System wide reliability impact of power converters in More-Electric Aircraft applications

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Abstract

The continued electrification of aircraft is required such that ambitious decarbonisation targets can be met. A significant challenge presented with this trend is the increased reliance on electrical systems to perform flight-critical operations in a manner that has not been seen in previous generations of aircraft. The power electronic converter is a key enabling technology in aircraft electrification. Its prevalence is such that the failure rate of flight critical-loads is closely linked with that of the associated power electronic converters. As such, there is a clear need to better understand the impact of improvements in both the reliability and failure estimation of novel power electronic converters at a systems level in future aerospace applications. Accordingly, this paper presents key highlights from literature on power converter research, summarising advances in reliability-enhancing features and more accurate Physics-of-Failure modelling methods. Simulation studies are then presented, which explore the impact of component-level advancements in power converters on the system-level failure rates and power system architecture configurations of flight-critical loads in more-electric aircraft applications.

Introduction

In recent decades, the electrification of air transport has been the focus of intensive research efforts that has already led to a reduction in carbon emissions. The More-Electric Aircraft (MEA) is a key milestone in the further decarbonisation of aircraft, where traditionally hydraulic and pneumatic secondary power systems are replaced with electrical equivalents [1]. Within MEA systems, power electronic converters (PECs) are a critical enabling technology, with their widespread use facilitating the introduction of novel source and load technologies, higher voltage DC distribution, and microgrid-like power systems [2]. In addition, there is an increased number of electrical loads, when compared to traditional aircraft platforms, that are critical to the safety of the aircraft. As such, the reliability of the PEC becomes central to the reliability of many flight-critical systems [2]–[5]. This trend will be further evident with future electric-propulsion aircraft concepts too. However, the reliability of PECs has been shown to be typically lower than that of other electrical systems in aircraft [6].

This paper presents the interim findings of a study evaluating the impact of the reliability of PECs on flight-critical electrical systems and to what extent the design of MEA electrical power system architectures can be influenced by reliability-enhancing advancements in power electronics technology.

The following sections present a summary of the research literature examining the state of the art in reliability-enhancing features for PECs, Physics-of-Failure lifetime prediction methodologies and theoretical concepts for the reliability analysis of aircraft power systems reliability. Model-based case studies are then presented examining the contribution of PEC reliability to the failure rates of flight-critical electrical loads in MEA applications, and the subsequent impact of improvements in the PEC reliability.

Improving Power Electronic Converter Reliability

Power converters have a number of failure modes including cracking, fatigue, and bond-wire lift-off. Temperature cycling and the switching of the device are generally regarded as the primary cause of power converter failures [7]–[10], although induced failures from cosmic rays are also recognised as a pertinent issue in aerospace applications [11].

Concepts to improve PEC reliability include the use of press-pack technologies to address the issue of the mismatch in the coefficient of thermal expansion in the materials which make up semiconductor switching devices [4] and can otherwise lead to bond-wire lift off. Condition monitoring (CM) approaches for PECs are also considered. These enable the health of the switching devices to be constantly monitored, allowing for estimations to be made regarding the remaining useful life of the device. Furthermore, methods of controlling circulating current allow for better junction temperature estimation and hence more accurate lifetime prediction [9].

From the literature it is clear that in order to enhance converter reliability, the issues pertaining to temperature must be addressed. CM techniques employed in the field of power electronics often consider temperature as the measurand, either directly or indirectly. In [7] it is presented that Insulated Gate Bipolar Transistor (IGBT) on-state emitter voltage and forward voltage are measured, allowing for the determination of a characteristic resistance which in turn infers the junction temperature. In [8] a similar approach is taken where the IGBT on-state emitter voltage allows for observation of the junction temperature on both low and high voltage sides of the converter. In [10], it is proposed that through both CM and active cooling methods, that the device will experience a decreased rate of failure over its lifetime, hence offering a means to increase reliability. Recommendations for improved cooling are also presented in the communications sector, whereby the provision of improved and an increased quantity of heat sinks can lead to a reduced thermal resistance, and thus a reduction in junction temperature [12].

