Reliability Considerations of the Common Unit in Hybrid Electric Propulsion

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Abstract. Since the beginning of aviation, reliability has been one of the most important elements in terms of flight safety and certification. Reliability starts from the smallest part of the aircraft and covers all components up to the entire system. The use of a hybrid-electric propulsion system has become one of the important study topics today. When hybrid-electric propulsion architectures are examined, it is seen that some elements are repeating which the authors named as common unit. This common unit is similar to the all-electric propulsion architecture and consists of a battery, battery management system, and power electronics which are used in conjunction with the hybrid-electric systems. In this study, the components and units used in the hybrid-electric propulsion system and the common unit has been examined for reliability. The common unit is proposed as a means of simplification of both the sizing and certification of the hybrid electric architecture. The reliability of the battery, battery management system, and power electronics within the system that makes up the common unit is discussed in detail for determining the reliability of the hybrid electric architecture.

1. Introduction

According to the European Union Commission's (Flightpath 2050) targets, aviation emissions are predicted to reduce by 75% in CO², 90% in NOₓ, and 65% in noise in 2050, compared to 2000 data. These goals necessitate improvements in not only aerodynamic and propulsion efficiency, but also air traffic management, infrastructure operations, and other aspects of aviation. New propulsion system concepts have been the subject of numerous investigations. As a consequence of this research, it was determined that the battery is the most important factor in the success of electric and hybrid-electric aircraft [1].

Reliability is the probability that a component, system or subsystem will perform its desired functions for a calculated and predicted period under certain environmental and operational conditions. The reliability function R(t) can also be called the probability of operating without error in the time interval [0, t]. The reliability of the system is time-varying, decreasing as the operating time progresses [2].

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It is seen that hybrid-electric propulsion occupies an important place in the literature. However, to apply this new technology especially in civil aviation, hybrid-electric propulsion must be shown to be safe. It must be demonstrated that it is safe for every user, passenger, other aircraft, and ground personnel (maintenance and operator). As certification in civil aviation is a cumulative effort which depends on lessons learnt on application, introducing a new technology such as hybrid-electric propulsion, makes it complicated as no experience is present for electric propulsion especially for larger civil aircraft.

When analyzing hybrid-electric propulsion architectures, some of the architectural elements are seen repeating and common among all. This grouping under common unit would provide convenience in certification, by focusing only on the newly introduced technology as a sub-system. Later w-including the interface and integration issues, the certification of the whole aircraft can be achieved without refusing the already present experience in reliability assessment of the gas turbine engines.

2. **Common Unit**

Hybrid electric propulsion architectures are examined and it is determined that they have a common structure. It is determined that this common structure is similar to the structure used in all-electric propulsion architecture. This common unit which is given in Figure 1 consists of a battery, battery management system (BMS), and power electronics. Authors propose to call this structure, which consists of three components, "Common Unit". The importance of the common unit is that it facilitates certification and examination. Especially during the design of hybrid-electric propulsion systems, the common unit provides sizing and certification ease which provides a specific focus on power and energy requirements.

Whatever the aircraft size and type is, it needs a battery to store electrical energy and for the propulsion system. In addition, batteries are used in almost all aviation platforms due to low failure rates, replacement costs, long life, and safety.

BMS keeps the battery pack at a sufficient performance level by providing charge and discharge synchronization of the cells that make up the battery. It monitors and predicts the voltage, current, temperature, SoC, DoD, SoH values of each cell. It detects possible malfunctions that may occur in the battery and provides protection. It establishes reliable communication between system components. BMS extends battery life and makes the battery more reliable.

Power Electronics prevents energy losses during power conversion, reduces maintenance costs, provides more efficient ways for power conversions to the system, and increases the life of electronic components.

![Figure 1. The common unit.](image)

3. **Battery**

Almost all aerospace platforms use batteries to store electrical energy on board. Whatever the aircraft, it needs batteries to store electrical energy. Air platforms are essential to carry all of the energy for the vocation and shall turn back without fully using it. Each task has its requirements. Therefore, unlike lead-acid battery technology, these batteries need to be designed for each type of aircraft.

