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Electric Power Systems in More and All Electric Aircraft: A Review

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ABSTRACT Narrow body and wide body aircraft are responsible for more than 75% of aviation greenhouse gas (GHG) emission and aviation, itself, was responsible for about 2.5% of all GHG emissions in the United States in 2018. This situation becomes worse when considering a 4-5% annual growth in air travel. Electrified aircraft is clearly a promising solution to combat the GHG challenge; thus, the trend is to eliminate all but electrical forms of energy in aircraft power distribution systems. However, electrification adds tremendously to the complexity of aircraft electric power systems (EPS), which is dramatically changing in our journey from conventional aircraft to more electric aircraft (MEA) and all electric aircraft (AEA). In this article, we provide an in-depth discussion on MEA/AEA EPS: electric propulsion, distributed propulsion systems (DPS), EPS voltage levels, power supplies, and EPS architectures are discussed. Publications on power flow (PF) analysis and management of EPS are reviewed, and an initial schematic of a potential aircraft EPS with electric propulsion is proposed. In this regard, we also briefly review the components required for MEA/AEA EPS, including power electronics (PE) converters, electric machines, electrochemical energy units, circuit breakers (CBs), and wiring harness. A comprehensive review of each of the components mentioned above or other topics except for those related to steady state power flow in MEA/AEA EPS is out of this article's scope and should be found somewhere else. At the close of the paper, some challenges in the path towards AEA are presented. Unless the discussed challenges are satisfactorily addressed and solved, arriving at an AEA that can properly operate over commercial missions will not be possible.

INDEX TERMS Aircraft electrification, all electric aircraft (AEA), electric power system (EPS), more electric aircraft (MEA), power distribution system, steady state power flow analysis.

ABAC Active Bridge Active Clamp
AEA All Electric Aircraft
APU Auxiliary Power Unit
ATRU Auto Transformer Rectifier Unit
ATU Auto Transformer Unit
BCRU Battery Charge and Rectifier Unit
BESS Battery Energy Storage System
BLDC Brushless Direct Current
BMS Battery Management System
CB Circuit Breaker
CIL Constant Impedance Load
CPL Constant Power Load
CSC Current Source Converter
CSD Constant Speed Drive

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DAB Dual Active Bridge
DPS Distributed Propulsion System
DS Distribution System
ECS Environmental Control System
EMC Electromagnetic Compatibility
EMI Electromagnetic Interference
EMS Energy Management System
EPDS Electric Power Distribution System
EPS Electric Power System
FIT Failure in Time
FSM Finite State Machine
FTA Fault Tree Analysis
GaN Gallium Nitride
GHG Greenhouse Gas
GPU Ground Power Unit
HVDC High Voltage Direct Current
IBCI Interleaved Boost with Coupled Inductors

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IDG	Integrated Drive Generator
IHM	Isolated Hybrid Microgrid
ILP	Integer Linear Programming
IM	Induction Machine
LCC	Line Commutated Converter
MEA	More Electric Aircraft
MIE	Minimum Ignition Energy
MPC	Model Predictive Control
NPC	Neutral Point Clamped
NPSS	Numerical Propulsion System Simulation
OCP	Optimal Control Problem
OPF	Optimal Power Flow
PD	Partial Discharge
PE	Power Electronics
PF	Power Flow
PMSM	Permanent Magnet Synchronous Machine
PWM	Pulse Width Modulation
RAT	Ram Air Turbine
SiC	Silicon Carbide
SRM	Switched Reluctance Machine
TRU	Transformer Rectifier Unit
UN	United Nations
VSC	Voltage Source Converter
VSCF	Variable Speed Constant Frequency
VSI	Voltage Source Inverter
VSVF	Variable Speed Variable Frequency
WIPS	Wing Ice Protection System
ZCS	Zero Current Switching
ZVS	Zero Voltage Switching

I. INTRODUCTION

NITED nations (UN) sustainable development goals outline 17 major goals to fulfill by 2030 that address global challenges; goal 13 is directed towards taking urgent actions to combat climate change [1]. Narrow body aircraft, such as the Boeing 737, and wide body aircraft, such as the Boeing 787 and Airbus 380, are responsible for about 43% and 33% of aviation greenhouse gas (GHG) emission, respectiveely. Aviation GHG, itself, was responsible for about 2.4% of all GHG emissions in the United States in 2018 [2]. This situation becomes worse when one considers the historical 4-5% annual growth in air travel [3]. Compared with conventional aircraft, more electric aircraft (MEA) result in less dependency on carbon-based fuels, less carbon and NOx emissions, higher efficiency, more reliability, and reduced noise, which could end night flight bans in many airports [4]. In addition, electrical subsystems can be used irregularly and only when needed [5]. Furthermore, fuel cost is the primary air travel cost. All electric aircraft (AEA) provide additional benefits to those of MEA, such as zero emissions and even cheaper travel cost as a direct result of removing the need for fuel. Nevertheless, reducing/eliminating fuel consumption in MEA/AEA does not necessarily bring about a reduction in total energy consumption or carbon and NOx emissions. Unless renewable electricity generation is assumed, this advantage may be negated [6].

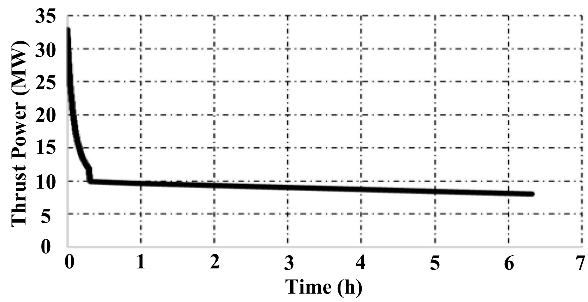

FIGURE 1. Thrust power profile for a typical flight of a narrow-body commercial aircraft [18].

The idea of MEA and AEA arose decades ago. In conventional aircraft, the power generated by an engine is converted into four main types of energy, namely electrical, mechanical, hydraulic, and pneumatic. Utilizing gearboxes, power is converted into mechanical power and then to electrical and hydraulic power [7]; also, using compressors, power (as bleed air) is converted to pneumatic power. Power from engines is employed to generate thrust for the aircraft to move. Apart from the power needed for thrust, the most vital power consumers in an aircraft are: avionics systems (electrical), pumps (either mechanical or hydraulic), actuation systems (hydraulic), the environmental control system (ECS) (pneumatic), and the wing ice protection system (WIPS) (pneumatic). The trend is to eliminate all but electrical forms of energy in aircraft power distribution systems. An MEA can be achieved by simply replacing a mechanical, hydraulic, or pneumatic subsystem with an electrical alternative. In the B787, an MEA launched for the first time in 2009, a no-bleed air system architecture was implemented [8] and, as a result, WIPS has been completely replaced by an electro-thermal anti-icing/de-icing system. In an AEA, however, not only will all replaceable systems be replaced with their electrical alternatives, propulsive power is also provided that utilizes electrochemical energy units such as batteries and fuel cells [9]. A 150-passenger narrow body, single aisle AEA that properly operates over typical commercial missions can be considered an achievable target within the next 20-30 years. On the other hand, electrification adds a great amount of electrical energy, e.g., tens of kVAs just by eliminating WIPS is needed in aircraft, which must be provided by the aircraft's electric power system (EPS). As an example, electrical power has increased from about 100 kVA in the first generation of the B737, launched in 1965, to 1 MVA in the B787. This 1 MVA electrical power does not include auxiliary power unit (APU) generation, which itself may be up to 450 kVA. In addition, depending on the flight profile, for a single aisle, narrow body commercial aircraft, the thrust profile could be depicted as shown in Fig. 1. For AEA, this huge amount of power must be provided by electrochemical energy units and delivered by an electric power distribution system (EPDS). Thus, electrification dramatically increases the complexity of aircraft EPS.

An EPS is comprised of different components, such as power electronics (PE) converters, electric machines, electrochemical energy units, circuit breakers (CBs, also known as solid-state breakers [10] or bus-tie breakers [11]), different loads, etc., that are all connected to appropriate busses and are needed to be taken into consideration when analyzing an EPS. In addition, even though there are similarities between an aircraft EPS and a ground-based microgrid, the aircraft EPS is an isolated onboard microgrid, which is different from microgrids on the ground [12]. Some differences are described below:

- A very high level of reliability and safety is needed in aircraft;
- Loads connected to aircraft EPS are more predictable;
- In aircraft, the load priority changes during a mission;
- Aircraft EPS allows for a better reconfiguration.