Investigations into increasing current carrying capacity, whilst seeing an improvement in fault-tolerance through the paralleling of switches within the module have been reported to be ineffective at improving reliability however [13]. This was in part due to the increased number of components within the system, but also due to the need for control circuitry to ensure equal division of current across the parallel switches. This work concluded that the use of an integrated power module would improve reliability of the switches by an order of magnitude.

In addition to failures within the semiconductor devices, capacitors within the PEC have, in the past, had an inherently high failure rate when compared with the other components [14]. More recently though, the move away from using electrolytic capacitors to using Metallized Polypropylene Film Capacitors (MPPF) with their inherent self-healing benefits, has brought about lower associated failure rates [15], [16].

Reliability Evaluation of Power Electronic Converters

Reliability, by definition, is a measure of a component or system's ability to perform the intended function over time without failure. Depending on the intended functionality of the system, the level of required reliability may change. In aerospace applications, the lower limit of acceptable system reliability is driven by the severity of the failure consequences, with the appropriate boundaries informed and stipulated in the industry standard for the assessment of reliability ARP4761 [17] and CS-25, which defines the minimum level of compliance accepted by the EASA [18].

Conventionally, the primary metric within reliability analysis is defined as failure rate, λ, which defines the rate in which a component can be expected to fail whilst operating in its useful range. Generally, it is accepted that this is a static parameter, given the assumptions and conditions that are determined prior to the analysis. Directly related to failure rate is Mean Time To Failure (MTTF), which can be defined as the inverse of the failure rate. MTTF is defined as

$$MTTF = \frac{1}{\lambda} = \int_0^\infty R(t)dt = \int_0^\infty e^{-\lambda t}dt, \tag{1}$$

Where *R(t)* is reliability in its simplest form, which is expressed in its simplest form as

$$R(t) = e^{-\lambda t}, \tag{2}$$

With time, *t*, defined in hours.

In systems where the consequences of a failure have the potential to be catastrophic, redundancy can be incorporated to increase the reliability within the system. This is however, not the only reason redundancy can be built in to a system. The practice is used when considering electrical systems to ensure the network can be reconfigured when necessary to re-establish the supply of power to flight-critical loads.

This will see channels within the system replicated, either partially or in their entirety, resulting in the governing mathematical equations in these cases being defined as

$$R_{\text{Parallel}}(t) = 1 - ((1 - e^{-\lambda_1 t}) \times (1 - e^{-\lambda_2 t}) \times ... \times (1 - e^{-\lambda_n t})),$$

(3)

Where $R_{Parallel}(t)$ is defined as the reliability of the parallel connected sections of the network.

Regardless of the composition of the system, when combining redundant or serially connected systems, the method for this remains consistent by taking the product of the individual reliability components which combine to form the total reliability, $R_T(t)$, this is defined as

$$R_{\mathrm{T}}(t) = R_1(t)R_2(t)R_{\mathrm{n}}(t). \tag{4}$$

Probability of failure is a useful metric that is used in the certification of aircraft and aircraft systems by regulatory bodies, such as EASA in CS-25. This is the base metric that is used to determine probability of failure per flight hour and is defined as

$$P_{\mathrm{Fail}}(t) = 1 - R_{\mathrm{T}}(t). \tag{5}$$

Where $P_{Fail}(t)$ is defined as probability of failure.

The use of the probability of failure metric will allow for corroboration with the failure boundary conditions in [18], and when combined with the use of a Functional Hazard Analysis (FHA): the consequence of failures, hence Design Assurance Levels [DALs] [19] can be categorised and compared against.

