

Impact of Engine Certification Standards on the Design Requirements of More-Electric Engine Electrical System Architectures

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ABSTRACT

The development of the More-Electric Engine (MEE) concept will see an expansion in the power levels, functionality and criticality of electrical systems within engines. However, to date, these more critical electrical systems have not been accounted for in existing engine certification standards. To begin to address this gap, this paper conducts a review of current engine certification standards in order to determine how these standards will impact on the design requirements of More-Electric Engine (MEE) electrical system architectures. The paper focuses on determining two key architectural requirements: the number of individual failures an architecture can accommodate and still remain functional and the rate at which these failures are allowed to occur. The paper concludes by discussing how the derived failure rates begin to define a set of design requirements for MEE electrical architectures, considering various operating strategies, and demonstrates their application to example MEE electrical system architecture designs.

CITATION: Fletcher, S., Norman, P., Galloway, S., and Burt, G., "Impact of Engine Certification Standards on the Design Requirements of More-Electric Engine Electrical System Architectures," *SAE Int. J. Aerosp.* 7(1):2014, doi:10.4271/2014-01-2119.

INTRODUCTION

The development of the More-Electric Engine (MEE) is potentially one of the next key steps in the greater electrification of aircraft systems [1, 2, 3]. The MEE concept focuses on the replacement of mechanically driven engine accessories such as fuel pumps and oil pumps with electrical equivalent systems, with possible benefits including reduction in overall system weight and size, and improved efficiency and maintainability [1, 2]. Clearly these design aspects are of high importance given the targets for increased fuel efficiency improvement for future generations of aircraft [4, 5] and reduction in aircraft maintenance requirements [4, 6] (including a desire for no unscheduled maintenance of aircraft by around 2020 [6]).

The inclusion of these electrical accessories will mean that the engine electrical power is likely to become more extensive than before, both in terms of cabling paths and power levels. The types of electrical devices which could be used within a MEE system are illustrated within Figure 1. These will also be far more critical to the engine's continued operation. However this increasing degree of importance for electrical systems has yet to be accounted for in existing engine certification standards which, with the exception of providing requirements for electrical engine control systems (EECS) design, do not explicitly cover electrical engine accessories. Therefore, there is a timely requirement to consider the certification requirements of MEE systems.

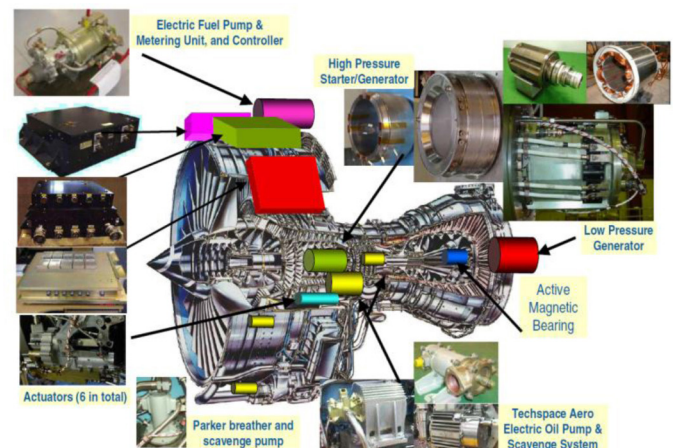


Figure 1. Example More-Electric Engine system with hardware from the ESVR demonstrator [3]

This paper will consider the MEE from the perspective of its electrical system architecture design. Two of the key requirements for the design of a certifiable architecture relate to reliability and redundancy, namely the number of individual failures an architecture can accommodate and still remain functional and the rate at which these failures are allowed to occur. In order to define these design criteria for MEE electrical architectures, the paper conducts an in depth review of relevant engine certification standards, such as CS-E [7]. From this, the paper identifies where clear guidance is given within

current standards, and also where they must be further developed to provide adequate coverage on MEE accessories. Where these gaps currently exist, the paper infers design requirements from existing functional descriptions contained within the standards in order to propose necessary design requirements.

The paper concludes by proposing a comprehensive set of design requirements for MEE electrical architectures for various operating strategies. The value of these requirements to future design programs is then demonstrated through their application to the feasibility evaluation of example MEE electrical system architecture designs.

