the authors' own experience of research in this domain, and proposals are then made for the mitigation of these. Building on the outcome of the FHA, potential power-system location-specific roles of NRPDs are then determined, considering the key outcomes from the previous stages of analysis. These roles suggest that there is a natural opportunity for the use of NRPDs in the protection of power sources and propulsion motors. The paper concludes with summative discussions on the future of NRPDs in eVTOL applications and on further research required for more wide-spread implementation.

2. Certification Guidelines

This section presents certification requirements from the EASA and FAA regulatory bodies that are applicable to the deployment of NRPDs in eVTOL applications. It should be noted at this point that the formulation of regulations is still ongoing with the certification process also still under development/amendment. As such, this paper lists the latest version of amendments and regulatory advice available at the time of writing.

2.1. Approaches to eVTOL Certification. One of the main approaches to certification for the past 5 years has been through the utilization of the FAA revised Part 23 (airworthiness standards for small aircraft) in accordance with Part 21.17(a) for winged eVTOL and wingless eVTOLs, which are considered as a special-class powered lift aircraft under Part

21.17(b) [15, 16]. The accepted means of compliance (MOC) within Part 23 is ASTM 23-64, where the F44 committee has recently updated the MOC for the certification of small electric aircraft [17, 18].

More recently, the FAA has modified its approach to certifying eVTOL aircraft through FAA Part 21.17(b) as special-class powered lift aircraft for all eVTOL types [15, 19]. This certification approach is tailored for aircraft with novel technologies or designs that the current regulations do not cover, which includes applications such as electric propulsion, tilt-rotor, tilt-wing, advanced flight control, etc. [15, 19]. This regulation combines all the policies of Parts 23, 24, 27, 29, 33, and 35 together, providing appropriate standards for the innovative aspects of eVTOL aircraft. As such, the FAA is encouraging early-stage engagement with aircraft developers in order to identify these potential gaps in regulations [20].

The European regulatory board, EASA, has proposed new special conditions, known as SC-VTOL, with associated MOC for VTOL certification, which is extensively based on CS-23 and elements of CS-27 [20, 21]. EASA plans to use the SC-VTOL to establish "a common set of conditions for the certification of these new concepts" [20]. Building on this, EASA has issued SC E-19, a special condition to address requirements and safety objectives for electric/hybrid propulsion systems in eVTOL aircraft [22]. The UK Civil Aviation Authority (CAA) [23] has adopted EASA's special conditions certification standards for eVTOL aircraft.

Although the EASA SC-VTOL document is extensively based on CS-23 and CS-25, the document is objective-based and prescriptive. The MOC provides details and guidance for an acceptable approach of conformance to SC-VTOL requirements [20]. The FAA approach, however, is performance-based and allows the applicant to propose their own MOC tailored to their specific application. Compliances proposed to address certain safety objectives will differ for EASA and FAA, where there might be gaps or misalignments in the safety objectives. This departure in certification approaches significantly reduces the harmonization between FAA and EASA, especially impacting eVTOL companies aiming for bilateral agreements [22, 24]. In system safety assessments, for instance, the worst-case acceptable probability for catastrophic safety objectives is 10^{-9} per flight hour following EASA regulations and 10^{-8} per flight hour following FAA regulations [25]. This can result in different lead times for technologies achieving compliance with the 10^{-9} per flight hour requirement, potentially increased weight due to redundancies in the system, and costs for aircraft manufacturers seeking certification with EASA. Additionally, FAA-certified aircraft with critical systems demonstrating a failure probability of 10^{-8} per flight hour might not be able to obtain certification from EASA.

Recently, the FAA and EASA released revised certification requirements for eVTOL aircraft with the aim of narrowing the gap between both regulations. The FAA has published an advisory circular (AC) for powered lift-type certification [26]. The AC provides guidance for the type, production, and airworthiness certification of powered-lift aircraft with a maximum gross weight equal to or less than 12,500 lbs (~5700 kg). EASA has also released an updated version of SC-VTOL [27], the updates reflect harmonization efforts made with the FAA. For instance, EASA increased the maximum take-off weight to 5700 kg from 3175 kg in SC-VTOL Issue 1. Other changes to harmonize with the FAA include requirement wording to VTOL.2250(c) design and construction principles and VTOL.2105(b) (1) VTOL.2250 performance data for vertiport altitudes [27].