Many models and approaches that have been proposed specifically for ground based microgrids can be applied and adopted, if needed, so as to be utilized in MEA/AEA. Furthermore, MEA/AEA EPS is intrinsically hybrid – it is comprised of both ac and dc busses and, thus, proposing/ adopting methods that properly deal with such an ''isolated hybrid microgrid'' (IHM) is a must. There exist published papers that have provided reviews on MEA/AEA; however, to the best of authors' knowledge, no review paper has focused on MEA/AEA EPS in particular. In [13], several aspects of MEA, including major subsystems and trends, were generally discussed and a section was allocated to discussing future challenges. An in-depth review of machine technologies as well as other issues, such as power electronics, were conducted in [14]; in addition, at the end of each section, informative tables were provided to summarize the presented information. The authors in [12] paid more attention to EPS and presented some distribution systems (DSs) in a case about structures to enable readers to compare. Additionally, reviews on PE converters, control, reliability, and protection were also provided. In [4], using an initial proposed schematic for an AEA EPS, relevant aspects and technologies were reviewed. Authors in [6] presented an entry point and provided an insightful overview of concepts and models of MEA. Moreover, they allocated a section to present a readable review of surveys that have been done on modeling, simulation, and optimization of aircraft concepts. The paper, however, was not prepared from an electrical engineering point of view and did not go beyond the basics. Authors in [15] focused on electric propulsion and provided a review on presented concepts and challenges for future electric propulsion concepts. Other papers exist that present reviews on subjects related to MEA/AEA. Specifically, the authors in [16] and [17] focused on PE converters and batteries in MEA, respectively.

The aim of this article is to provide a review of MEA/AEA in general and of MEA/AEA EPS in particular. Even though our focus remains on EPS, we try to provide a general discussion and technology review on other issues related to EPS such as PE converters and batteries, which are generally discussed under the "power electronics units" heading. The presented paper is organized as follows: in section II, aircraft EPS is taken into consideration; electric propulsion, distributed propulsion systems (DPS), EPS voltage levels, power supplies, and EPS architectures are discussed, and publications about power flow (PF) analysis and management of EPS are reviewed, and an initial schematic of a potential aircraft EPS with electric propulsion is proposed in this section. In section III, PE units are generally discussed, including PE converters, electric machines, electrochemical energy units, CBs, and wiring harness. Stability of PE converters in MEA/AEA EPS is discussed in this section as well. Section IV attempts to picture some challenges in the path towards commercial AEA. Ultimately, section V is allocated to summing up the most important concepts of the presented paper.

II. ELECTRIC POWER SYSTEMS IN MORE AND ALL ELECTRIC AIRCRAFT

Electrification dramatically increases the complexity of an aircraft EPS. In addition, considering the thrust profile for a single aisle, narrow body aircraft such as the B737 shown in Fig. 1, the peak thrust power needed for the takeoff phase is greater than thrice as much as that of the cruise phase. In MEA with electric propulsion and AEA, such a high amount of power must be provided and delivered by the aircraft EPS.

To combat the complexity of analyses, modular models of units seems to be an answer. Modular models conveniently allow for extension as well as reconfiguration of EPS. A modular model also enables designers to use the model with desired fidelity at every level of analysis – e.g., to neglect dynamics that have little effect in functional layer analysis, and to consider the very dynamics in behavioral layer of analysis [19].

In an aircraft EPS, power is provided by generators and/or electrochemical energy units, and distributed through PE converters, cables, circuit breakers, etc.; thus, one of the main challenges of aircraft electrification is the aircraft EPS itself and its PE units. A rigorous review of EPS is presented in this section and PE units are discussed in the next section. In this section, electric propulsion and DPS are first discussed and then we focus on EPS voltage levels, power supplies, and EPS architectures. An initial schematic of a potential aircraft EPS with an electric propulsion system is also proposed in this section. Ultimately, publications about PF analysis and management of aircraft EPS are reviewed.

A. ELECTRIC PROPULSION

Attaining an AEA that properly operates over commercial missions will take at least 20 years to solve; however, electric propulsion paves the way for distributed propulsion in MEA and would be of great significance. Electric propulsion systems can generally be classified as turbo electric, hybrid electric, or all electric [9], [20], as described below.

A turbo electric power train could be either fully or partially turbo electric. In a turbo electric powertrain, the power gained from the turbines (gas turbines) is converted to electrical energy and distributed, typically, by utilizing dc busses and then using PE converters (inverters in dc distribution), and is delivered to motors to provide fan shafts with propulsive power. While a full turbo electric powertrain provides all propulsive power by a turbo fan, a partial turbo electric powertrain provi des some portion of the propulsive power using electric propulsion [9]. A hybrid electric powertrain can be series hybrid, parallel hybrid, or a combination of both. Hybrid structures are similar to hybrid automobiles; but they bear more resemblance to plug-in hybrid automobiles than non-plug-in ones [6]. In a series hybrid structure, generated power is converted to electrical power and distributed electrically. The power can be used to charge the batteries or to generate thrust. In a parallel hybrid structure, a fan shaft is driven either by mechanically distributed power from turbines or motors that are powered by electrochemical energy units [21]. Hybrid structures allow turbines to work at or near optimal operating conditions and enjoy their highest efficiency. Readers can refer to [22] and [23] for more information on hybrid electric propulsion. Ultimately, an all-electric structure relies solely on electrochemical energy units to provide fan shafts with propulsive power. An all-electric powertrain for thrust accompanied by a completely electrified MEA results in an AEA.

Since ac transmission lines enjoy less loss compared to dc lines for the same amount of copper, and ac CBs are generally lighter than dc CBs, a survey was done in [24] on the electric power distribution of a single aisle turboelectric aircraft (the STARC-ABL, a single aisle turbo electric aircraft with an aft boundary layer propulsion) to see whether or not ac power distribution would be advantageous compared to dc power distribution, which has currently received more attention. Fig. 2-a to 2-c show the STARC-ABL concept, an aircraft with dc power distribution, and an aircraft with ac power distribution. Results of the survey showed that utilizing an ac distribution system resulted in less loss, lighter mass, and higher efficiency in the voltage range between 0.6 to 2 kV. However, as noted, insulation adds to the mass of the system in voltages above 2 kV, which should be taken into consideration. Different voltage levels will be discussed in the next sections in details.

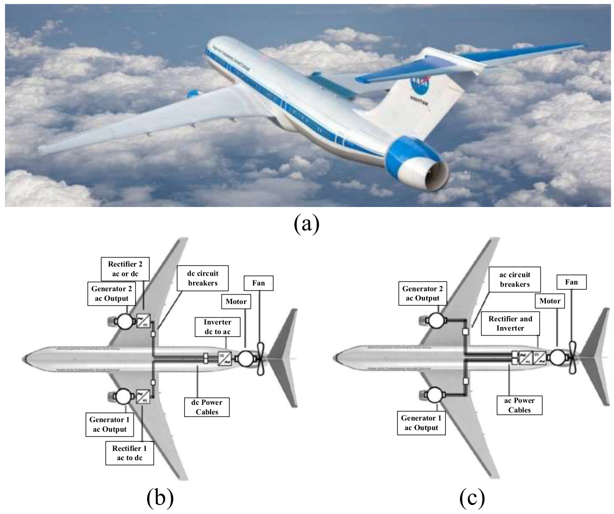

FIGURE 2. STARC-ABL: (a) the concept with a tail cone thruster (NASA image); (b) dc power distribution system [24]; (c) ac power distribution system [24].

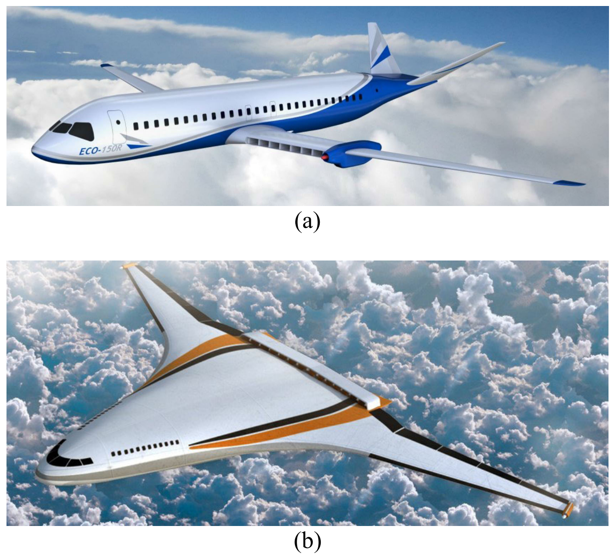

FIGURE 3. Examples of proposed concepts with distributed propulsion system (DPS): (a) ESAero ECO-150 (NASA image); (b) NASA N3-X (NASA image).

B. DISTRIBUTED PROPULSION SYSTEM

DPS is getting a great amount of attention and concepts employing DPS have already been proposed, such as ESAero ECO-150 and NASA N3-X, shown in Fig. 3. Generally, a DPS can be achieved by utilizing electric motors to accelerate airflow and/or using several propellers. Aerodynamically, the thrust is generated by blades and/or ducted/un-ducted fans. An obvious advantage of distributed propulsion is to allow for smaller motors (1 to 2 MW [9]) to be developed for electric propulsion in the next few years rather than high power motors that will not be feasible for years and possibly decades for large aircraft (narrow body and wide body commercial aircraft). In addition, DPS brings about higher efficiency and safety, cost reduction, and decreased noise [3], [25], but also leads to complexity in PE systems, central control units, and fault management [26]. In other words, DPS ends the era of large diameter fans and, at the same time, adds to the complexity of aircraft EPS as a direct consequence of integration complication.

