Methodologies for the Synthesis of Reliable MEA Electrical Power System Architectures

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Abstract— **This paper reviews the main optimization approaches and design frameworks found in the literature for the synthesis of power system architectures for More Electric Aircraft (MEA). System- and network- engineering are the main interdisciplinary fields that have been used to conceive new highly reliable architectural solutions that demands both disruptive technologies utilization and appropriate complexity management. Being safety the most important feature, it is imperative to explore the benefits these design approaches can offer in the formulation of a MEA power system design problem considering safety and reliability requirements.**

Keywords—Aircraft power system architecture, More Electric Aircraft, network design, system reliability, reliability-based design

I. INTRODUCTION

The MEA is a concept that defines the future of aircraft electrification. Global commitments for achieving a more sustainable environment have triggered several agreements committed to greatly reduce the amount of fossil fuel emissions. Given that the aircraft industry contributes around 3% to the total world's emissions [1], and this figure will definitely increase in the next decades, it is imperative to explore aircraft electrification as the key enabler for cleaner skies, emission reduction, and higher efficiencies [2], [3]. Certainly, electrical power system (EPS) plays a vital role in achieving aircraft electrification because energy conversion on-board will be redefined. With the production and commissioning of aircraft electrification flagbearers such as Boeing B787 and Airbus A380, transformation of hydraulic- and pneumatic- systems into more efficient electro-mechanical counterparts have become a requisite for improving overall performance while complying with rigorous reliability requirements. Being a safety-driven industry, the future MEA EPS will have to comply with the strictest safety and reliability specifications.

Today's aircraft power systems are divided in left- and right- sides, each one with their own electrical generation, auxiliary systems, and loads. Because of this configuration, it can be split into two autonomous microgrids with the possibility of reconfiguration whenever contingencies occur, such that safety is never compromised. Airworthiness specifications rule aerospace engineering in this matter and provides all the design guidelines to produce a reliable system [4]. Due to the adoption of new technologies and the integration of more-electric subsystems, known as *fly-by-wire*, the EPS will require to maintain or even exceed current reliability specifications due to the introduction of new topologies, devices and contingency types. In this context, the exploration of a broader design space, sometimes even unfamiliar with respect to the current state-of-the-art in aircraft engineering, could lead to innovative solutions for the MEA EPS architecture. Hence, it is imperative to examine both the design approaches and standards that will guide the synthesis of new architectures for MEA EPS. However, reliability- and performance- based optimization formulations will follow the industry driver's requirements to ensure feasibility. The rest of the paper is organized as follows. Section II describes the implications of reliability in the design of a MEA EPS. In Section III, the predominant reliability oriented design approaches are explored and discussed. Finally, the paper comes to its conclusion in Section IV.

II. RELIABILITY IN THE MEA EPS DESIGN

Safety is the condition of being secured from danger or disabled to cause danger. In order to assess the degree of safety, systems comply with a certain level of reliability. Safety can also be defined by other attributes such as robustness, resiliency, and survivability. Depending on the application, these attributes are defined on a set of functional and safety requirements. For instance, an EPS has survivability if they can supply critical loads under any failure condition [5], or it is resilient if it maintains the healthy operation of un-compromised circuits after a catastrophic event. In the MEA EPS design context, safety attributes can be defined as in Fig. 1 in which there are two qualifiers: failure recurrence, and failure impact.
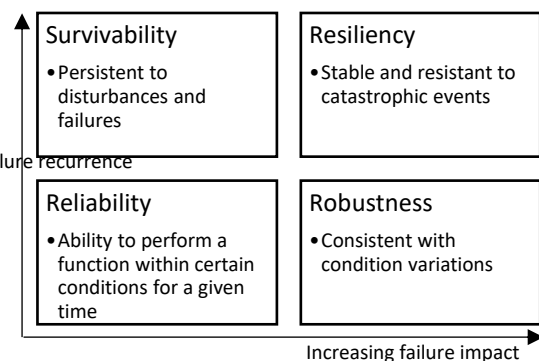