The assumption of constant failure rate is drawn from the bathtub curve methodology (illustrated in Figure 1), whereby it is predicted that outside of the infancy stages of development of the component, failure rate will be maintained as a constant until fatigue sets in. It is at this point that the reliability of the component will begin to reduce at an exponential rate. In handbooks such as MIL-HDBK-217 [20] and NPRD-16 [21], it is the failure rate in this useful life section of operation that is defined. Generally, system and component reliability can be determined from this data, with experimental data and empirical models used in its determination.

However, there are times where the data does not fully encompass the pertinent failure modes. This is particularly true for the case of power electronic converters [22]. In fact, it is now widely accepted that data from MIL-HDBK-217 [20] is no longer a reputable source when performing reliability analyses [23]. This is a consequence of the time that has passed since the database was last updated, in addition to its use of empirical relationships to determine the failure rate of the components. The working assumption of fixed component failure rates over the lifetime of components regardless of application and operational profile is also recognised as a limitation. The use of the MIL-HDBK-217 datasets for modern aircraft designs would likely lead to unnecessarily pessimistic outcomes [23], which have the potential to introduce inefficiencies in the design to ensure compliance with certification standards.

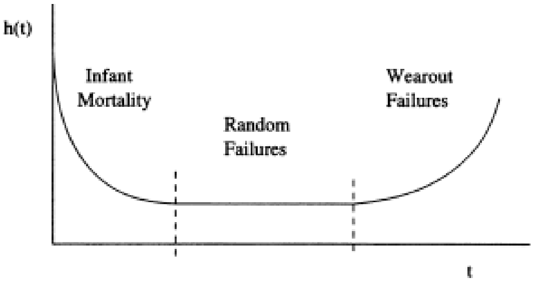

Figure 1: Bathtub curve showing reliability change over time [22]

For higher fidelity modelling, the conclusions from [4], [24], [25] are that temperature and the cycling effects of temperature are pertinent causes of failure in PEC systems. Physics of Failure (PoF) approaches based on [5], [26], [27] detail such electrical and thermal modelling of the power converter and can be incorporated into Monte Carlo simulations to provide a more accurately defined lifetime estimate for the converter.

System-Wide Impact of Power Converters on Reliability

This section provides a system case study to examine PEC reliability impact at system level. As part of the case study, an electrical architecture similar to the Boeing 787 (B787) [28] was used (Figure 2). In this, it is assumed that there are electric flight surface (FS) actuators supplied from the four 230Vac busbars and electric Environmental Control System (ECS) loads supplied from the four ±270Vdc busbars. The failure rate parameter values and associated data sources used in the study are shown in Table 1. In the first instance, fixed failure values are employed, although values derived from more accurate PoF methods are later used for comparison.

Baselining Case Study

In order to generate baseline results, the loss of power supplied to all FS/ECS loads were considered for the top-level failure events. The ECS and FS loads are selected as flight-critical [19]. Accordingly, to

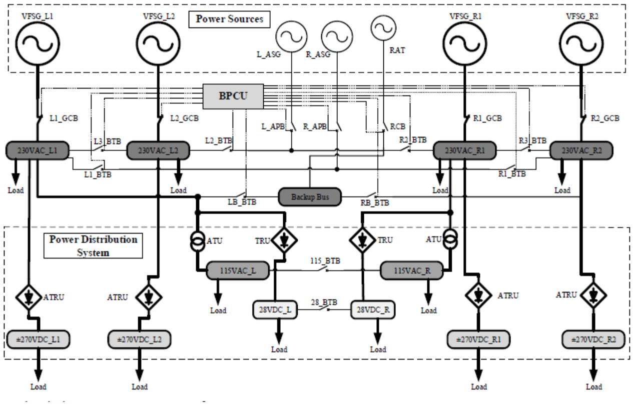

Figure 2: Electrical power system of the Boeing 787 [28]

Table 1: Failure Rate Data [20], [21]

Failure Rate Data	
Component	Failure Rate (hour^{-1})
Cable	8.09×10^{-7}
Busbar	3.96×10^{-9}
Motor	2.306×10^{-6}
Circuit Breaker	5.28×10^{-6}
Generator	1.41×10^{-5}
Power Converter	4.54×10^{-5}
ATRU	1.33×10^{-5}
Transformer	6.57×10^{-7}

satisfy the criteria for safe operation, the probability of complete failure per flight hour of the ECS/FS loads, respectively, must be less than 10^{-9}. For this case, the system was evaluated to the upper-limit of a long-haul fight, which is approximately 20 flight hours.