As mentioned in [9], a series hybrid electric propulsion structure is well-suited for concepts with distributed propulsion. In [27], [28], even though five distributed propulsion architecture candidates were presented for a particular concept, the results seem to be applicable to other concepts as well. The five architectures are as follows: baseline architecture, inner bus tie concept, 3-bus multifeeder concept, cross-redundant multifeeder concept, and 4-bus inner bus tie multifeeder concept [28]. One difference between the proposed architectures is whether the busses are supplied independently by generators. In addition, in different architectures, busses must be able to provide a certain portion of the power, at least 33.3% and at most 66.6% of the total power. Indeed, the proposed architectures differ in weight, complexity, response against failures, number of utilized components, redundant power, breadth of the protection scheme, and ease of modeling [28]. In the aircraft EPS proposed in the next sections, although a DPS is assumed, no specific DPS architecture is depicted. Choosing an appropriate structure requires a deep examination of each architecture, which falls outside the scope of the presented paper.

Numerical propulsion system simulation (NPSS) is a standard modeling and simulation package for propulsion systems [29]. It was not intended for EPS in its first revision; however, the ability to design, analyze, and integrate EPS components [30] enables NPSS to be a powerful software to wholly analyze the power system and propulsion system in MEA/AEA. Finally, readers can refer to [15], [31]–[34] to find more references for further study about DPS.

C. STANDARDIZED VOLTAGES IN AIRCRAFT ELECTRIC POWER SYSTEM

An aircraft EPS is, in fact, a multi voltage level system. An EPS is comprised of busses with different voltage levels that are connected by PE converters. Additionally, the authors in [35] focused on the efficiency impact of different EPS design voltages and concluded that the voltage level mostly affects PE components. In compliance with standards such as MIL-STD, there exist standardized voltage levels in MEA described below [19]:

- dc voltage levels: 540 V (±270 V), 270 V (±135 V), and 28 V.
- ac voltage levels: $230_{ph}/115_{ph}$ V with variable frequency (e.g., 350-800 Hz in the B787), 230_{ph} V with fixed frequency (400 Hz), and 115_{ph} V with fixed frequency 400 Hz.

Standardized voltages are provided at airports for maintenance purposes and components, such as batteries and PE components, which are designed and commercialized to be compatible with standard voltages. In [4], an initial schematic of an AEA EPS was proposed. A voltage level of 3 kV_{dc} was assumed, which does not comply with the MIL-STD-704 and DO-160 standards. Nevertheless, the lower the voltage, the higher the current, and vice versa. On the one hand, low voltages lead to very high, unbearable currents in the trend towards electrification of aircraft propulsion systems; on the other hand, motivated by Paschen's law, voltage levels in standards are kept below 327 V_{dc} to avoid a voltage breakdown. In AEA, a voltage level of about 2 to 3 kV for an electric propulsion system seems essential and the primary supply bus to supply non-propulsive components seems advantageous.

D. ELECTRIC POWER SUPPLIES IN AIRCRAFT ELECTRIC POWER SYSTEMS

Generators that are coupled with engines generate a voltage level (e.g., 115_{ph} V_{ac}) with variable frequency. This is due to the variable speed on the generators' shafts. If a constant frequency is desired, a constant speed drive (CSD) can be utilized to provide generators with constant speed shafts. In addition, the CSD can be integrated with the generator that leads to an integrated drive generator (IDG) [36], [37]. IDG is a mechanical facility and is not only, in the trend towards electrification, out of date, but its removal also results in an improvement in dispatch reliability [13]. It is also possible to use an ac-ac or ac-dc-ac PE converter at the output of the generator to provide constant frequency, which leads to a variable speed constant frequency (VSCF) structure. Utilizing the VSCF technique necessitates the total power passing through a converter [19]. Such a converter deteriorates system reliability and, furthermore, with today's technologies, implementation of such a converter is not feasible. On the other hand, in MEA such as the B787, the output of generators is directly connected to a primary ac bus – a variable speed variable frequency (VSVF) approach. In [38], for a VSVF MEA EPS, a steady state operation simulation was performed. Considering both VSCF and VSVF approaches, the answer seems to lie between these two extremes. Employing PE converters to connect many loads such as motors is inevitable; these loads can be supplied by a variable frequency supply bus, whereas other loads that can directly be connected to a supply bus would be connected to a fixed frequency bus.

Apart from main generators, there exist APU and ram air turbine (RAT) generators in aircraft. Apart from generators, batteries and fuel cells are usually found in aircraft APU as well. APU is used when the aircraft is on the ground and in emergency situations. The voltage generated by APU is similar to the main engine generators, e.g., 230_{ph} V_{ac} with a fixed 400 Hz frequency. In [39] and [40], APUs consisting of batteries and fuel cells were designed to be connected to 270 V_{dc} and 200 V_{ac} busses, respectively. The rating of APU in the B787 is about 0.45 MVA, which makes the overall electric power of the B787 be 1.45 MVA (four main generators, 250 kVA each, and two auxiliary power generators, 225 kVA each). RAT generators are used in the case of multiple failures in emergency situations; in the B787, there are small propellers installed at both sides under the fuselage and are used, for instance, for a dead-stick landing. RAT generators are not connected to the main supply bus under normal conditions; instead, they supply a backup bus. In failure scenarios where all generators (main and APU generators) fail to supply EPS, RAT generators supply the system. It should be pointed out that not all loads are supplied when utilizing RAT, since the RAT power rating is typically around 5 to 70 kVA in commercial aircraft [41]. Ultimately, a ground power unit (GPU) is typically used for maintenance purposes on the ground at airports [42].

E. ARCHITECTURE OF ELECTRIC POWER SYSTEMS

Different aircraft EPS architectures lead to different net weight, efficiency, and reliability. Thus, it is of great significance to properly design an EPS so that it can then be

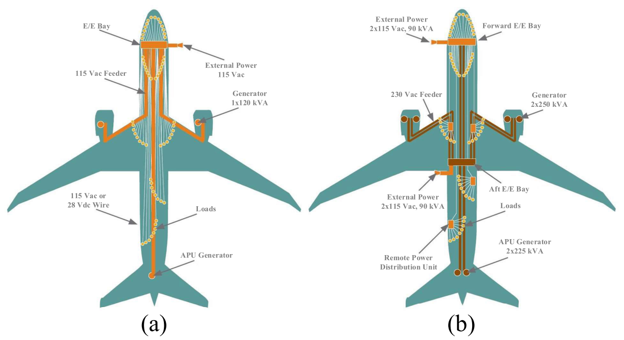

FIGURE 4. Aircraft EPS [8]: (a) Centralized, (b) Remotely distributed.

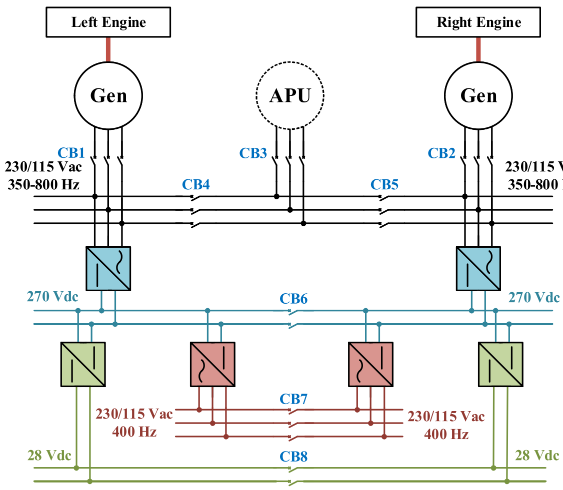

FIGURE 5. EPS with primary dc 270 V bus (HVDC EPS). Different loads are connected to corresponding busses.

appropriately utilized in PF analysis to conveniently keep the flow of power when a failure occurs.

Although a hybrid system comprised of both ac and dc voltages seems inevitable, aircraft EPS can be either centralized as shown in Fig. 4-a or remotely distributed as shown in Fig. 4-b. A remotely distributed EPS allows for optimization and results in higher reliability and weight benefit, and enables distribution units such as PE converters to be placed closer to loads [12]. In many EPS architectures proposed in publications, a primary high voltage direct current (HVDC) bus is assumed [43], [44]. Even though it is called HVDC, the order of magnitude never reaches 10^3 V_{dc}. An example of a dc (HVDC) EPS is shown in Fig. 5; different loads are connected to each of the blue, green, and red colored busses. In [45], a survey was conducted and four EPS architecture candidates for an MEA EPS were assessed. The investigation was done based on architecture stability, system weight, power conversion, and complexity of integrating energy supplies. However, cost and efficiency were neglected when deciding on an architectture that was the best.