Lithium-ion batteries are widely used energy storage media thanks to their energy density and power capacity and are preferred in different applications. Batteries are used in satellites, unmanned aerial vehicles, electric vehicles, and aircraft due to their low failure rate, replacement costs, long life, and safety. Nevertheless, lithium-ion batteries are inherently complex and can cause safety, malfunction, and performance degradation issues. Conventional battery safety and reliability tests based on standards such as IEEE 1625/1725, IEC 61960, UL 1642, and UN 38.3 are based on pass/fail criteria and do not provide information that can be used in system design and risk assessment.
Failure modes, mechanisms, and effects analysis (FMMEA) are used to characterize potential failures in lithium-ion batteries, how to identify failures, which processes cause failure, and how failures are modelled for failure prediction. This provides a failure physics approach to battery life prediction that considers battery life cycle conditions, failure mechanisms, and their impact on battery health and safety.

Mechanisms that take place in batteries are discovered later in 1896 than the construction of the first battery in 1800 by Volta [3]. In spite of the fact that enormous effort is given, and a good amount of data is collected on battery systems, there is still a need for further research and development on the battery and related systems to discover mechanisms and increase the capabilities of the battery.

Batteries have a multidimensional structure, and battery systems are made up of active materials including raw materials, cells, battery management systems, and connectors, as well as related switches and fuses. Each of these subsystems has its own set of problems with reliability. Figure 2 depicts a schematic representation of the relationships between the various components of the battery system [4].

![Figure 2. Multi-physics Interactions Across Varied Length Scales [4].](image)

A battery consists of nanoscale raw materials that combine to form microscale electrodes and active materials, and these materials are used to produce cells with specific heat management and conductive design elements. These cells were combined in packages with conductive elements that were supposed to cover electricity and energy needs, and these packages were later combined with the integration of BMS and other mechanical, safety, and control elements in battery modules. Since the battery system consists of several layers and components, its reliability and safety depend on reliability and safety and functionality under operating load conditions (durability). The issues related to each component are given in Table 1 and Table 2.

**Table 1. Functional Properties.**

| Property of the Battery | Active Material | Cell | Module | System |
|------------------------|----------------|------|--------|--------|
| Temperature            | X              | X    | X      | X      |
| Recyclability          | X              |      |        |        |
| Power Density          | X              |      |        |        |
| Energy Density         | X              |      |        |        |
| Cost                   |                | X    | X      | X      |
| Property of the Battery | Active Material | Cell | Module | System |
|-------------------------|-----------------|------|--------|--------|
| Safety                  | X               | X    | X      | X      |
| Reliability             | X               | X    | X      | X      |
| Durability              | X               |      |        |        |
| Availability            |                 |      | X      |        |
| Maintainability         |                 |      |        | X      |
| Predictability          |                 | X    |        | X      |

Batteries come in various electrochemistry which has varying characteristics. Those characteristics can be listed as heat response behavior, power capability, energy density, internal resistance, etc. These characteristics depend not only on the nanoscale properties but also cell size, shape, and number of the cells used in the battery. Some of the characteristics such as internal resistance of the cells also change due to use modes such as a number of cycles, environmental conditions, and so on. The internal resistance of the cell is also a function of the state of charge (SoC) at the moment. Because of these variable characteristics, management of the battery system shall consider these complex properties for safe and reliable operation, which also complicated the certification of the battery systems.

### 3.1. Reliability of The Battery

The qualities of the battery and each component should be checked if the battery is to be certified. Active material levels consist of an atomic scale, particle scale, and electrode scale. For the active material to be used in the battery, it must meet certain safety and durability requirements. Provide safety, reliability, and predictability. To achieve the battery's certification at the pack level, it must be safe and reliable. The battery system must supply all properties to ensure certification of the battery system level. When looked at separately in terms of safety, materials that do not cause fire when the material overheats should be chosen at the active material level, overcurrent protections should be implemented at the cell level, unwanted situations should be avoided at the pack level, and at the system level, the battery management system should be able to generate warnings and regulate the system. As a result, battery system verification begins at the atomic level and progresses to the system level.

Liu et.al. (2017) developed a reliability evaluation method that depends fundamentally on the state-of-health (SoH) estimation of the cells [6]. This state estimating of the failure modes of the cells is required to give an idea of the battery reliability.

The authors of this research propose that the reliability of the battery shall also consider the suitability of the electrochemistry to the operational requirements. For example, cells with an iron-phosphate electrode is made with mechanically stable elements and provide safety for a wide range of temperatures, on the other side they have a low energy density compared to other electrochemistries. Also, the degradation models of the cells shall be regarded by the soft functions of the BMS to adjust the SoH estimations in a safe and economic margin. The selection of the right electrochemistry is the primary measure of reliability. There is one other means of increasing the reliability of the battery by deploying a larger capacity of battery than required. In this manner, the discharge ratio (C) and cycle rates will decrease hence increasing the reliability [7]. Although it adds up cost of weight of battery, reliability trade-off shall be performed on this possibility.