2.2. Requirements for NRPDs. More specific to electrical protection devices, EASA's SC MOC VTOL.2525 for system power generation, energy storage, and distribution refers to CS 27.1357 Amendment 6 [28] certification specifications, which provide the following circuit breaker and fuse circuit protection requirements for certification:

1. "If the ability to reset a circuit breaker or replace a fuse is essential to safety in flight, that circuit breaker or fuse must be so located and identified that it can be readily reset or replaced in flight," according to CS 27.1357 [28]. The definition of "essential to safety" according to CS 23.1357(b) amendment 3 [29] is that, "Essential to flight safety is related to those whose failure is classified as "major," "hazardous," or "catastrophic."
2. When the failure condition of the loss of the function is determined to be "major," "hazardous," or "catastrophic" (according to CS 27.1309 and AC 23.1309-1E safety assessment, which also considers operational and airworthiness requirements), it has a significant impact on safety in flight and is considered "essential to safety in flight" [28, 30].
3. According to 27.1357(b), "Protective devices, such as fuses or circuit breakers, must be installed in all electrical circuits other than (b)—a protective device for a circuit essential to flight safety may not be used to protect any other circuit" [28].
4. "Each resettable circuit protective device ("trip free" device in which the tripping mechanism cannot be over-ridden by the operating control) must be designed so that (2) if an overload or circuit fault exists, the device will open regardless of the position of the operating control." 27.1357(2) [28].

In addition, the following statements from the FAA powered lift [26] guidelines provide requirements for protection systems:

1. "The system must provide mechanical or automatic means to mitigate a faulted electrical-energy generation or storage device from affecting the safe transmission of electrical energy to the electric engine or detrimental engine effects in the intended aircraft application." PL.3326(3) [26].
2. "Protection systems. The engine electrical system must be designed such that the loss, malfunction, interruption of the electrical power source, or power conditions that exceed design limits will not result in hazardous engine effects", as defined in PL.3375(g) (2).

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Table 1: The definition of failure conditions according to the severity of a fault and its impact on the aircraft and passengers.

Failure conditions	Failure impact on aircraft
Negligible	No effect on safety margins, aircraft functional capabilities, or passenger comfort.
Minor	Slight reduction in safety margins or functional capabilities of the aircraft, resulting in physical discomfort to passengers.
Major	Significant reduction in safety margins or functional capabilities of the aircraft, resulting in physical distress to passengers. Aircraft can continue safe flight but at reduced efficacy.
Hazardous	Large reduction in safety margins or functional capabilities of the aircraft, resulting in serious injury to passengers. Aircraft descent is possible but with limited control.
Catastrophic	Loss of the aircraft and the inability to continue flight or land safely resulting in passenger injuries or fatalities.

2.3. Challenges in the Certification-Compliant Use of NRPDs. Considering all of these requirements further, it is clear that it is necessary to first determine the impact of a failure in the systems/subsystems protected by nonresettable devices. Where the aircraft/EPS design is such that the impact of a failure is considered to be less severe than "major," there appears to be a degree of freedom in the use of NRPDs. However, if the impact of any associated failures is considered to be "major" or worse, then significant restrictions will apply.

In this manner, point (1) effectively impedes the use of NRPDs as primary protection devices in most applications with a "major" or worse failure severity unless it can be shown that the need to reset such devices is not essential to safety in flight or that device replacement is possible. As it is likely to be difficult to replace Pyrofuses manually and in a timely manner in flight, it is, therefore, necessary to demonstrate that the likelihood of potential causes for the need to reset devices in flight, for example, spurious maloperation due to failure effects such as electromagnetic interference (EMI), lightning strike or thermal aging, is sufficiently low.

The requirements laid out in point (2) place restrictions on the design of the NRPDs and the surrounding EPS, requiring that the impact of a single failure does not cause a "major" or worse impact on flight safety. Assuming that the loss of the protected system will result in this condition, it is, therefore, necessary to either demonstrate that the protection device design is single fault tolerant or to revisit the EPS design so that the loss of the protection device no longer results in this condition.

In point (3), the requirement to use separate protection devices for essential-to-safety loads to prevent a protection response to failures in nonessential loads causing a subsequent loss of an essential function can be readily demonstrated. Additionally, according to point (4), each resettable device must be designed to isolate a persisting fault regardless of the location and not be resettable by operating control [31]. These requirements indicate that assurance is required to show that ambient conditions (e.g., temperature, electrical load dynamics, or EMI environment) are highly unlikely to disrupt the operation of the NRPD. The requirement to prevent operational control resetting the device is naturally obtainable in an NRPD.