REVIEW OF ENGINE CERTIFICATION STANDARDS AND RELIABILITY REQUIREMENTS

In order to properly quantify the certification requirements for new electrical loads it is important to understand the context of existing standards and their high level functional requirements. The following sections will therefore review the key certification standards for engine systems. The European Aviation Safety Agency's (EASA) Certification Specifications for Engines (CS-E) [7] and large aeroplanes (CS-25) [8] are used as the main point of reference within these sections however note that similar certification regulations do exist from the Federal Aviation Administration (FAA), with FAR part 25 [9] referring to transport category airplane and FAR part 33 [10] detailing the FAA regulations for aircraft engines. The sections define acceptable failure rates for various 'engine effects' before consideration is given to which of these main failures may be influenced by the engine electrical system. This enables the derivation of design requirements for the various electrical components within this system as will be illustrated.

Engine Failure Types and Acceptable Failure Rates

Information from the standards related to the classification of different failure types and the maximum acceptable rate at which these are allowed to occur is presented in the following subsections.

Acceptable Maximum Failure Rates

Table 1 describes the acceptable maximum probability of occurrence for various failure classifications. Failures are classified based on their severity and likely impact on the aircraft. Clearly the aircraft should be designed in such a way so the failures of increasing severity occur less frequently.

Note that the reliability specifications within AMC 25.1309 [8] define an additional category. This is:

Extremely Improbable Failure Conditions: Extremely Improbable Failure Conditions are those so unlikely that they are not anticipated to occur during the entire operational life of

all aeroplanes of one type, and have a probability of the order of 1×10^{-9} or less. Faults classified as 'Catastrophic Failure Conditions' (where loss of hull and/or multiple fatalities would be expected if the fault were to occur [8]) must be shown to meet this target.

For MEE applications, the reliability of the electrical accessories and supporting electrical architecture is shaped by these general targets as described in later sections.

Table 1. Summary of CS-E failure rate specifications [7]

General failure type classification	Probability (average failures per flight hour)	General description	Engine specific terminology
Extremely remote	10^{-7} to 10^{-9}	Unlikely to occur when considering the total operational life of a number of aircraft of the type in which the Engine is installed, but nevertheless, has to be regarded as being possible.	Hazardous Engine Effects
Remote	10^{-5} to 10^{-7}	Unlikely to occur to each aircraft during its total operational life but may occur several times when considering the total operational life of a number of aircraft of the type in which the Engine may be installed.	Major Engine Effects
Reasonably Probable	10^{-3} to 10^{-5}	Unlikely to occur often during the operation of each aircraft of the type but which may occur several times during the total operational life of each aircraft of the types in which the Engine may be installed.	Minor Engine Effects

Examples of Various 'Engine Effects'

The following sections provide examples of the types of defined within AMC-E 510 [7] as 'Hazardous', 'Major' and 'Minor'. Whilst these are primarily designed to regulate the performance of non-electrical engine system, various entries may still be relevant to MEE accessories and architectures. For example, the 'non-containment of high-energy debris' is appropriate for electrical machines, particularly any high-speed designs that may be considered.

Hazardous Engine Effects

Hazardous engine effects include:

1. Non-containment of high-energy debris
2. Generation and delivery of toxic products caused by abnormal engine operation sufficient to incapacitate the crew or passengers during the flight.
3. Significant thrust in the opposite direction to that commanded by the pilot.

4. Uncontrolled fire.
5. Complete inability to shut the engine down.

Major Engine Effects

Major engine effects include:

1. Controlled fires (i.e., those brought under control through engine shutdown or onboard extinguishing systems).
2. Case burn-through where there is no propagation to Hazardous Engine Effects.
3. Release of low-energy parts where there is no propagation to Hazardous Engine Effects.
4. Thrust in the opposite direction to that commanded by the pilot (below the level defined as hazardous).
5. Generation of thrust greater than maximum rated thrust.
6. Significant uncontrollable thrust oscillation.

Minor Engine Effects

A minor engine effect is an engine failure which only results in a partial or complete loss of thrust and associated secondary engine services. As these failures are expected to occur in service, the aircraft should be capable of controlled flight following an event of this nature.