Another popular aircraft EPS architecture is ac EPS. For example, an ac EPS is illustrated in Fig. 6. Different loads are connected to blue, green, and red colored busses. Loads such as the electric propulsion system may directly be connected to

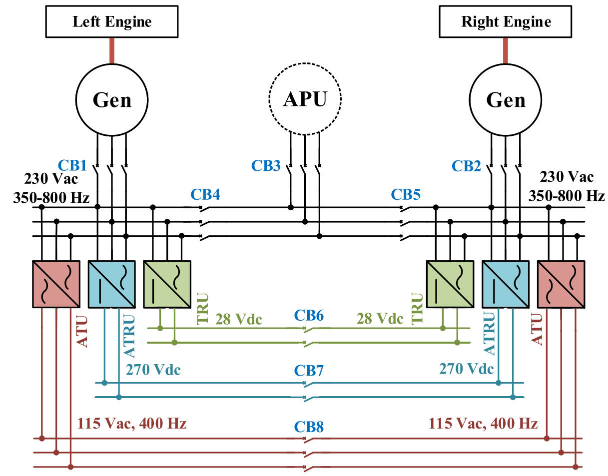

FIGURE 6. EPS with primary ac 230 V with variable frequency 350-800 Hz bus. Different loads are connected to corresponding busses.

the black colored bus and are directly supplied by the primary ac bus. The B787 EPS is similar to the one depicted in Fig. 6; in the B787 EPS, however, two main generators are coupled to each engine and there exist two APU generators that provide a 230_{ph} V_{ac} on the primary ac bus as well. In addition, voltage levels in Fig. 6 were chosen as they are in the B787: 230_{ph} V_{ac} on the primary ac bus, 115_{ph} V_{ac} on the secondary ac bus, 270 V_{dc} on the HVDC bus, and 28 V_{dc} to supply avionics. All busses are directly derived from the primary ac bus utilizing PE converters, namely the auto transformer rectifier unit (ATRU), the transformer rectifier unit (TRU), and the auto transformer unit (ATU):

- ATRU is in fact an ac/dc PE converter that is used for supplying large dc loads, such as ECS. This unit converts the primary ac bus to a HVDC 270 V_{dc}. In [46], a generic model is proposed for an 18-pulse (3×6) ATRU.
- TRU is a combination of a transformer unit and a rectifier (typically diodes) and converts the primary ac bus to 28 V_{dc} for avionics in commercial aircraft. Other solutions are also possible to convert the voltage, e.g. battery charge and rectifier unit (BCRU) and two-stage power conversion (ac-dc-dc converters) [47]. An optimization method was proposed and utilized to design a regulated TRU for MEA in [48].
- ATU is a transformer unit to convert the primary ac bus to 115_{ph} V_{ac} with variable frequency between 350-800 Hz or a fixed frequency at 400 Hz to supply loads.

A single line representation of a potential MEA EPS is illustrated in Fig. 7. To keep the clarity and to better show the flow of power, components such as sensors and controllers are not shown in the figure. Two main engines are assumed, each of which is connected to two generators. APU consisting of generators and batteries is also considered. In addition, RAT generators (depicted as one generator) are assumed to supply the primary ac bus in the case of multiple failures. An electric propulsion system is assumed, which is directly supplied

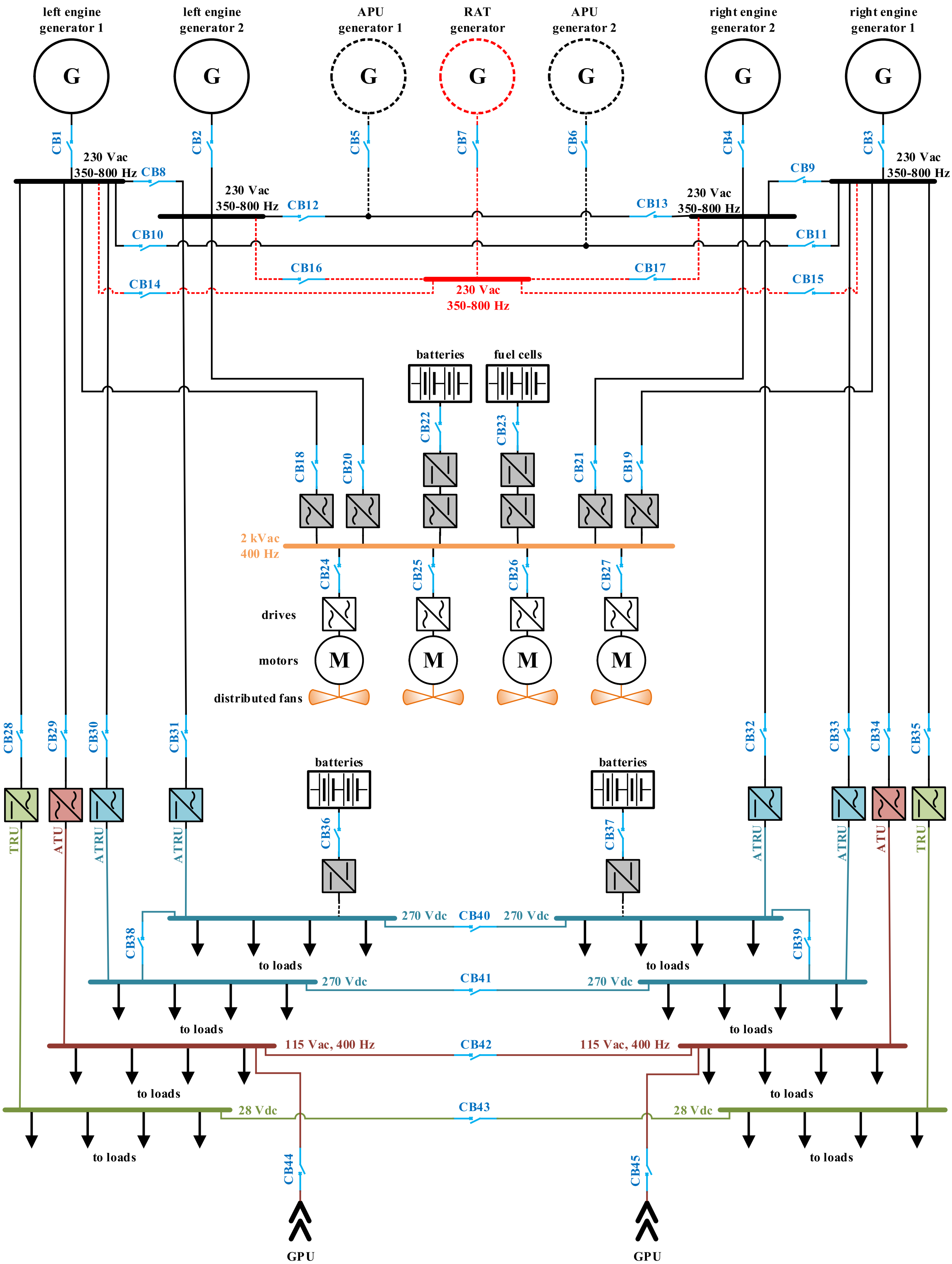

FIGURE 7. Single line representation of a potential aircraft EPS with electric propulsion system.

from the primary ac bus; a 2 kV_{ac} bus is considered for the electric DPS, but no particular architecture is assumed and four fans are depicted in the figure to represent the DPS that could be comprised of many fans. In addition, different busses are derived from the primary bus using ATRU, TRU, and ATU. Based on their characteristics, loads can be connected to busses with or without PE converters. However, constant power loads could easily threaten the stability of the EPS and must be taken into consideration. CBs are utilized so as to appropriately keep the flow of power under different conditions and/or prevent a failure from being propagated in emergency cases. Ultimately, GPUs are considered for maintenance on the ground at airports.

F. MODULAR MODELS AND POWER FLOW ANALYSIS

Once the aircraft EPS is completed and all loads are connected to busses, modeling, management, stability analysis, and control of the EPS must be taken into consideration. As far as modeling is concerned, modular models seem to be appropriate candidates, since they allow for extension and reconfiguration of aircraft EPS. Modularizing is not limited to aircraft EPS and is an interesting approach in spacecraft EPS analysis as well [49]. It is essential to provide models with different fidelities, e.g., a very precise PE converter model is needed for behavioral level simulations and stability analysis of the converter. However, in functional level analyses and from a system level point of view, a linear input-output equation is well-suited. For example, a modular model derived from a turbo electric propulsion system, as shown in Fig. 8, is suitable for PF analysis. Modularizing paves the way for models with different fidelities so as to be considered in a different level of analyses. For the system shown in Fig. 8, a power equation for the synchronous motor was presented as [50]:

$$\mathrm{P} = \eta \tau \omega \tag{1}$$

where P represents power, ω is rotational speed, τ is torque, and η is efficiency and represents the machine's drive (its PE converter) as well. By completing all modules, such as electric machines, PE converters, all loads, etc., the whole EPS can be modularly built and analyzed. In [51], a framework for stability analysis of aircraft EPS was presented; a module based approach for stability analysis was employed to analyze the B787 EPS.