In point (5), the requirement to provide automatic means of disconnecting a faulted energy storage unit to prevent propagation of failures to healthy systems can be demonstrated using Pyrofuses. The controls of the externally triggered Pyrofuse can be designed to automatically detect and isolate faulted systems or disturbances to protect connected equipment from damage.

The FAA requirement in point (6) implies that the protection system for electric motors shall prevent hazardous effects causing uncontrollable fire or the inability to control/shutdown the motor as per PL.3375(g) (2) safety analyses. Similar to the above, the Pyrofuse can be designed to detect and isolate short-circuit failures to achieve these requirements.

From points (5) and (6), the requirements for protection systems are high-level, referring to the continuation of power transmission after a fault, and that a failure of protection systems only, or in combination with a fault event in the motor, shall not result in hazardous conditions leading to fire or loss of aircraft control. An example for the failure of a Pyrofuse is a contact separation failure within the pyroswitch, which can fail in a latent manner where it does not operate when required. In mitigation of this, the numerical probability for the event of a contact separation failure and aging of the pyrotechnic device shall be detailed in the aircraft maintenance manual.

3. Propulsion-Focused FHA of Different eVTOL Configurations

As the impact and severity of propulsion failures on an aircraft are influenced by its aerodynamic configuration and propulsion design, the acceptability of the use of NRPDs for primary protection will be, in part, shaped by the design of the aircraft configuration and electrical and propulsion systems. Methods like FHA [31, 32] are necessary to derive the architecture-specific severity of failures of subsystems which are considered essential to flight safety, helping shape the acceptability of the use of NRPDs in these applications. The definitions and classification of failure conditions (i.e., minor, major, hazardous, and catastrophic) according to the severity of a fault and impact on aircraft and passengers as based upon AC 23.1309-1E are shown in Table 1.

This section presents FHA studies for three conceptual eVTOL design configurations. These are (1) multirotor, (2) vectored thrust, and (3) lift + cruise. A brief description of these configurations is presented to support each FHA and underpin later understanding of the unique resultant failure behavior.

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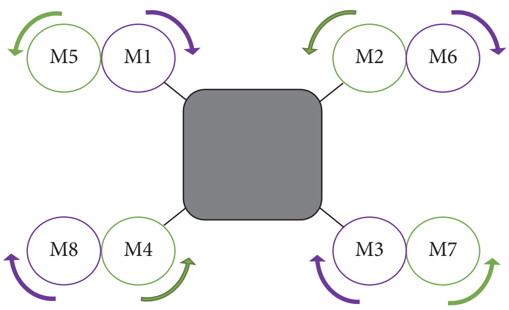

FIGURE 1: Example of a multirotor configuration.

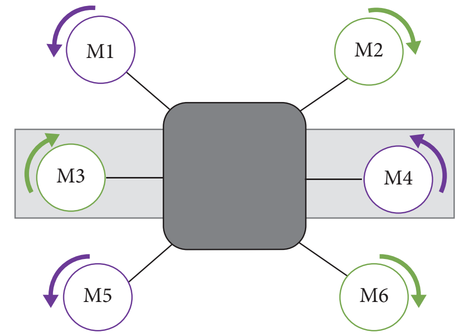

FIGURE 2: Example of vectored thrust configuration.

3.1. Multirotor Configuration. Multirotor configurations are wingless aircraft with fixed-axis distributed electric motors utilized for powered lift during the hovering and cruise phases. The large combined total rotor surface area provides an improved hover capability but with reduced cruise speed and efficiency when compared with other eVTOL configurations. These attributes make this eVTOL type best suited for short-distance transportation [33].

Figure 1 shows an illustration of a multirotor eVTOL configuration. This particular example is a quadrotor configuration with stacked motors and fans. The motors are colored differently to illustrate the clockwise and anticlockwise rotation of the rotors.

For a multirotor configuration with less than 10 motors, any loss of the available motors is likely to be classified as a major failure or worse unless a significant degree of oversizing is employed in the propulsion motors and associated drives. For example, the loss of one motor in a stacked eight-motor configuration (as in Figure 1) would create an offset from nominal hovering states requiring the opposite motor to reduce power in order to balance the resultant asymmetric thrust, effectively reducing the number of thrust-producing motors to six.

For a multirotor configuration with 10 or motors, the loss of one motor would leave a minimum of eight effective motors remaining (allowing for symmetric thrust balancing). The loss of an additional motor leads to six remaining useful motors, from which continued flight at a reduced efficacy would be assumed to be possible with sufficient sizing. Accordingly, the loss of a single motor would likely be classified as a minor failure, assuming that appropriate motor oversizing and off-nominal flight control are implemented.