Failure Conditions and Operating Strategies Influenced by the Electrical Architecture Design

Based on the above review of failure types, two general design aspects have been identified which drive the reliability requirements of an engine system. These can be broadly categorised as:

- The reliability of the engine itself and the components it contains (*physical failures*)
- The reliability of control systems within the engine (*'control failures which lead to unwanted physical effects'*)

The following sections will identify and describe two key failure cases which are influenced by the MEE electrical system architecture design. In each case, two important pieces of information are sought after from an architectural perspective. These are:

- What is the maximum allowed rate of occurrence for the given failure condition?
- How many redundant electrical supply paths are required to loads/supply points to prevent this failure occurring?

The following review will be carried out with these questions in mind.

Single Engine in-Flight Shutdown

ETOPS regulations define performance requirements for any aircraft flying long distance routes or beyond certain distances from a suitable airport. The FAA ETOPS requirements are summarised in [9], with the equivalent EASA requirements

published within [12]. Both sets of standards are primarily concerned with the operation of twin engine aircraft and stipulate performance requirements of the remaining healthy engine following the failure of the other engine. Approval for ETOPS is based on the time within which a second engine failure would be extremely remote, where the time relates to the flight time to the nearest suitable airport with the aircraft travelling at a single engine speed.

These regulations can influence an electrical architecture in two main ways: the provision of backup electrical supplies and the engine in-flight shutdown (IFSD) rate. The relevant sections from the regulations are discussed below.

ETOPS Electrical System Requirements

The following relevant ETOPS electrical system requirements are derived from [9] (Chapter II, section 7). Note that paragraph numbers have been retained for ease of cross referencing with [9]. These requirements are:

6. During extended duration single-engine operation, the remaining secondary power (electrical, hydraulic, pneumatic) will continue to be available at levels necessary to permit continued safe flight and landing.
7. In the event of any single failure, or any combination of failures not considered Extremely Improbable, electrical power should be provided for essential flight instruments, warning systems, avionics, communications, navigation, required route or destination guidance equipment, supportive systems and/or hardware as well as any other equipment deemed necessary to continue safe flight and landing at an ETOPS en-route alternate aerodrome. Information provided to the flight crew should also be of sufficient accuracy for the intended operation (typical functions are described in [9]).
8. Three or more reliable and independent electrical power sources should be available. As a minimum, following failure of any two sources, the remaining source should be capable of powering the items specified above [in (7)]. When one of the 3 independent electrical power sources is time-limited (e.g. batteries), this power source should have a capability to provide sufficient power for the items listed above for continued flight and landing to an ETOPS en-route alternate aerodrome.
9. For ETOPS approvals above 180 minutes, the following additional requirements exist:
 1. Unless it can be shown that the failure of all 3 independent power sources required by paragraph (8) above is extremely improbable, following failure of these 3 independent power sources, a fourth independent power source should be available that is capable of providing power to the essential functions referred to in paragraph (7) for continued safe flight and landing to an adequate ETOPS en-route alternate aerodrome.

Depending on the criticality of engine accessories, these requirements may impact the necessary level of engine redundancy.

ETOPS Engine IFSD Rates

Both [9] and [12] provide examples of the average IFSD rate which engines on a twin engine aircraft should achieve in order to meet certain ETOPS authorisation levels. The clearest definition (in the opinion of the authors) for the different ranges of applications is provided by EASA [9] (although the FAA and EASA guidance is generally consistent). These various levels are summarised below within Figure 2 and Figure 3.

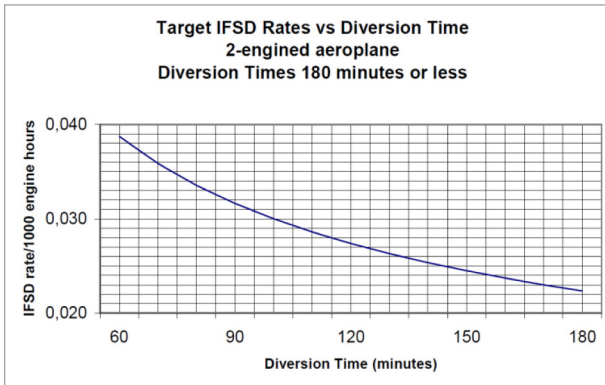


Figure 2. EASA derived ETOPS curve for IFSD rates against diversion time for diversions of less than 180 minutes [9]