### 3.2. Battery Management System

The large number of cells used in batteries creates safety, integration, cost, and reliability concerns. Therefore, a battery management system (BMS) is necessary for safe operation. BMS must be efficient and also safe in itself to keep the battery system ready to go anytime, anywhere [8].
The main functions of the BMS are as follows: it collects battery information including total voltage, total current, module voltage, temperature, and similar important signals, determines the fault status of the battery, and also calculates the charge status of the battery [9].

In addition, the battery management system must ensure that the voltage value of each cell is at the same level. The BMS also ensures that the battery operates at the expected voltage and temperature and prevents the battery and each cell from being overcharged or over-discharged. Thermal loads created by the charging and discharging of the battery shall be controlled for BMS for safety. BMS ensures that the battery operating temperature is in the safe limit range values and temperature difference among the cells are at an acceptable level. It provides this balance with the thermal management system. In favor of all this, BMS increases the lifetime, safety, and reliability of the battery and electronic system.

Because of the thermal issues related to the battery, thermal management shall be incorporated into the battery system. BMS is expected to handle the thermal management system according to utilization rates, SoC, and SoH values of the battery. Thermal issues can be grouped under two titles one is the safety thermal management and the other is optimal operation thermal management. In the first one, the cells are handled in the safe temperature range zone to avoid any deterioration or capacity fading as shown in Figure 3.
In the second type thermal management is utilized to operate the cell in the optimal range suitable to its electrochemistry. As shown in Figure 4, cell performance highly depends on the thermal window it operates. Thus, BMS shall be specifically adjusted for each electrochemistry used in the battery pack.

The main functions of the BMS are given in the schematic in Figure 5 [5]. These functions can be performed by both software and hardware elements of the system [10]. The software components of the BMS shall be capable of managing both static and changing characteristics of the battery beside the characteristics that depend on the electrochemistry.

3.3. Hazards Associated with Common Unit and Battery System

The following hazards can be listed to be related to the Common Unit. Hazards listed should be considered for each design project in relation to aircraft and propulsion system design. It is important to mention that any hazard shall be considered related to other functions and elements of aircraft systems and their operation.

- **Aircraft propulsion battery fire**: This hazard is mostly related to the abnormal operation, physical damage of the battery system, and thermal runaway.
- **Unexpected cell degradation**: Cell electrochemistries degrade by time in operation. It is important not only to report to the pilot about the level of charge but also the availability of the charge in the expected operation. As most of the calculations of SoC depend on the open terminal voltage of the battery, a redundant means of capacity fade tracking or SoH shall be regarded.
- **Overheating of the cells**: as all of the electrochemistries depend on temperature by means of SoH and SoC, the specific focus shall be given on tracking of the battery temperature.
- **Propulsion bus failure**: any means of loss of electric transmission from the battery to motor.
- **Avionics bus and communication failure**: failure of the correct communication between Common Unit and the aircraft systems.
- **Battery modules separate from attaching points**: physical separation of the battery from its fixed points.
- **Electromagnetic interference in flight BMS**: interference which creates the possibility of misoperation of the BMS electronic circuits.
- **Personnel exposed to high voltage/current**: during operation or maintenance, direct contact of personnel to high voltage terminals.
- **Inadvertent system activation**: as a part of the propulsion system, Common Unit shall also be aware of the aircraft operation mode.
- **Electrical discharge/shock/arc flash**: hazard of open contact of terminals or output of the system to conducting elements in an unwanted manner.
- **Electrical fire**: hazard of open contact of terminals or output of the system to conducting elements in an unwanted manner and starting of fire because of this.
- **Loss of hardware communication link**: loss of physical medium of communication with aircraft.
- **Parasitic electric current on the bus**: the presence of unwanted disturbances on the bus.

3.4. Reliability of Battery Management System

The reliability and cost-efficiency of the air vehicle depend directly on the battery system. Therefore, BMS plays an important role in obtaining the level of safety and reliability of the platform. BMS ensures safe operation of the battery and monitoring the battery. As a general rule, BMS takes care of soft and hard limits of the safety borders of the battery. The battery management system provides both soft and hard limits to ensure the safe operation of the battery in terms of voltage, current, and temperature dimensions. A soft limit is usually provided digitally, i.e., software. Hard limits provide analog for example fuse, contactor, etc. A schematic description of the BMS safety application is given in Figure 6.