Based on this analysis, the use of NRPDs for system protection functions cannot be used in multirotor configurations of less than 10 motors where the loss of the protection device can lead to a major failure at best. In multirotor configurations featuring 10 or more propulsion motors, NRPDs could potentially be utilized as long as the loss of a single protection device does not lead to more than one propulsion motor being lost, or if it does, that the worst-case loss of a propulsion motor does not constitute as a major or worse failure.

3.2. Vectored Thrust Configuration. Vectored thrust configurations utilize distributed electric propulsion along with a wing to generate additional lift during the cruise phase. Thrust vectoring, or the tilting of propulsion fans, is employed for cruise thrust. This type of configuration possesses attractive advantages over multirotor designs in that it combines a vertical take-off capability with higher cruise efficiency [33]. However, the tilting mechanisms of the vectored thrust configurations present additional reliability considerations during the transition phase, where the tilting actuators represent an additional failure point in the system [34, 35].

Figure 2 shows an example of a vectored thrust configuration with six rotors, where M3 and M4 are the wing tip motors. The motors are colored differently to represent the clockwise and anticlockwise rotation of rotors, where each motor is rotating in the opposite direction to the adjacent motors to produce balanced torque. The shaded gray rectangular box represents the aircraft wing.

Similar to the multirotor configuration, the number of installed motors on the UAM platform has a large impact on the nature of the failure conditions and their associated severity classification. As before, the loss of a single motor requires a reduction of thrust from the diagonally opposite motor to a symmetrically balanced thrust. As such, it can be assumed that for vectored thrust configurations with less than 10 motors, the loss of a single motor considerably impacts the safety margins of the aircraft, resulting in a major failure classification, or hazardous failure classification at worst, unless significant oversizing is employed (as in Figure 2). While the aircraft can be designed to land safely with only wingtip motors operating in conventional flight mode (hence potentially accommodating the failure of several other motors), this ability is clearly dependent on the availability of a nearby runway and wingtip motors and hence does not reduce the failure severity of nonwingtip motor loss. With regards to the availability of a nearby runway; prior to operation, a study on the aircraft concept of operation, which includes emergency and contingency operations, must be performed by UAM operators [36–38]; this study shall ensure that the allocated emergency battery capacity is sized enough to support conventional landing on nearby runways at any point in flight. Such mitigations help with achieving compliance with hazardous safety objectives set in the FHA.

Similar to the multirotor configuration, the loss of one motor in a vectored thrust aircraft with more than 10 motors would likely result in a minor failure condition.

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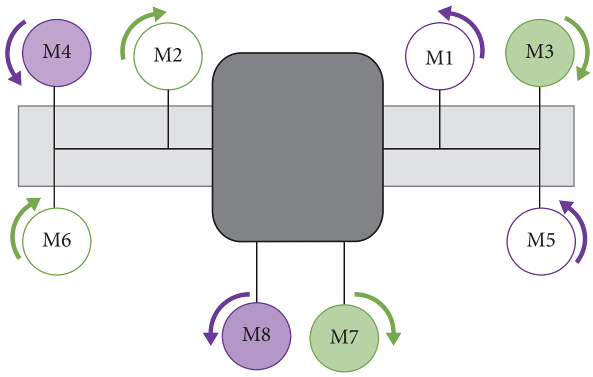

Figure 3: Example of lift + cruise configuration.

On this basis, the use of NRPDs for system protection functions in vectored thrust configurations with less than 10 motors is dependent on the sizing of the EPS, controllability of the aircraft, and demonstration that the loss of a single protection device does not lead to a major event or worse. The conditions for the use of NRPDs in vectored thrust configurations for 10 motors and more are the same as multirotor configurations with 10 motors and more. However, the increased criticality of the wingtip motors is such that the use of NRPDs for the protection of these subsystems is unlikely to be possible without the incorporation of additional redundancy measures, further discussed in Section 5.3.

3.3. Lift + Cruise Configuration. The lift + cruise configuration is similar to the vectored thrust design but with a mixture of fixed and tilting propellers optimized for a single flight phase, rather than all rotors being fully tilting or vectoring [39]. For instance, the Beta Alia 250 uses four propellers for VTOL and a single rear pusher propeller for the cruise phase [40]. Similarly, the Eve Air Mobility aircraft uses eight propellers for VTOL and two rear propellers for the cruise phase [41], while Supernal S-A1 eVTOL uses four propellers for the take-off phase only and four tilting propellers for take-off and cruise phase [42].