The calculated probability of complete failure of the ECS/FS loads against elapsed time is plotted in Figure 3 and summarised Table 2. Whilst adherence to certification requirements is judged on the basis of probability of failure per flight hour, it is also useful to have visibility of how this probability of failure increases exponentially over the course of an extended flight. Figure 3 and Table 2 also show how the greater number of components in the network channel supplying the ECS loads increases the likelihood of failure of these loads, as the impact of the power converter failure rates for both FS and ECS loads is consistent.

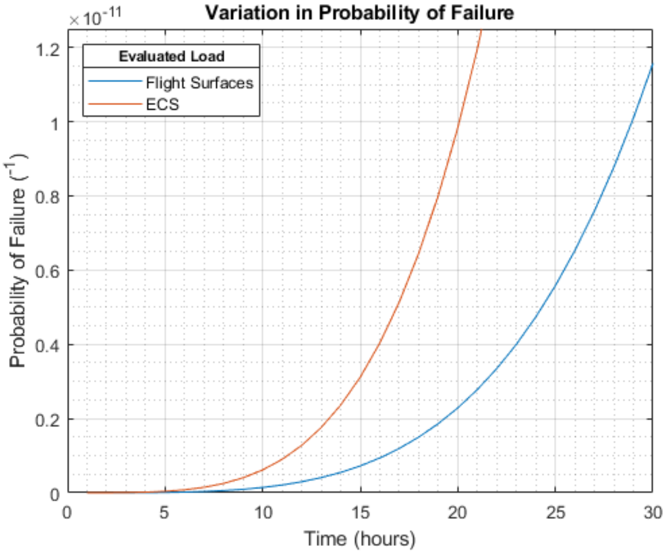

Figure 3: Probability of failure variation over time of the selected flight-critical loads.

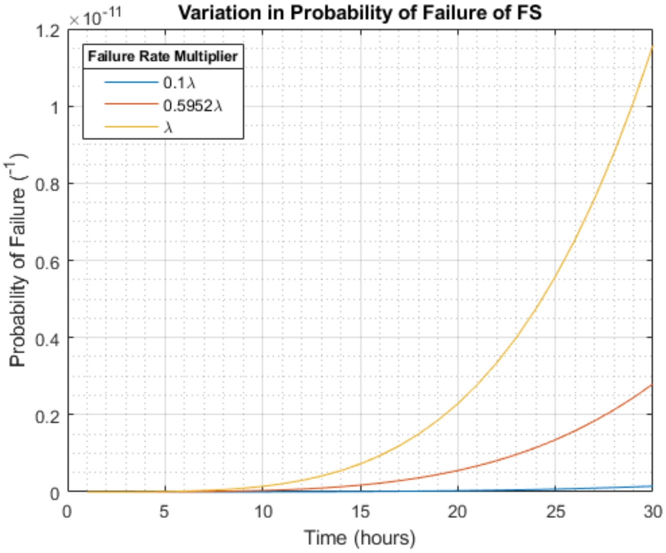

Figure 4: Flight surface probability of failure over time (230 V_{ac})

Converter Sensitivity Case Study

As discussed in Section 3, converter failure rate can be reduced by adopting new technologies, monitoring regimes and improved active cooling methods. In [13], integrated power modules are analysed and show that a ten-fold improvement in failure rate is possible and in [9], a 68% increase reliability is claimed by using an innovative circulating current control scheme. Using these stated advances in power converter failure rate as multipliers for the power converter baseline failure rate previously drawn from NPRD-16 [21] (set as 0.1base and 0.5952base respectively), the benchmarking case study is then revisited, demonstrating the systems-level impact of these improvements. As before, probability of complete failure of the ECS and FS loads is calculated against elapsed time, with the results plotted in Figure 4 and Figure 5 for ECS and FS, respectively.