One advantage of modular analysis is to start from one point and move forward by calculating voltages and powers that are needed to be calculated in PF analysis. Gauss-Seidel, Newton-Raphson, and fast decoupled methods are conventionally utilized for PF analysis [52]. PF analysis methods can be classified as sequential, unified, and integrated (a combination of both sequential and unified) methods; all the above-mentioned methods are classified as sequential methods. Sequential methods solve the dc and ac parts separately at each iteration. Even though sequential methods can simply be adopted for a DS, they are time consuming; in addition, convergence would be problematic, since most of the

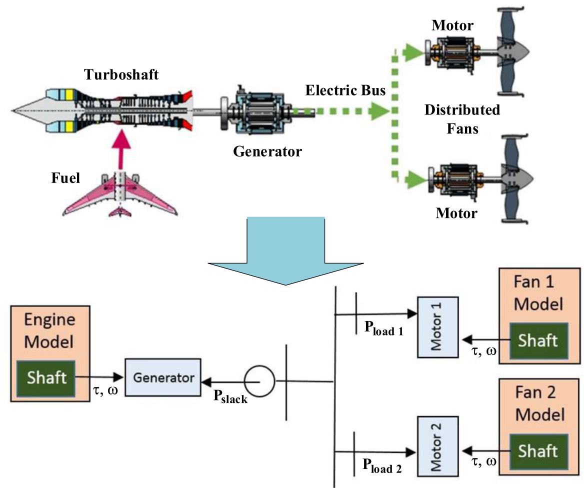

FIGURE 8. Modular model of a turbo electric propulsion system [50].

sequential methods assume decoupled ac and dc networks. On the other hand, in earlier unified methods, e.g., [53], the extended dc variable method is used, making it hard, if not impossible, to be combined with developments in the ac parts [54]. Based on the Newton-Raphson method, the authors in [50] presented an adjusted approach to modularly solve the PF problem. The functional layer analysis began from the upstream node and continued by determining the downstream voltage and then calculating the current between two nodes.

As mentioned earlier, an aircraft EPS is an IHM and, accordingly, methods that are able to solve the PF problem in a hybrid ac-dc microgrid are needed. There exist papers that adopted conventional methods and came up with new ideas to properly solve the PF problem in a microgrid in general and in a hybrid ac-dc distribution system in particular. In [55], possible connections between ac and dc busses are presented as shown in Fig. 9; connections exist in aircraft exactly as they were presented in [55] for a ground-based distribution system. In the paper, a general PF model of possible hybrid configurations was calculated. The approach was to remove the reactive parts of equations and for ac-dc power conversion, voltage source converters (VSCs) were assumed. The authors in [56] presented a review of line commutated converters (LCCs) and VSCs and made an assessment of both converters in HVDC EPS; they ultimately concluded that the trend would be to use VSCs. Even though voltage levels in an aircraft HVDC EPS is different from a ground-based HVDC EPS, the conclusion in [56] seems applicable to an aircraft EPS as well. In [57], a modified Jacobian matrix was proposed, with the help of dc and ac PF equations, which were integrated and solved. In addition, required models of PE converters, and VSC models in particular, were also represented. Apart from that, in [58] and [59], VSC models were proposed to be employed in dynamic and steady state analyses, respectively. Losses were also included and the proposed models were suitable for large ac- dc hybrid systems. Employing the

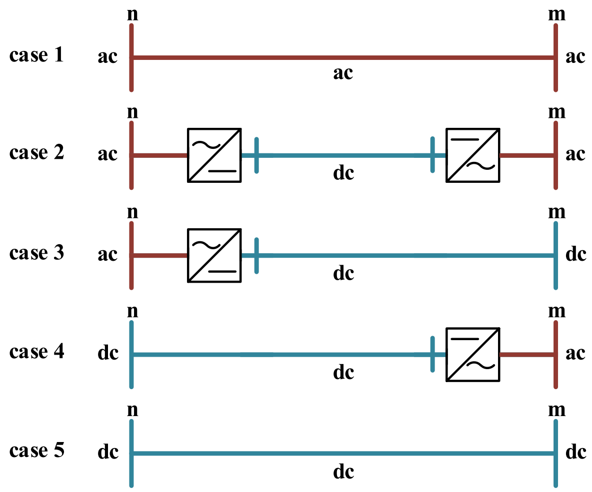

FIGURE 9. Single line representation of possible cases of ac-dc connections [55].

proposed models, a sequential power flow algorithm was then proposed in [60], which is applicable in any configuration.

G. MANAGEMENT OF AIRCRAFT ELECTRIC POWER SYSTEMS

Electrification adds a great amount of complexity to aircraft EPS and, accordingly, a management system is needed to ensure power quality and stability of the EPDS. As almost all power supplies, loads, busses, etc. are connected by CBs, reconfiguration (use CBs to determine power paths [61]) can be employed so as to let an EPS reach its highest possible safety and reliability. Under normal conditions, generators supply their own loads; in other cases, such as in an emergency, the configuration of EPS changes by CBs so as to still provide loads with electrical power. As a result, the EPS can be optimized for the highest safety and reliability before and during a mission. Based on the EPS architecture proposed in [62], a platform-based methodology was employed in [63], while [64] presented a need-based design approach based on the EPS architecture. In both papers, however, a fault tree analysis (FTA) accompanied by an interpretation of failure in time (FIT) as failure probability was utilized, and both employed integer linear programming (ILP) to minimize cost when satisfying safety and reliability criteria.

A behavioral level simulation of an MEA HVDC EPS was carried out in [65]. The authors concluded that the power quality in an EPS is dramatically influenced by inverters and motors in ECS. The authors in [66] and [67] focused on stability analysis of MEA EPS. Both papers utilized *dq* modeling as well as state space averaging. Nevertheless, averaging methods cannot guarantee the stability of the EPS models due to the omission of fast dynamics [68]. Due to the modularity, droop control would be an interesting approach in control of MEA/AEA EPS. For a single bus HVDC EPS architecture with multiple source and multiple loads, in [69], a dynamic droop controller was proposed and impedance analysis was performed and, then, in [70], control design and stability analysis procedures were taken into consideration. A PF management system for an isolated multi-port converter was proposed in [71]. The converter was connected between three HVDC busses in an MEA EPS. Using a small-signal model, voltage droop and phase-shifted controllers were designed, and stability analysis was performed and the effectiveness of the system was investigated under normal and fault conditions as well. The authors in [72] presented a simulation model of MEA EPS; an HVDC bus was assumed and models of a generator, transformer unit, and PE converter units were proposed. Nevertheless, a single bus model was assumed and, moreover, the whole system was not simulated and performance of the different units verified separately. In [43], the dynamics of generators and batteries were taken into account and a three stage hierarchical optimal control problem (OCP) – namely (as the authors named them), the power scheduling and allocation problem, generator dynamics synchronization, and voltage regulation – was calculated for the power management system in an MEA.

In [73], uncertainties were taken into consideration and although a ground based ac-dc hybrid system was assumed, the idea could be applied to MEA/AEA EPS. A multistage scenario tree was employed and possible scenarios were determined in advance; using a rolling planning method, a decision was made based on constructed scenarios; in addition, regarding new uncertainties, new stages were added to the scenario tree. In [74], loads were classified as vital loads and non-essential loads, and then reactive systems were employed so as to model an EPS by states and transitions between states. A finite state machine (FSM) was designed to ensure the stability of the system under emergency scenarios by reconfiguration, such as losing a generator. In order to ensure the power path to vital loads, a similar approach was also employed in [75] and the effectiveness of the designed FSM verified under the condition of losing dc-dc PE converters. In [76], for an ac-dc hybrid EPDS, a two-stage energy management system (EMS) was proposed; in the first stage, the optimal reconfiguration was determined to minimize energy loss, and in the second stage, real-time optimal power flow (OPF) was calculated to minimize cost. In addition, a stochastic planning model and a stochastic multi-objective optimization model for planning were also proposed. Even though the methods were presented for a ground-based grid/microgrid, they could be adopted to be employed in MEA/AEA.

Regardless of the proposed architecture of the electric power system, using an electrochemical unit in EPDS is necessary. When the generated power is more than the amount that loads need, it is usually stored in electrochemical units such as batteries, supercapacitors, etc. When batteries are fully charged, the extra power must be dissipated; otherwise, anti-runback diodes may disconnect generator units from the grid, which cause generators to lose their control over EPS. The authors in [77] considered a chopper in the storage unit as the answer. The chopper can be modeled as a resistor in parallel with the electrochemical unit. In the paper, a two-stage management strategy was proposed; the total power that is needed to be absorbed/generated is calculated in the first stage, and the power to be stored and to be dissipated are determined in the second stage (by a fuzzy logic approach as a multi objective approach). Decentralized EMS were taken into consideration in [78] and [79]. In [78], a virtual impedance consisted of a resistor and an inductor was utilized to adjust the power sharing ratio both in the transient and steady state. In [79], an EMS was proposed for APU comprised of fuel cells and supercapacitors. The demand was split into low frequency and high frequency components, and was allocated to fuel cell and supercapacitor units, respectively. However, batteries were neglected in the paper.