With the use of battery systems for aircraft propulsion, higher current and cycle times shall be considered. Especially in comparison to electric cars which have lower reliability requirements under lower loading conditions such as lower current levels and lower cycle requirements. This is one of the reasons the authors propose the term "propulsion battery" to differentiate the requirements of "supply battery" for supporting...
electric buses of the aircraft. As the main component of the battery system, the reliability of the BMS provides a critical requirement for the design of the battery [9].

Xiong Shu et al. calculated the reliability of the entire battery system. They found out that with advancing service hours of the battery such as 5,000, 10,000, 15,000, and 20,000 hours, the calculated reliability index gradually reduces from 95.3%, 90.9%, 86.7% down to 82.6%. This shows us that the reliability of the battery gradually decreases as the operating hours increase [11]. This study does not take into account the reliability of the software and the suitability of the algorithm used in the software. With the degradation of the capability of electrochemistry, BMS functions shall be capable of coping with this change. Therefore, BMS reliability calculations shall consider each functionality of the BMS separately.

Airborne BMS design is subject to the following standards:
- RTCA/DO-178B, Software Considerations in Airborne Systems and Equipment Certification
- RTCA/DO-160D, Environmental Conditions and Test Procedures for Airborne Equipment
- RTCA/DO-254, Design Assurance Guidance for Airborne Electronic Hardware

Reliability aspects of the BMS can be listed as follows:

The hybrid-electric propulsion aircraft provides sufficient flexibility to accommodate increased engine and aircraft integration while requiring that the engine and control system continue to operate safely and reliably in the event of a failure of either power or data from the aircraft, or both, resulting from the use of electronic control technology. This case requires possible modes such as only electric or only internal combustion propulsion. An "unacceptable change in power or thrust" is one that has a severe influence on the battery's performance margins, such as high current demand from the battery. The BMS shall be capable of handling such cases as per the certification requirements mentioned in CS-E.

In order to fulfill the requirement of “In case of loss, corruption or failure of aircraft supplied data or power, the engine should continue to function in a safe and acceptable manner, without unacceptable effects on thrust or power, hazardous engine effects, or loss of ability to comply with the operating requirements” the BMS shall be able to continue the communication with the aircraft by an alternative means such as redundant communication channels and analog.

Also, a maintenance plan must be developed during the design of the BMS. Maintenance requirements shall include periodic inspections or tests for required shielding, wire shields, connectors, and equipment protection components.

4. Power Electronic

Power electronic (PE) systems are increasingly used for adjustable speed drives, interfacing renewable energy sources, energy storage systems, hybrid electric aircraft, and hybrid electric vehicles. Power electronics offer these systems more efficient solutions for power conversions. Power electronic reliability is very important to design components, reduce energy losses and maintenance costs, and prolong their lifetime. Therefore, mathematical estimations are important to analyze the reliability of the power electronic system.

Power electronics have been used in aviation applications for a long time and therefore reliability issues are studied up till now. For example, the application of Full Authority Digital Engine Control (FADEC) is a good model of successful application of such a system in aviation, as the propulsion subsystem. The use of PE in the battery system now makes the application a part of the propulsion system. Therefore, the initial certification of the aircraft system now shall address the PE reliability and functionality.

5. Conclusion

A "Common Unit" is defined for the easiness of the certification and design processes of the aircraft. The common unit consists of both software and hardware components. The Common Unit manufacturer should ensure that the safety and reliability objectives of the system are consistent with the associated aircraft requirements. Reliability of both shall be considered and the suitability of algorithms used in the BMS shall be demonstrated.
The hazards associated with the common unit are listed. Regarding aircraft and propulsion system design, the hazards outlined should be considered for each design project. It is important to mention that any hazard shall also be considered related to other functions and elements of the aircraft system and its operation. Certification of battery system shall consider all dimensions starting from the atomic scale up to system level. Suitability of the electrochemistry to the specific mission shall be regarded. The battery system has a BMS on top, which is a critical element for safety and certification. BMS soft functions such as SoC and SoH shall be mature and shall be suitable with nano and microelements of the battery.

For battery safety and reliability, if higher battery capacity is used, this can improve the safety of the battery as the discharge and cycle rate of the battery will be reduced. As it will add up in cost and weight, the reliability gain shall be optimized. Common unit reliability analyze can be performed separately, also by using the experience gained on the all-electric propulsion. The certification of the hybrid-electric propulsion can be performed using the reliability data and experience on the conventional propulsion system, taking special care on integration and interface requirements.

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