The results presented in Figure 4 and Figure 5 can also be interpreted using the MTTF measurand. As shown in Equation 1, MTTF can be determined using the reliability expression for a full system channel. The reduction in the MTTF between the benchmark PEC failure rate and the 0.1base case, is 68.6% and 72.0% at a system level for the FS and ECS loads respectively.

Table 2: Probability of Failure per Flight Hour for Flight-Critical MEA Electrical Loads

Probability of Failure per Flight Hour				
Load	1 Flight Hour	5 Flight Hours	10 Flight Hours	15 Flight Hours
ECS	1.1102×10^{-16}	3.8525×10^{-14}	6.1584×10^{-13}	3.1148×10^{-12}
FS	$<10^{-17}$	8.9928×10^{-15}	1.4311×10^{-13}	7.2420×10^{-13}

Table 3: Effects of PEC failure rate alteration and redundancy reduction on MTTF on ECS loads

MTTF for Critical Loads (Hours)		
Critical Load	4 Channel	3 Channel
1	23159	20422
0.5952	30859	27302
0.1	49199	44198

Table 4: Effects of PEC failure rate alteration and redundancy reduction on MTTF on FS loads

MTTF for Critical Loads (Hours)		
Critical Load	4 Channel	3 Channel
1	32316	28615
0.5952	43105	38480
0.1	66068	60900

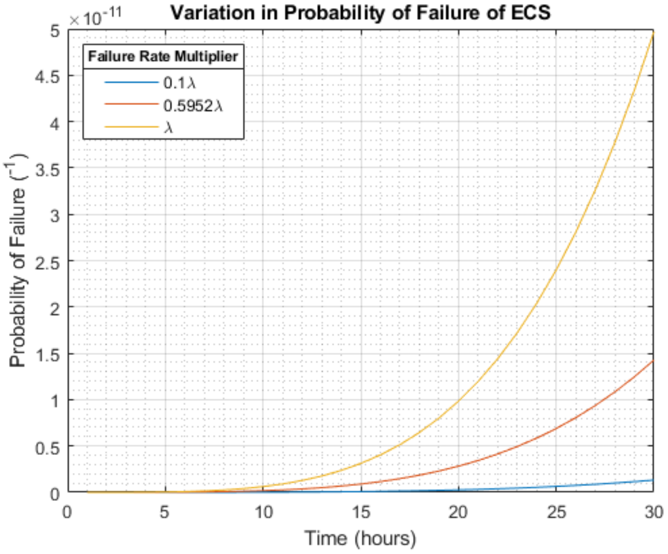

Figure 5: Environmental control system probability of failure over time

Electrical Power Architecture Case Study

A final study is presented, whereby the impact of reducing the number of redundant systems within the ECS and FS loads (and associated power system supply channels) is evaluated, both for baseline and improved PEC failure rates. In this study, the probability of failure and MTTF are calculated for the FS and ECS loads for configurations with three redundant channels. Figures 6 and 7 show the probability of the complete failure of the ECS and FS loads against elapsed time. Tables 3 and 4 show how the MTTF varies with the reduction in redundancy, coupled with the variation in PEC failure rate. Interestingly, for both ECS and FS loads, a 68% improvement in PEC failure rate results in a 3-channel architecture enhanced MTTF which is comparable to the original 4 channel architecture MTTF. This suggests that architectural changes may be possible to an MEA power system based upon advances in PEC system reliability (although other influencing factors also need to be considered).