Finally, to provide peak power demand in MEA, generators can be overdesigned. However, this dramatically deteriorates a system's efficiency. Techniques such as load shedding or approaches similar to ground-based peak load shaving approaches [80] seem possible as well. In [10] for a dc bus, to determine behavior of loads, modification of the bus voltage was taken into consideration. As a result, power consumption was managed with regard to available power, including the power that has been generated and redistributed.

III. POWER ELECTRONICS UNITS

PE units play a key role in aircraft EPS specifically in power conversion, distribution, and storage. Moreover, in the trend towards electrification, PE units will play a more critical role and modeling, control, and stability analysis of these units would be essentially important. In this section, a general discussion and review of PE units, including PE converters, electric machines, electrochemical energy units, CBs, and wiring harness are provided. In this section, we avoid an in-depth review and generally discuss the above mentioned units; a comprehensive review and discussion should be found somewhere else.

A. POWER ELECTRONICS CONVERTERS

In previous sections, it was mentioned that an MEA/AEA EPS is intrinsically an IHM with multi voltage levels. Accordingly, PE converters play a major role in interfacing different loads (avionics, motors, etc.) with supplies (generators, batteries, etc.) through busses; in addition, PE converters are needed for power conversion. This requires a relatively large number of PE converters onboard MEA/AEA compared to conventional aircraft; these converters should not only enjoy high power density and high reliability, but also can be analyzed conveniently in case of modeling, control, and stability analysis. In addition, models with different fidelities are needed so as to enable engineers to consider or omit some dynamics in different levels of analyses.

Depending on the application, uni-directional or bi-directional converters can be employed. For instance, a battery pack necessitates a bi-directional converter to interface with a bus, while a uni-directional converter would suffice to connect a fuel cell to a bus [81]. PE converters are generally classified as ac/ac (frequency changer), ac/dc (rectifier), dc/ac (inverter), and dc/dc (dc converter). ATRU, TRU, and ATU also fit in the classification as ac/dc, ac/dc, and ac/ac PE converters, respectively. As summarized in Table 1, the authors in [16] provided a review of PE converters in MEA and presented potential topologies to be utilized in aircraft. A discussion of the advantages and disadvantages of possible topologies is beyond the scope of this article; however, in Table 1, readers are provided with references about every topology.

TABLE 1. Potential power electronics converter topologies in MEA/AEA (information is based on [16]).

Type	Topology	Ref.
ac/ac	matrix converter	[82], [83]
	cyclo-converter	[82]
ac/dc	two level rectifier	[84]
	neutral point clamped (NPC)	[85]
	three level rectifier	[84]
	Vienna rectifier	[86]
dc/ac	two level voltage source inverter (VSI)	[87]
	neutral point clamped (NPC)	[85]
	three level inverter	[84]
	T-type inverters	[88], [89]
	Z-source inverters	[90]
dc/dc	resonant converters	[91]
	dual active bridge (DAB) converters	[92]
	interleaved boost with coupled inductors (IBCI)	[93]
	active bridge active clamp (ABAC) converters	[94]
	multiport converters	[71], [95]

Another issue is whether a PE converter should be isolated or non-isolated. Indeed, isolated topologies have an advantage over their non-isolated counterparts, since an isolated topology prevents failures from being propagated in EPS. However, transformers are known to be too heavy compared with other components in isolated topologies and add a great amount of weight to the converters. The weight of PE converters is already an issue. For instance, associated electronics drop the specific power of each of the four main generators of the B787 from about 2.2 kW/kg to 1.1 kW/kg [9]. Nevertheless, an increase in switching frequency brings about a reduction in the size of electromagnetic components and, thus, alleviates the problem.

Regardless the topology, switching in PE converters is inevitable. In this article, wherever we talk about switching, a VSC is assumed. With today's technologies, possible switch technologies include Silicon (Si) based switches and wide-bandgap devices including Silicon Carbide (SiC) and Gallium Nitride (GaN) switches. In [4], an in-depth review of wide-bandgap technologies was provided under the heading of semiconductor technology. Compared with Si based switches, wide-bandgap switches enjoy higher power density, higher slew rate, better thermal conductivity, higher critical field strength, and, thus, better resistance to radiation.

Generally, two approaches are used for switching: the fixed frequency technique known as pulse width modulation (PWM) and the variable frequency technique.

As mentioned earlier, higher switching frequency results in a reduction in the size of electromagnetic components. Nevertheless, an increase in switching frequency dramatically increases switching loss and necessitates employing soft switching techniques. Soft switching includes zero voltage switching (ZVS) and zero current switching (ZCS). ZVS means turning on a switch when the voltage of e.g., drain-source in MOSFETs is zero and ZCS is to turn off a switch when the switch current is zero. Utilizing soft switching techniques enables a converter with Si based switches to work at frequencies of hundreds of kHz, while wide-bandgap semiconductors (SiC and GaN switches) make it possible to further increase the switching frequency up to a 10^8 Hz order of magnitude. However, providing a switch with soft switching requires a resonant tank topology, and because these resonant switching tanks operate at or near resonant frequencies, the stability is a major challenge and must be carefully taken into consideration. In addition, high switching speed gives rise to serious electromagnetic interference (EMI) concern due to high voltage and current slew rates (dv/dt and di/dt), e.g. dv/dt up to 100 kV/μs. As mentioned [96], concerns over electromagnetic compatibility (EMC) lead to a trade-off between efficiency and EMI. EMI in PE converters was discussed in publications [96]–[100] and employing filters as well as novel approaches were introduced and investigated as solutions to alleviate the problem. A detailed discussion of EMC and EMI is beyond the purpose of the presented paper; readers may refer to [101] and abovementioned references for further study and to be provided with additional references.

B. STABILITY

A discussion of stability is presented here, and not in previous sections, because it is difficult to split stability and dynamic behavior of PE converters. The stability of MEA/AEA EPS is of great significance; generally, stability can be interpreted either as small signal stability or large signal stability. For small signal stability analysis, a small signal model that has been linearized around an operation point is typically used. However, large signal stability analysis could be problematic, since it concerns how a converter responds to a disturbance and how state space variables reach steady state [5]. In addition, PE converters must be resilient against variations in input voltage and the load. Accordingly, stability analysis of PE converters is of great significance and needs models with other fidelities than those utilized in system level analysis and steady state. Extracting an ac equivalent circuit model was proposed in [91]; modeling approaches usually employ averaging and then linearize the model around an operating point [91], [102]. These models cannot be utilized in large signal stability analysis and, thus, nonlinear models are required so as to be utilized in designing stabilizing controller and stability analysis. Many nonlinear modeling approaches lead to an awkward model that makes controller design and stability analysis onerous, if not impossible. Thus, nonlinear systematic techniques are of interest to provide models that can conveniently be utilized in controller design and EPS stability analysis, while not compromising required preciseness. A discussion about modeling is beyond the scope of this article; however, stability issue is discussed hereunder.

The trend towards electrification let power-electronics-intensive [103] aircraft EPS to be the new kind of microgrids. This makes the MEA/AEA EPS to be prone to instability, since PE converters may be controlled and stable by their own, while their interconnection lead the EPS to instability. This could be due the difference between small signal and large signal stability. In addition, considering the tightly regulated output voltage of dc-dc and ac-dc converters, and the tightly regulated speed of actuation drives systems (supplied by the output of dc-ac or ac-ac converters) in aircraft, most of the loads in MEA/AEA are constant power loads (CPL). CPLs may be seen as a negative resistance. The negative incremental input impedance of CPLs could be problematic and lead the MEA/AEA EPS to instability [104].

Having considered multiple CPLs, authors in [105] analyzed the stability of a hybrid ac-dc MEA EPS. Also, large signal and small signal stability based on Lyapunov methods and robust stability methods were studied in [106] and [107], respectively. To combat and eliminate the problem caused by CPLs, authors in [108] found the solution in real-time power estimation employed and developed by an adaptive back stepping controller. A third degree cubature Kalman filter algorithm is developed to estimate microgrid's states as well as total demanded power and then a stabilizing backstepping controller is designed to stabilize the EPS and regulate the dc bus voltage. Apart from that, authors considered a simplified EPS comprised of a synchronous generator, 18-pulse ATRU, and a CPL in [109] and proposed an analytical technique based upon Brayton-Moser mixed potential to anticipate large signal stability behavior. Having considered large disturbances, a detailed dynamic behavior and stability analysis of a hybrid ac-dc EPS were performed in the paper.

Droop control, as a decentralized, passive control approach takes a great amount of attention in aviation industry since it results in an improvement in EPS modularity and reliability. With the consideration of system modularity, a voltage regulation method in a multi-source MEA EPS was proposed in [110] so as to improve load sharing accuracy under high droop gain cases. CPLs, resistive loads, and constant impedance loads (CIL) were all considered when proposing the method. The paper aimed to provide better voltage regulation and, at the same time, a proper power sharing between sources.

Eigenvalues in small signal stability analysis performed in [66] are needed to be calculated with varying parameters and, thus, authors in [111] provided analysis utilizing eigenvalue sensitivity and participation factor in MEA EPS. Besides, authors showed that simulation results differ in a meaningful way when cabling is considered, that omitting cables can lead to misleading simulation results.