An example of S-A1 architecture is shown in Figure 3. The fixed propulsion rotors are mounted for the hovering phase with a reduced blade count to reduce drag. In hovering mode, all the propulsion rotors are used to lift the aircraft, while for the cruise phase only the tilting propulsion rotors are used for generating longitudinal thrust with the lift support from the wing. The fixed propulsion rotors can provide additional lift thrust and redundancy for VTOL operations. The tilting components have increased criticality as they provide control during all phases and facilitate maneuvering necessary for safe landing [34, 35].

An example of a lift + cruise configuration with four tilting rotors and four fixed VTOL rotors is shown in Figure 3. The shaded gray rectangular box represents the aircraft wing with six mounted motors. The motors are colored differently to represent the clockwise and anticlockwise rotation of thrust, and the color filling represents the tilting rotors that provide thrust generation during both lift and cruise. Each motor is rotating on the opposite direction to the adjacent motors in the opposite axis to generate balanced torque.

Table 2: Summary of FHA classification results for each configuration.

Configuration	No. of motors	Use of Pyrofuses
Multirotor	<10	Major or hazardous at worst
	>10	Minor or Major at worst
Vectored thrust	<10	Major
	>10	Minor
Lift + cruise	<10	Major or hazardous at worst
	>10	Minor or major at worst

Abbreviation: FHA, functional hazard assessment.

The loss of any single motor in a lift + cruise configuration with fewer than 10 motors is likely to result in a hazardous failure condition, restricting the use of NRPDs in the manner described for previously considered configurations. Major classification can be achieved for this architecture with considerable oversizing and efficient flight controls of the aircraft. However, a subsequent failure causing the loss of a wingtip motor would result in a catastrophic failure. In addition, the increased criticality of the tilting motors may also prevent the application of NRPDs for their protection without the implementation of additional subsystem or system-level safety features. As such, increasing the redundancy in the configuration to 10 motors or more will likely to result in a minor or major failure, at worst, for the loss of any single motor.

In summary, the loss of a single motor for multirotor, vectored thrust, and lift+cruise configurations with 10 or more motors is likely to be classified either as a minor safety effect with a slight reduction in safety margins or functional capabilities or, at worst, a major safety effect, depending on the arrangement/allocation of motors. For configurations with fewer than 10 motors, the loss of a single motor is likely to be deemed a hazardous safety effect, requiring the consideration of additional safety measures before the use of NRPDs for the protection of primary distribution systems could be considered. Such safety measures are further discussed in Section 5.3. Table 2 provides the summary of the results of the FHA classification for each architecture.

4. Causes of Common Failure Modes and Impact on the Use of Nonresettable Devices

Once the system-level classification of thrust-loss failure conditions has been established, it is then necessary to consider the potential root causes of common mode and common cause failure conditions that might impact on the requirements and use of NRPDs. In doing so, any need for additional protection, redundancy, and fail-safe mechanisms can be identified.

Table 3 shows a range of potential common electrical failure modes/causes that could lead to the loss of a propulsion motor. These electrical common-mode failure types are most commonly considered electrical failure conditions for distribution systems [43] and are ultimately relevant/concerning to the considered use of NRPDs. These include short-circuit line-line and line-ground faults, lightning strikes,

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Table 3: Causes of key electrical common failure modes and the impact on the electrical power system with associated protection devices.

Root cause	Effect on the system	Protection requirements
Short circuit fault (line to line and/or to ground)	Large current and voltage transients (unless a fault is to IT ground or high-resistance ground). High energy at the point of fault. Electrical equipment in the fault path may also be damaged.	Fast isolation of fault, minimization of the extent of isolation of healthy equipment, and timely restoration of power supply to remaining loads.
Lightning strike	Transient high voltage/current waveforms. It may induce multiple or common-mode failures.	Diversion of high transient energy away from sensitive electrical systems to avoid/minimize damage and other disruptions to operation.
EMI	Disturbance to and potential maloperation of aircraft systems and electronic devices.	Shielding/filtering to suppress EMI propagation.

Abbreviation: EMI, electromagnetic interference.

and EMI. For each of these failure conditions, the potential effects on the electrical power and propulsion system are described, and associated protection system requirements are described. Further discussions around these failure modes are provided in the following subsections.