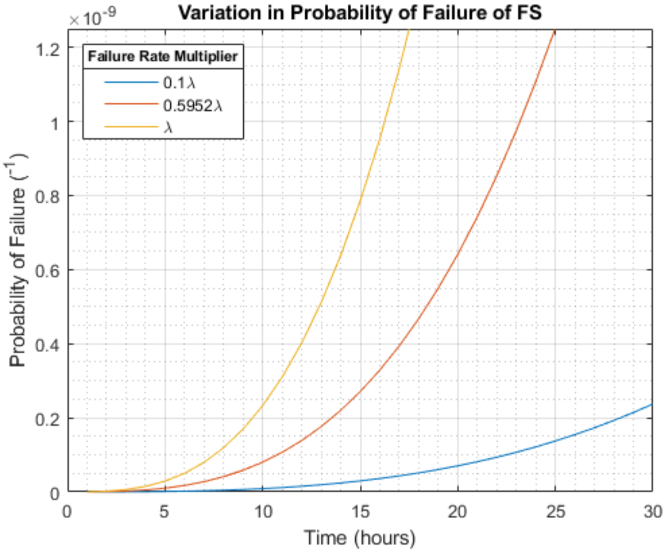

Figure 6: Flight surface probability of failure over time when level of redundancy has been reduced to 3 channels (230 V_{ac})

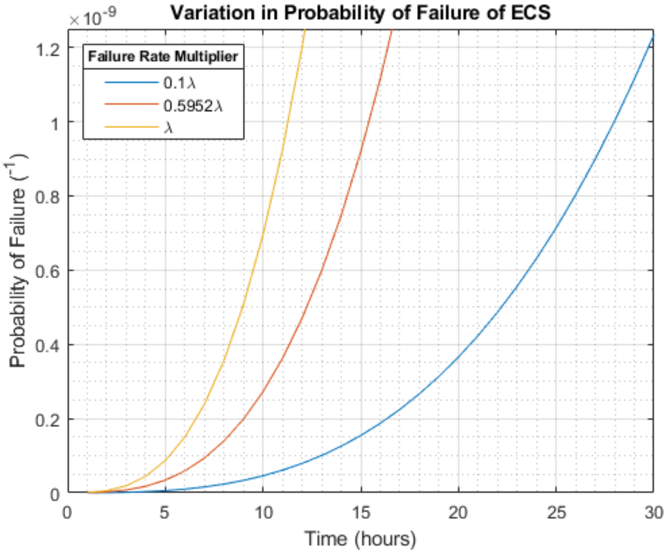

Figure 7: Environmental control system probability of failure over time when level of redundancy has been reduced to 3 channels

Conclusion

This paper has explored the growing use of power electronic converter systems to supply flight-critical electrical loads within MEA systems, highlighting the impact of the PEC system reliability on the overall failure rates of these loads. Model-based studies have been conducted to illustrate the potential systems-level effects arising from improvements in both PEC failure rate prediction and overall reliability, which highlight the opportunity for potential future system architecture change. Building on this work, the authors intend to further investigate PoF methodologies in order to better capture the PEC operational profile on system reliability and to explore a wider range of power system architecture variations that may be facilitated through improved PEC reliability.

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Abbreviations

B787 Boeing 787.

CM Condition Monitoring.

ECS Environmental Control System.

EPS Electrical Power System.

FHA Functional Hazard Analysis.

FS Flight Surface.

IGBT Insulated Gate Bipolar Transistor.

IGCT Insulated Gate Commutated Transistor.

MCS Monte Carlo Simulation.

MEA More-Electric Aircraft.

MTTF Mean-Time-To-Failure.

PEC Power Electronic Converter.

PoF Physics of Failure.

Nomenclature

λ	Failure Rate
λ_{base}	Baseline Failure Rate
$P_{\text{Fail}}(t)$	Probability of Failure
$R_{\text{parallel}}(t)$	Parallel Reliability
$R_T(t)$	Total Reliability
V_{ac}	AC Voltage
V_{dc}	DC Voltage