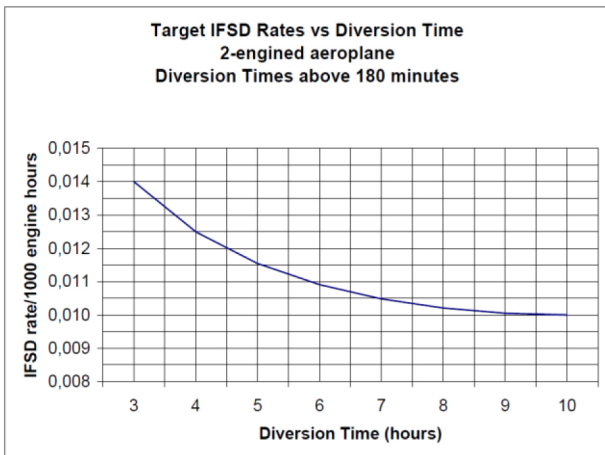


Figure 3. EASA derived ETOPS curve for IFSD rates against diversion time for diversions above 180 minutes [9]

Interpreting the above per engine IFSD rates from EASA; these are generally derived from two main influencing factors: the target reliability for twin engine failure and the diversion time to a safe landing area. The relationship between these factors can be simply represented as

$$IFSD \text{ rate} = \frac{\text{overall probability target}}{\text{Diversion time}} \quad (1)$$

Within (1), the overall reliability target will be around a probability of 1×10^{-9} failures per flight hour - this being the maximum probability for the occurrence of any catastrophic failures (although this target appears to vary at different points - for example two different targets are provided for the 3 hour

diversion within Figure 2 and Figure 3). Within Figure 3, for 10 hours diversion time to be acceptable the overall probability target is equal to 1×10^{-10} failures per flight hour (i.e. a rate of 1×10^{-10} failures per flight hour for 10 hours). A plot based on (1) (which is the authors' simplification of the IFSD rate calculation) with an overall target of 1×10^{-9} failures per flight hour is shown in Figure 4 for reference. Note that the resultant IFSD rate is lower (for the shorter diversion times at least) than the EASA plot in Figure 2 highlighting that this overall target can be higher than 1×10^{-9} failures per flight hour.

The impact of these various failure rates will be to place different requirements on the engine reliability, and hence on the components responsible for maintaining continued engine operation.

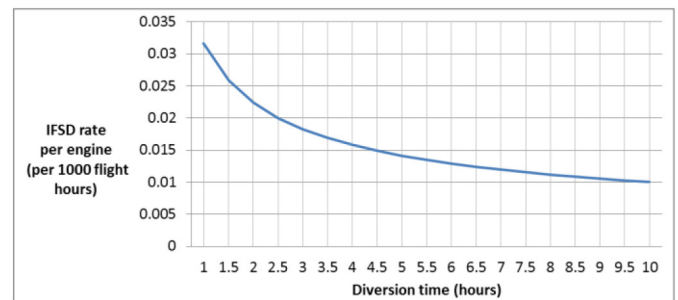


Figure 4. Example IFSD rate based on equation (1) with a twin engine failure target of 1×10^{-9}

Summary of Requirements for Prevention of Engine IFSD

The above sections have shown that there is some variability in the allowed IFSD rate of engines, with this mainly depending on the whether ETOPS certification is required and if so, the desirable 'diversion time' of the given aircraft.

CS-E classes engine failure (provided no additional external issues occur) as a minor engine effect and so on this basis its allowed failure rate ranges anywhere between 1×10^{-3} to 1×10^{-5} failures per flight hour. Bringing in the requirements for ETOPS from Figure 2, Figure 3 and Figure 4 narrows this range to 3.9×10^{-5} to 1×10^{-5} failures per flight hour, depending on required diversion time. This is this allowed failure rate of the overall engine system inclusive of the combined failure rate of relevant electrical components along with all other engine components which would contribute to an engine failure.

To determine the impact this has on the engine electrical system and its components requires two main steps:

1. A qualitative failure analysis of the electrical system to assess which fault types will cause an engine IFSD to enable the allowed probability of these occurring to be assessed and quantified.
2. A quantitative failure analysis of the non-electrical engine parts which could result in an engine shutdown to enable the allowed electrical system failure rate to be determined.