4.1. Short Circuit Faults. Following the occurrence of a short-circuit fault on an electrical power and propulsion system, the electrical protection systems should isolate the faulted components from the remainder of the power system network in as short as time as possible [28]. In addition, protection devices whose operation is not required to isolate the faulty equipment should not trip, as doing so may lead to a more widespread loss of thrust. Hence, the use of NRPDs requires the early identification of potential short circuit cases that may cause the (mal) operation of multiple protection devices. In particular, previous studies have identified the risk of fault-induced capacitor discharge events in DC power systems leading to the tripping of multiple overcurrent protection devices [44], which would require careful attention if NRPDs were to be utilized.

4.2. Lightning Strike. Lightning strike-induced current and voltage surges can be damaging to the carbon fiber material used in the aircraft surface as well as its internal structure and joints [45]. In addition, the electrical surges can cause damage to the propeller structure or cause misalignment of the motor bearings, which could potentially lead to motor failure [46]. This necessitates adequate surface protection to prevent the lightning surges from damaging the carbon fiber material and entering the power system [47]. Methods used to minimize/prevent damage include the design of passive surface protection according to lightning zoning on the aircraft, which identifies the probability/severity of the lightning current magnitude at different locations on the aircraft [47, 48]. The embedded metallic mesh and diver tips used in this create a conductive path for the large current to flow, diverting the current away from sensitive components to a suitable exit point without causing hazardous damage [47].

Yet, a lightning strike could still potentially enter the electrical system indirectly through the cables and cause damage to its insulation and sensitive devices [49]. This could potentially result in a catastrophic condition where multiple protection devices trip due to the induced voltage and current surges. This failure scenario is particularly concerning for NRPDs, where the mal-triggering of protection could lead to a significant reduction in available thrust, with no option to subsequently restore service. Hence, it will be necessary to assure the effectiveness of a dedicated power system protection strategy for indirect lightning effects against mal-tripping of NRPDs before their use could be considered, further discussed in Section 6.

4.3. EMI. The key concern around the impact of EMI on the utilization of NRPDs in aircraft applications relates to the use of external triggering of these devices, where EMI may potentially cause maloperation of any digital and electronic systems on the aircraft. This will cause the external triggering device to erratically trip all the Pyrofuses on the aircraft. Consequently, the introduction of software requires the designer to demonstrate compliance with DO-178C [50] software considerations in airborne systems and equipment certification. This standard provides stringent certification processes for the development of airborne software systems to guarantee that the intended function of the developed systems is performed with a high level of reliability. As such, the triggering control of the Pyrofuse must demonstrate the highest level of design assurance level (DAL), DAL-A, following DO-178C guidelines to eliminate catastrophic impact on an aircraft due to EMI failures. This will necessitate redundant controls with immunity to EMI effects. The recently published patent in [51] has proposed a method for redundant control of an externally triggered Pyrofuse consisting of both digital and analog-to-digital signals that address common mode failures, yet demonstration of immunity to EMI effects is still required.

Currently used methods of EMI suppression/containment include cable shielding and filters [52, 53]. In addition, the use of self-triggered devices can provide an additional layer of mitigation.

5. Impact of Protection Device Location

The final stage of analysis required for the potential use of NRPDs is the consideration of their location within the EPS. In this manner, the impact of the loss of the device or failure to reset can be established. For consistency, the authors recommended quantifying the extent of the impact in terms of the number of motors lost (drawing on the FHA and associated linkage to requirements conducted previously).

In this manner, it will be possible to evaluate whether the anticipated EPS configuration may alleviate or compound the severity of a failure associated with the loss of a particular protection device.

The following subsections consider the application of NRPDs at broad locations within an eVTOL power system, protecting the feeders to motor drives, protecting the power distribution system busbars and interconnecting cables, and providing power source isolation/protection.

5.1. Source and Source Feeder Protection. Protection devices at the terminals of electrical energy sources (e.g., batteries) or their designated interfaces typically provide two functions. The first is to disconnect the energy source if an electrical fault occurs within the supplied element of the EPS that cannot otherwise be removed by another dedicated protection device (or if that dedicated device has failed to operate). The second function is to isolate the source from the power system if the source itself fails (e.g., as a result of an internal short circuit event). This second function may require an external trip capability within the device, as self-tripping due to overcurrent transients may not be possible. For NRPDs, this external trip requirement may impact on the resilience to EMI-related spurious trip issues.