Fig. 1. MEA EPS's safety attributes conceptual map

Aerospace engineering design have consistently focused on reliability, which includes survivability, resiliency, and robustness indistinctly. However, in addition to compliance to these attributes, a safer and more reliable MEA EPS also relies on economic feasibility. Opportunities for regional markets face conflicting requirements, quicker mission deployments, new technology adoption that requires substantial training or additional *power-by-the-hour* contracts, increased complexity in systems' integration, faster time-to-market requirements, and cost-effective business case implementations. On one hand, conventional design has proven to optimize the system by optimizing each component separately yet observing

reliability specifications. On the other hand, future designs pose an engineering challenge for which current tools are left unprepared. In the past, severe accidents due to unexpected failures have not been oblivious to the aircraft industry. Thus, reliability and safety are of utmost importance in the MEA design, and this is why future design frameworks has the challenge to provide solutions that exceed today's performance, regardless of their level of complexity. With such premise, there is no room for error. In an attempt to depart from conventional design methods, MEA EPS design has revisited system's engineering principles and network design formulations. In any case, a reliability-based optimization has served as a tool that provides the mathematical framework to explore the design space to construct an optimal architecture. For the rest of the paper, reliability is used to define the degree of safety of a MEA EPS. The implications of conventional design flow and the aerospace design guidelines are outlined shortly.

A. Conventional Design

The main structure of conventional design (CD) consists of an iterative process where unsatisfied performance evaluation generates new specifications as shown in Fig. 2, until it achieves the expected performance.
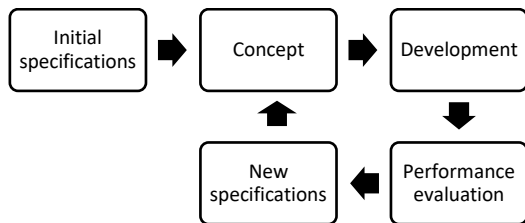

Fig. 2. Conventional Design (CD)

A common application of CD is sub-system design, with very high reliability solutions. However, with the increase in MEA complexity, CD could be time- and resource-consuming, especially when driven by a large number of conflicting specifications. Besides, limiting the investigation of innovative and disruptive solutions is likely because uncertainty forbids diversion from known designs. The exploration of new EPS architectures for MEA demands a novel construction process that merges design and performance evaluation in an integrated manner, unlike the iterative locally-optimized CD's method, with careful attention to smart utilization of constraint resources (weight, volume, cost) for optimal power density and efficiency. An efficient way to explore the MEA EPS requires the adoption of system engineering and network design approaches, as shown in Fig. 3. On one hand, network design and graph theory allows the definition of an interconnected structure for generators-to-loads power transfer. On the other hand, system engineering provides the principles to integrate and manage complexity and performance evaluation over the system's life cycle. In recent years, novel design frameworks based on the integration of performance evaluation and the design space search have produced MEA prototypes, with the potential of producing accelerated time-to-market developments and synthesizing innovative architectures.
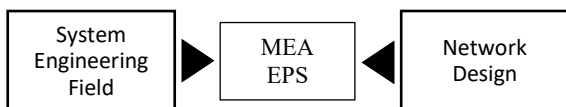

Fig. 3. Field contributions for MEA EPS design

B. Aerospace Design Guidelines

In the aircraft industry, designs must comply with military and aerospace standards and guidelines, which are also followed by commercial aviation. MIL-STD-217 and other reliability standards shown in TABLE I. are mandatory for aircraft electrical systems certification. However, these standards will experience profound transformations to reflect new functional and operational requirements because the exploration of future MEA will lead to radical different topologies and technological innovations [6].

TABLE I.   RELIABILITY STANDARDS AND GUIDELINES FOR ELECTRICAL SYSTEMS

Standard	Description
MIL-HDBK-217 / MIL-STD-217	Developed by the US DoD for military and aerospace. It is used as a reliability prediction methodology. The Stress Analysis section is applied on different operating conditions (environment, temperature, voltage, current, and power levels). Latest version: 217F, 2nd rev. 1995
MIL-STD-1553	Standard for data buses that allows electronic sub-systems to interact with each other and other on-board flight computers.
SAE-ARP-4761	Used to determine compliance with Federal Aviation Regulations (System Safety Assessment). Primary analyses: Reliability Prediction, FMEA and FTA, Common Cause Analysis, and Failure Mode and Effects Summary.
SAE-ARP-4754	Guideline developed by SAE International that addresses the development processes that support the certification of aircraft systems.