Authors in [104], as it is named in the paper, proposed large signal stability constraining dichotomy solution based model predictive control (MPC) in a cascaded ac system in an MEA

EPS with primary dc supply bus. In [112], the application of a predictive controller for a current source converter (CSC) was taken into consideration to interface aircraft generators with onboard dc microgrid. In addition, a review and an in-depth discussion of the application of predictive control in microgrids was provided in [113]. On the down side of MPC for aircraft EPS, this is the most complex form of classic control, and as mentioned [114], it should be employed only when no simpler controller is applicable.

It should be noted that a comprehensive review and discussion on stability in MEA/AEA is beyond this article, and in this section, we briefly reviewed and discussed some important aspects of stability; however, a detailed review should be found somewhere else.

C. ELECTRIC MACHINES

Electric machines, both as generators and motors, are of great significance in MEA/AEA and are needed in a wide range of applications, e.g., propulsion system, ECS, etc. Furthermore, in the trend towards commercial AEA, electric motors play a major role; noise emission of electric motors is far less than that of compressors and turbine components [3]. To select electric machines for given tasks, they are compared by their efficiency, reliability, fault tolerance, etc. In MEA/AEA, the trend is to employ permanent magnet synchronous machines (PMSM), induction machines (IM), and switched reluctance machines (SRM). The authors in [14] provided an in-depth review of PMSM, IM, and SRM. In [115], an analytical comparison between the above-mentioned machines for electric propulsion application was provided. In [116], a review of SRM for application in electric vehicles with a focus on its intrinsic torque ripple and radial distortion was presented that is applicable in aircraft as well. Brushless dc (BLDC) motors also take considerable attention, e.g., for distributed propulsion and actuation systems. The authors in [117] presented a permanent magnet brushless dc (PM BLDC) drive for an actuation system in aircraft.

In [118], a review was performed on electric machines with a focus on high power applications; different aspects including machine components, materials, mechanical, and thermal issues were considered when assessing different machines. In this section, we avoid an in-depth discussion on electric machines and readers may refer to references presented in [14] to be provided with references for further study.

D. ELECTROCHEMICAL ENERGY UNITS

Electrochemical energy units onboard MEA are already being used in APU for engine start up, transient smoothing, and in emergency cases. However, AEA solely rely on electrochemical energy units to provide thrust. These units could be batteries, fuel cells, or supercapacitors. Capacitors are large, heavy, and have a great amount of loss [119]. This could be problematic, since thousands of capacitors are installed onboard MEA and even greater numbers in AEA. While supercapacitors are able to be directly connected to a bus, batteries and fuel cells need PE converters for interfacing. A uni-directional converter would suffice to connect fuel cells, while utilizing bi-directional converters to interface batteries with a bus is a must. In addition, fuel cells and batteries are usually used along with each other, as fuel cells have lower efficiency and lower chemical reactions compared to batteries [39], [40], and are suitable only for steady state situations. Furthermore, it is unlikely that fuel cells would be used in large aircraft in their propulsion system to provide thrust due to their low specific power.

Battery chemistry possibilities with today's technologies are Lead-acid (Pb-acid), Nickel-Cadmium (Ni-Cd), Nickel-metal (Ni-metal) hydride, Lithium-ion (Li-ion), Lithium-Sulfur (Li-S), Zinc-air (Zn-air), and Lithium-air (Li-air) batteries [25]. Despite the accident in Li-ion batteries installed on a B787 in 2013, they are still in use, but the battery system has been redesigned [123]. Even though Li-ion and Ni-Cd batteries are typically used in MEA, only Li-air batteries seem to be capable of providing enough energy in electric propulsion systems, since they enjoy the highest specific energy among battery chemistries.

The authors in [17] conducted a survey to see what type of battery is most suitable for application in MEA. Table 2 illustrates information about three different types of battery chemistries taken into consideration in [17], namely Pb-acid, Ni-Cd, and Li-ion. The authors concluded that Li-ion batteries result in a reduction in weight as well as cost. In [124], a 6.4 kWh, 50 kW Lithium-ion battery energy storage system (BESS) was designed and the system would be connected to HVDC distribution bus in MEA. Connecting batteries to the HVDC bus (270 V_{dc}) and not to the, for instance, 28 V_{dc} bus would be advantageous, as it results in lower cost and higher efficiency. In addition, the higher the altitude, the lower the temperature, and the lower the batteries' efficiency [125]. Thus, operating conditions, such as temperature and humidity, must be taken into consideration when installing batteries onboard. While it is not the case for batteries installed in the fuselage, batteries installed inside the wings will mostly be affected. A battery management system (BMS) is also needed for monitoring, managing charging/discharging, thermal management, etc. [125]. Discussion on BMS does not fit within the scope of this article and readers may refer to [125] and the references provided in that paper for more information.

E. CIRCUIT BREAKERS

As can clearly be seen in Fig. 7, CBs are of great importance both in normal operation and in failure conditions in an EPS. They connect generators, supply busses, components such as PE converters and electrochemical energy units, and different loads to one another and enjoy very low contact resistance due to efficiency requirements. If, for instance, a generator or battery pack cannot supply the associated loads due to a malfunction, CBs continue the flow of power from another generator, battery pack, etc. by reconfiguration. CBs allow for reconfiguration and, moreover, they are also utilized to suppress a failure from being propagated. The most critical

TABLE 2. Comparison of three types of battery chemistries [17], [120]–[122].

Criteria	Li-ion	Ni-Cd	Pb-acid
nominal cell voltage (V)	3.20	1.20	2.00
typical battery cost in USD (V, Ah, Wh)	207 (12, 21, 252)	100 (12, 20, 240)	67 (12, 20, 240)
cost per Wh (USD)	0.82	0.42	0.28
cycle life (no.)	3000	1500	250
cost per cycle (USD)	0.069	0.067	0.268
cost per Wh per cycle (USD)	0.00027	0.00028	0.00112
specific energy density (Wh/kg)	135	65	40
operating temperature (ºC)	-20 to 60	-30 to 60	-20 to 60
self-discharge/month	2-3%	4-6%	15-20%
overcharge tolerance	very low	moderate	high
maintenance	not required	1-2 months	3-6 months

situation for CBs in AEA would be a short circuit failure in the takeoff phase. In [126], a circuit breaker for short circuit currents up to 20 kA was proposed.

The authors in [4] provided an in-depth review of CB technologies and a comparison was performed between potential circuit breakers in terms of voltage level, current, switching operation, dc operation, galvanic isolation, contact resistance, explosion protection, and weight. Readers may refer to [4] to be provided with more references about CBs.

F. WIRING HARNESS

Electrification tremendously adds to the amount of wiring needed in aircraft. However, detecting a damaged wire is onerous, since a wiring degrade may take place in years. As mentioned, a wiring problem is virtually guaranteed in EPS of an aircraft after twenty years of flight [127] and, thus, cable aging should be carefully taken into consideration [128]. Wiring problems caused by insulation degradation were blamed for several catastrophic accidents, e.g. the B747 downing in 1996. Insulation materials have been being introduced to combat insulation degradation [129], [130]. In addition, a review of wiring insulation materials was carried out in [131]. Also, by the same authors, a method was proposed in [132] to not only detect corona effect in usual pressure ranges during commercial flights, 20 kPa to 100 kPa, but also allows for locating the discharge point. In [133], authors focused on the proximity effect between conductors caused by tightly wired cable bundles and proposed a new method to calculate ac resistance directly under specified frequency.

Another critical issue in wiring system is partial discharges. Generally, two kinds of discharges may occur: disruptive discharge and partial discharge (PD). Surface discharge known as corona is also categorized as PD. Disruptive discharges usually take place across airgaps that may occur between connector pins, uninsulated bus bars and ground planes, or between insulated cables especially bundled ones [134]. It leads to a sudden high flow of current

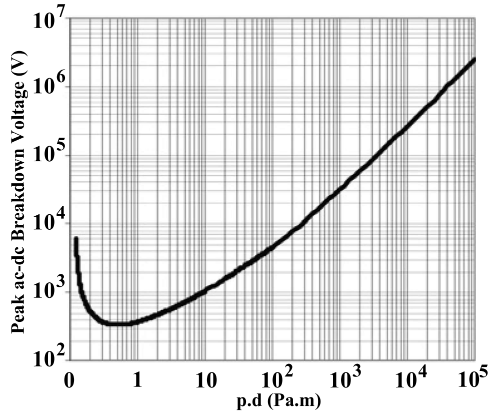

FIGURE 10. Paschen's curve for air [136].

and is usually impeded by CBs [135]. PD, however, does not usually cause immediate problems; instead, it leads to the degradation of insulation, which in long term causes serious problems. It should be noted that PD is also able to ignite hydrogen in cases that hydrogen-based fuel cells are employed as a source of energy; this is due to the very low minimum ignition energy (MIE) of hydrogen gas. As fuel cells will be employed in future MEA/AEA, ignition problem caused by PDs must also be taken into consideration.