The impact of a power source loss (as a result of the loss of an associated NRPDs) on the number of available thrust motors is ultimately determined by the number of energy sources utilized in the eVTOL power system, the level of interconnectivity between sources and propulsion motors, and the extent of power and energy capacity overrating in the power sources. In this manner, if an eVTOL aircraft utilized only two power sources, the loss of a single battery would likely result in hazardous failure conditions, even if appropriate power system interconnectivity and source overrating were implemented, as the further loss of a power source would be catastrophic. However, in aircraft with three or more power sources, the loss of one battery could potentially result in no loss of thrust motors, and the aircraft could still tolerate further failure without catastrophic consequences.

In this scenario, NRPDs could potentially be used for this protection function, even if the aircraft itself features fewer than the 10 motors otherwise required for motor feeder protection (discussed in Section 5.3), as long as the risks of common-mode failure-driven multiple protection device losses are extremely improbable [15, 19]. On this aspect, if the risks of EMI-related spurious trips for externally triggered NRPDs cannot be sufficiently mitigated, the use of a separate resettable contractor might offer a useful alternative.

5.2. DC Busbar and Interconnecting Cable Protection. The DC busbars and interconnecting cabling are the main power transmission links in the electric power system, ensuring flexible and redundant power flow from the energy sources to the propulsion motors. Protection devices for these systems must be fast-acting against faults on the protected equipment, while being restrained to responding faults elsewhere in the power system.

Similar to a source loss, the impact of a loss of a busbar or interconnecting cable (as a result of the loss of an associated NRPD) on the number of available thrust motors is ultimately determined by the level of interconnectivity between sources and propulsion motors, and the extent of power and energy capacity overrating in the power sources. In addition, the impact of combinatorial faults must be considered, whereby the loss of a busbar or cable may result in the more severe consequence of a subsequent source loss. In this sense, in highly interconnected networks, the loss of a busbar or interconnecting cable may actually be more severe (i.e., resulting in a greater number of propulsion motors lost) than the loss of a source or motor feeder.

Consequentially, unless a large number of low-connectivity busbars are implemented, it is unlikely that the use of nonresettable devices for their protection will be possible. Split or ring-bus arrangements may offer a route to lessening the severity of a bus protection device loss (i.e., leading to only a partial bus loss), although if busbar sectioning is realized with NRPDs, the risk of common-mode faults (for example, due to DC fault transients) must be shown to be sufficiently low. In addition, protection discrimination must be assured so that faults immediately adjacent to a busbar do not cause maltripping of busbar protection. This may be challenging in physically compact electrical networks.

5.3. Propulsion Motor and Feeder Protection. Protection devices for propulsion motors, drives, and feeders are primarily required to act quickly in response to a fault on the protected equipment in order to minimize the disruption to the remainder of the power system, preventing the operation of back-up protection at the busbars or power sources.

The impact of a protection device loss on the number of motors lost here is easiest to quantify due to the direct connection between devices, with the aircraft-level FHA undertaken earlier providing clear guidance between the number of installed propulsion motors and their position on the airframe or role on the applicability of the use of NRPDs for their protection.

The use of dual-redundant drives (mechanically or electrically coupled) may serve to lessen the impact of a single protection device failure (and hence may be attractive for use in wingtip or vectored thrust motor applications). Particular susceptibility to lightning strike-induced common-mode failures may also need additional consideration though.

6. Discussions

From the analysis conducted, the most suitable use of Pyrofuses has been found to be for energy source protection. This is mainly due to their rapid operating time preventing hazardous current levels and fire in the battery, and their current availability at a high TRL. The use of Pyrofuses here is suitable as long as there is redundancy in energy sources and redundancy and/or interconnectivity in the EPS design for continued safe flight after a single failure. This is to satisfy the regulations' safety requirement that the loss of a single critical device should not cause a "major" impact on aircraft safety.

For motor protection, the feasibility of NRPDs is directly linked to the number of motors and aircraft designs. For

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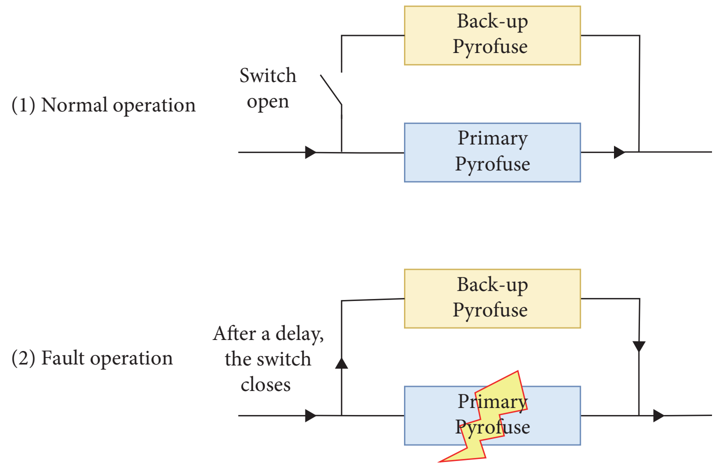