III. MEA RELIABILITY ORIENTED DESIGNS

The MEA EPS design comprises not only the architecture generation, i.e. topology structure, but also the performance evaluation, being reliability the main performance index. According to IEC 60050-191, system's reliability is the probability of performing the system's function all over a time interval t. This concept dominates reliability oriented approaches have been used in the design of MEA EPS. TABLE II. presents a survey on recent design approaches and applications for MEA EPS found in the literature.

A. System Engineering Approach

System's design defines a structure that satisfies a number of functional specifications based on the expected system's performance. Given a set of reliability specifications, system's design becomes a collection of methodologies intended to maximize reliability targets, hence, mathematical optimization is the key enabler. Recently, MEA EPS synthesis has been assessed either with unified framework approaches (UF) or reliability-based design optimization techniques (RBDO), as shown in Fig. 4. It is relevant to mention that Platform Based Design (PBD), a method originated in the electronic devices industry, has been introduced in the MEA EPS design with strong adoption of new performance-verification' tools and novel specification languages. Although PBD has been applied in micro-electronics systems design due to its high complexity and large scale integration (millions of components), it has also been applied to the electric power system design with two main approaches: Correct by Construction (CbC) and Contract based design (CbD). The latter has included controllability performance evaluation within the design process.
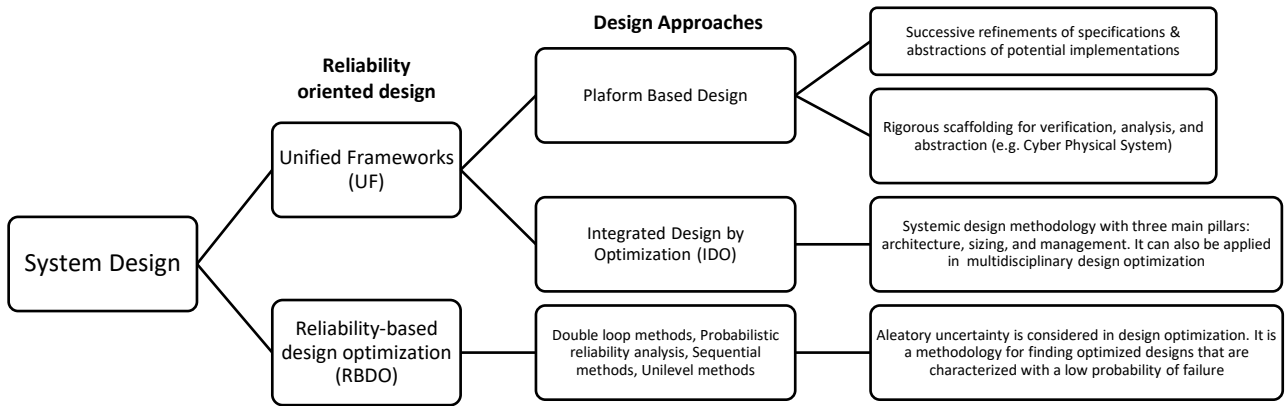
Fig. 4. Reliability-oriented approaches for system design