Paschen's curve for air is shown in Fig. 10, where p is air pressure and d is gap distance. According to the curve, the breakdown voltage increases for p.d $<$ 0.4 Pa.m that could be the case for aircraft in extreme altitudes [136]. According to this curve, designers are advised to keep the voltage below 327 V to avoid a breakdown. Nevertheless, as mentioned previously, higher standardized voltage for future MEA/AEA is a must to keep the weight of aircraft in a reasonable range, and to guarantee safety and lifetime. An investigation was carried out in [136] so as to investigate the optimal voltage level for wiring system in MEA. Authors concluded that increasing the voltage level to the highest possible levels is not ideal and a tradeoff between weight and power transfer capability needs to be considered. In addition, authors concluded that the use of grounded dc system results in an optimal design. A voltage level around 2 kV as selected in the presented paper is close to the optimal voltage under many circumstances in MEA/AEA.

Lightning hits an aircraft once a year averagely [137] that could cause direct and indirect problems to wiring system. In addition, a damaged wire can adversely affect EMC and lead to EMI. Even though we avoid a detailed discussion, readers may refer to [138]–[140] for further study.

It should be noted that a comprehensive review and discussion on wiring harness is beyond the purpose of the presented paper; it is a broad are of research and we briefly presented some critical issues about wiring harness in MEA/AEA.

IV. TOWARDS ALL ELECTRIC AIRCRAFT

A narrow body, single aisle AEA that properly operates over commercial missions, i.e., 3600 nmi (nautical miles; almost 6700 km), as is for B737, seems achievable. It is not "if" but rather "when" this will happen and it seems possible within the next 20 years [25]. The future of the aviation industry is challenging, since there are many aspects in the aviation industry in which huge advances are needed to let such an aircraft become a reality. The authors in [140] compared EPSs of all electric vehicles, all electric ships, and MEA; they concluded that critical challenges in the path towards AEA are energy density, weight, and the cost of batteries.

While desired electric power in a wide body MEA such as the B787 barely reach 1 MVA, electrical peak power demand in a single aisle aircraft in the takeoff phase reaches above 30 MVA, which must be provided by electrochemical energy units in AEA. This huge amount of power necessitates an increase in voltage so as to prevent the current from being too high, and, in addition, necessitates developing new standards for voltages in aircraft. On the other hand, at high altitudes and due to low pressure, partial discharge increases. As a result, new insulation systems and electric conductor spacing regulations are needed [9].

One major challenge in the path towards AEA is weight. Each kilogram adds about 1000 USD to costs and each kilogram saving results in about 5400 tons/year less carbon emission [142]. Up to 40% of fuel-powered large aircraft weight is due to fuel weight, which is being lost during a flight. However, a Breguet range equation for a battery-powered aircraft is proposed below [6], [143], [144]:

$$R = \frac{L}{D}\eta_P\eta_{int}\eta_e\,\frac{e_b}{g}\,\frac{m_b}{m_{TO}} \tag{2}$$

where L/D is the lift to drag ratio, η_P is propulsive efficiency, η_{int} is efficiency due to propulsion integration loss, η_e is the total efficiency stack-up of the electric propulsion system, e_b is battery specific energy, g is acceleration of gravity, and m_b/m_{TO} is the ratio of battery weight to takeoff gross weight [6]. According to (2) and considering the fact that the weight of the battery packages almost remains unchanged during a mission, and even increase in Li-air batteries, AEA carry extra weight that deteriorates the performance of the whole system in long distance missions.

An AEA that could be competitive to conventional aircraft, such as the B737, must enjoy a peak specific power density of at least 12 kW/kg and a cruise efficiency of at least 93% [18]. Today's commercialized aircraft provide a whole system efficiency of about 75% and, thus, an above 90% efficiency is far higher than today's technologies. Advances are needed in PE converters and motors, and a distributed propulsion system would also be advantageous. In the PE area, [25] drew goals to achieve a specific power density of 19 kW/kg with 99% efficiency with a non-cryogenic cooling system and a specific power density of 26 kW/kg with >99% efficiency with a cryogenic cooling system. Such a cooling system, however, adds further weight to the aircraft. In [18], a specific power density of 30 kW/kg was predicted to be achievable by using advanced cooling systems. Indeed, advancements in device physical layers, e.g., wide-bandgap switches, accompanied by modeling and control techniques will pave the way towards a commercial AEA. In the electric machines area, super conducting motors with >20 kW/kg have been achieved and >35 kW/kg motors seem to be achievable according to NASA roadmaps for 2035. Since superconductivity is achieved at lower temperatures, insulation could be a potential challenge. Insulation materials, fortunately, work more satisfactorily at cryogenic temperatures [145]. According to [25], some required advances are:

- 3 times increase in power density of PE converters.
- 3-5 times increase in power density of electric motors.

Another challenge is aircraft batteries. While jet fuel specific energy reaches 12000 Wh/kg with a useful specific energy more than 4000 Wh/kg, a Li-ion battery specific energy barely reaches 250 Wh/kg, let alone its useful specific energy. However, Li-air batteries' useful specific energy reaches 2000 Wh/kg and seems the only potential battery type to be utilized in electric propulsion systems. Indeed, Li-ion and Ni-Cd batteries that are already used in MEA such as the B787 and the A380 may also be utilized in non-propulsive applications in future AEA. As a turbo electric propulsion system does not rely on batteries, turbo electric MEA seems to be able to be commercialized sooner than MEA with hybrid electric propulsion systems and AEA [9].

All the above mentioned advancements increase the complexity of aircraft EPS. Various EPS architectures must be proposed and carefully assessed in terms of complexity of modeling, stability, reliability, ease of reconfiguration, weight, number of components, voltage level, redundant power, etc. In addition, a well-suited modeling approach, an appropriate EMS, etc. are all needed so as to conveniently analyze an aircraft EPS. Even though arriving at an appropriate EPS architecture (both for the propulsion system and for non-propulsive purposes) with satisfactory voltage and current ratings could be very challenging, the complexity of EPS does not seem the major challenge in the path towards AEA. Many theories already exist for ground based microgrids and electrified vehicles and ships that should be adopted, if needed, to be employed in the aviation industry. It does not seem to be the most critical challenge and can appropriately be confronted by advanced modeling and analysis approaches before other above mentioned problems are addressed and solved, specifically challenges regarding batteries, PE converters, and electric machines.

V. CONCLUSION

In this article, electric power systems (EPS) of more electric aircraft (MEA) and all electric aircraft (AEA) was discussed. The trend is towards elimination of all but electrical forms of energy in aircraft power systems. This makes the aircraft EPS a very complex onboard microgrid. MEA/AEA EPS is an "isolated hybrid microgrid" (IHM) comprised of both ac and dc voltages, which, although different from ground based microgrids, bears some degree of resemblance to terrestrial microgrids. Thus, apart from methods that should be developed for MEA/AEA EPS analysis, methods and approaches developed for ground based microgrids can be adopted as well to be utilized to analyze MEA/AEA EPS.

Regarding the high amount of power needed for thrust, employing a distributed propulsion system (DPS) seems essential. DPS allows for developing components that are feasible with today's technologies or will be feasible in the near future. In addition, new standardized voltage levels must be introduced at least for propulsion distribution systems; insulation challenges, however, may arise that must be taken into consideration.

In section II, an initial schematic of an aircraft EPS with electric propulsion was proposed and busses' voltage levels were determined. A 2 kV_{ac} bus was considered for the electric propulsion system, while a 230 V_{ac} with a variable frequency 350-800 Hz bus was assumed as the primary supply bus. Three other distribution busses, 270 V_{dc}, 28 V_{dc}, and 115 V_{ac} with fixed frequency 400 Hz, were considered and all were assumed to be derived from the primary bus utilizing power electronics (PE) converters.

Publications about power flow (PF) analysis and management of EPS were also taken into consideration and reviewed in this article. In order to perform a PF analysis, modular models could be advantageous. Furthermore, modular models allow for analyses at different levels, e.g., system level, behavioral level, etc.

In section III, PE issues related to aircraft EPS were generally discussed, including PE converters, electric machines, electrochemical energy units, circuit breakers (CB), and wiring harness. Ultimately, challenges in the path towards commercial AEA were discussed in section IV. Advancements in all areas are needed; however, the most crucial challenges are related to electrochemical energy units, such as batteries, and PE converters. For PE converters, it seems essential to utilize wide-bandgap switches, soft switching techniques, and nonlinear modeling approaches to provide models that can be conveniently utilized in controller design and stability analysis. For batteries, the only type of battery that may be capable of providing propulsion power in future AEA propulsion systems is the Lithium-air (Li-air) battery, even though Lithium-ion (Li-ion) and Nickel-Cadmium (Ni-Cd) batteries are already commercialized and in use in MEA and could be utilized in future AEA for non-propulsive purposes as well.

Advancements are also needed in adopting methods to be used in the aviation industry. For instance, a PF method specifically applicable in analyzing MEA/AEA EPS is essential. Unless mentioned challenges in section IV are satisfactorily addressed and solved by promising solutions, arriving at a commercial AEA that properly operates over commercial missions will not be possible.

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