FIGURE 4: Parallel-redundant Pyrofuse set-up.

example, the use of NRPDs is feasible for multirotor configurations with more than 10 nonstacked motors or for a minimum of eight propulsion arms for stacked-motors. For vectored thrust and lift+cruise configurations with less than 10 motors, dual redundant machines per propeller can be utilized to potentially reduce the failure impact of a single motor to a minor classification, which in return offers a route for the feasible application of NRPDs. Wingtip motors have a higher criticality and, as a result, are unlikely to be suitable for the application of NRPDs.

Similar to motor protection, the use of NRPDs for busbar and interconnecting feeder protection is directly linked to the level of interconnection utilized in the aircraft power system. However, the level of redundancy required to render the severity of a single failure to minor or better is such that it is unlikely that the use of NRPDs will be possible for these cases.

The development of mitigation measures to prevent common failure modes and reduce the impact of a single failure to an acceptable level is critical to NRPD usage, especially in areas such as protection coordination, EMI, and lightning strikes. In this manner, the use of surge arrestors or other similar overvoltage devices may provide the necessary protection against lightning strikes and switching transients. Careful prior systems analysis should mitigate poor protection coordination risks.

To prevent EMI-related spurious trip issues and generally reduce the severity of an NRPD device failure, a potential mitigation measure is the use of a redundant NRPD set-up, as shown in Figure 4. For example, if using Pyrofuses, an externally triggered Pyrofuse could be connected directly to the rest of the system as the primary protection device with a self-triggered Pyrofuse in an open-circuit parallel connection acting as a back-up device. During normal operation, the self-triggered Pyrofuse could be disconnected from the rest of the system and only connected after the primary operates if a reset operation is required. A time-delay can be used to clear the fault before connecting the back-up Pyrofuse. The time-delay chosen has to be adequately selected before the bus voltage drops below acceptable limits and shuts down the affected branch. If a short circuit condition persists, the self-triggered Pyrofuse should trip near-instantaneously upon reconnection. Additionally, overvoltage protection is required to prevent the voltage transient from causing nuisance tripping of the externally triggered Pyrofuse. This concept should provide a degree of immunity against EMI and overvoltage faults, but requires further study and analysis to validate the concept.

7. Conclusion

Through the review of relevant safety requirements, eVTOL configurations, and location-specific failure modes, this paper has highlighted the challenges of the wide-spread certification-compliant implementation of NRPDs in eVTOL applications. However, through this preliminary certification compliance assessment, opportunities for NRPD use have still been identified, particularly where the loss of a single protection device does not cause a major or worse failure. As such, it has been shown that NRPDs can most easily be utilized in locations within the power system where there is likely to be considerable natural redundancy and oversizing (often due to other design size, weight, and cost design drivers), for example at the propulsion motors and power sources. However, the assessment presented in this paper has highlighted that considerable further work is still required to derive component and system-level solutions to common mode and common cause failures, which are perhaps the biggest obstacle to the implementation of NRPDs. In particular, while this paper presents a potential mitigation measure in the use of a redundant NRPD set-up, a true systems trade of adding redundancy/oversizing against weight saved in NRPDs is required to provide clearer guidance to the eVTOL community.

Additionally, verification evidence is required to demonstrate compliance with certification authorities of the usability of Pyrofuses in aerospace applications. This includes modeling the set-up in simulation software, testing the coordination of Pyrofuses with the rest of the power system in the event of lightning transients, and performing quantitative safety assessments of the proposed solutions.

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Overall, Pyrofuses introduce advancements in nonresettable devices, where it is possible to realize advanced control, monitoring, and with further redesign, resilience to common mode and common cause failures. Therefore, the authors believe that there is merit in adapting the existing regulations to account for controllable, nonresettable devices, which differ in nature to conventional fuses. In doing so, this may encourage more widespread and safe adoption throughout the industry.

Data Availability Statement

There are no underlying data collected or produced in this article.

Disclosure

The content of this article is one of the main outcomes of the PhD work presented in the author's thesis available in STAX, University of Strathclyde [54].

Conflicts of Interest

The authors declare no conflicts of interest.

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