In [7], CbC develops some mathematical equivalences for functional and reliability specifications in 4 steps or platforms: 1) generation selection and generator-load pairing, 2) power distribution design based on previous generator selection solution, 3) control system synthesis, and 4) embedded system design. Each platform constitutes a high level optimized solution whose proximity to physical implementation depends on the platform's abstraction itself and the number of refinement steps. Optimization in CbC has utilized Mixed Integer Linear Programming (MILP) formulations due to its convergence to a global optimum and the availability of efficient commercial solvers. The main objective performs trade-off between weight and cost minimization, with reliability and efficiency maximization. The control and embedded systems design are still object of investigation. On the other hand, CbD uses *contracts* to translate high-level functional specifications into detailed performance descriptions, e.g. exact propositions that are satisfiable and verifiable [8], [9]. CbD has been applied in the synthesis of MEA EPS architecture (topology) and the definition of its control system [5]. The cost of integrating performance evaluation within the design has been the introduction of new computational tools and mathematical languages explicitly adapted from the computer science field into the aerospace design area. In [5], Linear- and Signal- Temporal Logic (LTL/STL) are used as formal languages to describe in detail the functional specifications within a minimum cost design assessment. System's reliability is measured as a probability of failure (not being able to supply critical loads), which is evaluated with an Integer Programming modulo approach [10]. LTL has required the use of advanced computational synthesis tools, such as the reactive protocols synthesizer SR(1) [8]. Following this line, applications for MEA EPS have been reported in [9], [11] with some testbeds developed on TULIP [12]–[14] which has been implemented in CAD with the JTLV verification scripting environment [15]. Further plans to investigate automatic generation of contracts and contract language definition [5] are expected [16]. CbD presents a rigorous methodology for the design of MEA EPS consisting in three main stages: 1) topology synthesis, 2) control synthesis, and 3) simulation-based design exploration and verification. CbD and CbC have been part of Cyber Physical Systems initiatives for MEA designs, including real-time performance assessment [17].

TABLE II.   DESIGN METHODOLOGIES APPLIED ON MEA ELECTRIC POWER SYSTEM

Methodology	Approaches	MEA Design Application
Platform Based Design (PBD)	Contracts for System Design CbD [18]	Contract-based methodology for aircraft power system design [5], architecture synthesis for aircraft power systems [19], contract based design for cyber-physical systems [20].
	Correct-by-construction CbC	Correct-by-Construction Design of Aircraft Electric Power Systems [7], Platform-Based Design for Aircraft Electric Power Systems [21], Synthesis of reliable cyber-physical architectures [10],[22], Managing complexity in aerospace systems [23].
Integrated Design by Optimization (IDO)		Opportunities on coupling new architectures and technologies to optimize integrated power sub-systems [24], Several design objectives involving numerous areas of progress in terms of power integration at both the component and device level [3], Design methodology based on a systemic viewpoint [25], A system level integrated design by optimization is explored on MEA [26].
Conventional Design Flow (CDF)		There have been applications for aircraft design project management [27]. Some reliability tools for the design process are Failure Mode Effects (FMEA, FMES), Monte Carlo Simulation, and Fault Tree Analysis (FTA), Highly Accelerated Life Tests (HALT), Highly Accelerated Stress Screening (HASS), and Accelerated Life Test (ALT) [4].
Reliability Based Design Optimization (RBDO)		Most of the applications are for civil and structural engineering [28], with rare attempts in electrical networks [29]. The 1st-order- and 2nd-order methods FORM & SORM are well known in structural engineering design [30].
Other optimization-based methods	Multi-objective optimization, higher complexity methods with reliability, multidisciplinary optimization	Architectural options: MEA topology options [31],[32], system architecture for adaptability [33], power conversion modelling based on building blocks models [34], design simplification based on high level of abstraction simulation models [35]. Improvements of current electrical performance: reconfiguration and balancing problem in aircraft AC networks (*Airbus operations*) [36], weight saving optimized distribution system with modern concepts (*Airbus operations*) [37], optimization of energy-supply-structure of modern aircraft utilizing conventional power system technologies [38]. Exploration of new architectures: exploration of several HVDC-architectures for aircraft applications (*Airbus operations*) [32], Ptolemy II-Metropolis/Metro II tools for architectural explorations (*IBM, UT, Bosch, NI, Toyota*) [39], analysis of HVDC parallel electric power system for MEA [40].

Still, there is an enormous potential to explore MEA EPS with novel design frameworks considering the integration of computation, communication, and control into a highly integrated system.

B. Network Design Problem

In the current stage of MEA EPS early development, interest in network flow and graph theory have increased dramatically. Power balance and other performance constraints based on power or energy flow are linear, which is the reason why MILP is amenable to network design formulations. The EPS is a network whose purpose is to route electrical energy from generators (sources) to loads (sinks) in a reliable and efficient manner. Network design fits adequately as a synthesizer of an EPS network because it can formulate a network construction problem [41]. Network design has been extensively used in the planning and operation of transmission and distribution EPS [42]. A classification of network design approaches according to the problem's objective is shown in Fig. 5. It is relevant to highlight the fact that resiliency and survivability constraints can be seamlessly added to a network problem without the necessity of a separate performance analysis. This provides an efficient way to integrate reliability performance evaluation. For instance, system's survivability to any single-component failure event ($N-1$ rule) can be modelled as a constraint in which given a set of failure states, the distribution system provides sufficient paths for generators to reach the critical loads.
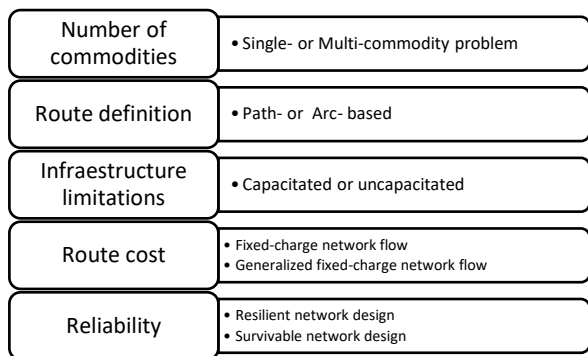
Fig. 5. Network Design according to problem formulation

C. Other Reliability-based Design Approaches

Apart from the PBD inspired and the network design approaches, Integrated Design by Optimization (IDO) focuses on the use of model-based analysis with advanced simulation tools [24], [26]. IDO consists in a group of techniques, algorithms, and optimization tools that enables integrated performance evaluation in the design of complex systems via advanced model-based description of components. This representation involves a high number of inter-element and inter-domain couplings, and system-mission interactions, i.e. system as a multi-disciplinary equipment. The IDO's design process consists in linking the system's model to an optimization algorithm with multiple decision criteria such as geometry, efficiency, and dynamic performance. These criteria are optimized to accomplish quality, stability, and compatibility (electrical, thermal, magnetic, etc.). In [25], there are several IDO-based methods to manage data processing, sizing, multi-level, and multi-criteria design in electrical energy systems. The formal analysis, synthesis, and management methods used in IDO are presented as systemic design methodologies in [43]. IDO reports MEA EPS

generation system optimization efforts and other electromechanical actuator sub-systems designs in [24].

In addition to IDO, Reliability-Based Design Optimization (RBDO) is a tool that has been extensively applied in civil and structural engineering, albeit seldom in MEA EPS. TABLE II. enumerates some applications of RBDO in structural analysis and design. The main purpose of RBDO is to consider aleatory (random) uncertainty in design optimization. In most cases, reliability requirements are stated as hard constraints in an optimization problem, each constraint related to a given failure mode and its probability of failure. There have been very limited applications of RBDO in electrical engineering, e.g. attempts in [29], [44] introduced probabilistic constraints in an EPS design optimization problem, while in [45] a piezoelectric energy harvester is designed. However, beyond these applications no other approach in EPS has been reported. Although this methodology could aim in developing a reliable design, it lacks of the flexibility to integrate the majority of functional control requirements explicitly. Further to IDO, and RBDO approaches, there have been other contributions in optimizing existing EPS architectures in order to improve specific attributes. For instance, [36], [37] performed research to optimize current AC three-phase aircraft infrastructure, and also explored HVDC configurations for future MEA [32]. Although not adopting rigorous frameworks such as PBD or RBDO, these methodologies are still reliability-oriented. Other efforts have been directed towards investigating MEA pre-defined architecture selection [46], adaptability under different operational scenarios [33], candidate architecture analysis via stability performance [47], among other technologies adoption and complexity management [2].

In summary, MEA EPS design is being shaped by a number of framework and techniques that, although unfamiliar to in the synthesis of new architectures, have shown advantageous in managing increasing complexity, innovative technologies, and reliable topologies.

IV. Conclusions

A brief discussion on the existing contributions for the design of novel architectures for future MEA power systems considering reliability has been presented. Due to the increasing complexity of the technology that will become part of MEA, it is necessary to combine efforts between several engineering fields to produce an efficient design framework that needs to depart from conventional design if integration challenges must be faced. PBD, Cyber Physical Systems, IDO, and other optimization based approaches places MILP as an efficient tool to achieve an optimized solution. Given the early stage in which MEA EPS design resides, there is still potential to introduce innovative methods in MEA.

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