INVITED PAPER

The More-Electric Aircraft and Beyond

This article presents a historical retrospective of aircraft electrification and an overview of the existing frameworks of aircraft electrification.

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ABSTRACT | Aviation is a significant contributor to greenhouse gas (GHG) emissions in the transportation sector. As the adoption of electric cars increases and GHG emissions due to other modes of transport decrease, the impact of air travel on environmental pollution has become even more significant. To reduce pollution and maintenance, and ensure cheaper and more convenient flights, industry and academia have directed their efforts toward aircraft electrification. Considering various types of aircraft, several frameworks have been proposed: more-electric aircraft (MEA), hybrid electric aircraft (HEA), and all-electric aircraft (AEA). In the MEA framework, propulsion is generated by a conventional jet engine; however, all secondary systems (hydraulic, pneumatic, and actuation) are electrified. By further increasing electrification, electric motors can provide propulsion with the electric power supplied by the conventional engine (i.e., HEA) or from electrical energy storage (i.e., AEA). Power electronics and electrical machines play a key role in this scenario in which electric power must be efficiently generated, distributed, and consumed to satisfy extremely high requirements of aviation safety. This article provides an overview of recent advancements in aircraft electrification, and trends and future developments referenced to the global aviation roadmap.

KEYWORDS | Electric transportation; more-electric aircraft (MEA); power electronics.

I. INTRODUCTION

Air transportation is the enabler of modern globalization and the backbone of mail and goods transportation. EUROSTAT [1] statistics show that the interest in and the number of passengers of air travel have steadily increased each year. Accordingly, aircraft reliability and efficiency are paramount. In China, aerospace constitutes a strategic industry with major investments. The Commercial Aircraft Corporation of China Ltd. has been funded in 2008 to support an expanding air market (with a growth rate reaching 30%). Worldwide, more than 2000 aircraft are sold each year, and in 2016, the total revenue exceeded \$20 billion. In the market, the Boeing 787 aircraft, with its 1450-kVA electric generators (see Fig. 1), offers considerable electrical power. The growth in the sector is supported by the forecasts of big players in which Asia is anticipated to lead the growth by 2030, as presented in [2].

In conventional aircraft, fuel is combusted to produce propulsive power, which partially supports the onboard system. The gearboxes power the central hydraulic pump, which is used for the actuation system (see Fig. 2). Hydraulic actuators afford the distinct advantage of simple high-power density control. However, its infrastructure, which is composed of pipes, is extremely bulky. Moreover, it presents a reliability problem because the presence of leaks can impair hydraulic actuation and simultaneously release corrosive fluids. Consequently, unscheduled maintenance due to a fault in the hydraulic system can ground the aircraft.

To reduce aircraft weight and fuel consumption, and increase reliability, the concept of more-electric aircraft (MEA), i.e., aircraft with more electric power, was proposed [4]. In reality, the idea of eliminating hydraulic systems from aircraft was conceived 30 years ago. However, only recently has the advancement of technology in conjunction with investments in new aircraft brought this topic into the spotlight. The basic concept is that hydraulic actuators can be replaced by electromechanical actuators, thereby eliminating the hydraulic distribution system. To power these actuators, electric power must be generated and distributed.

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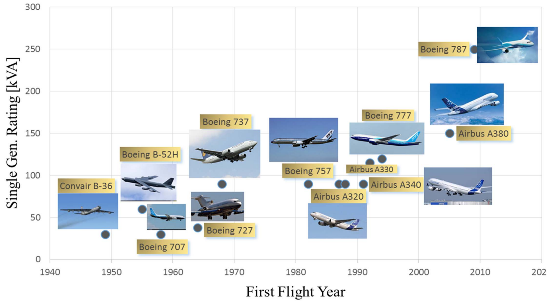


Fig. 1. ***Aircraft electrification history [3].***

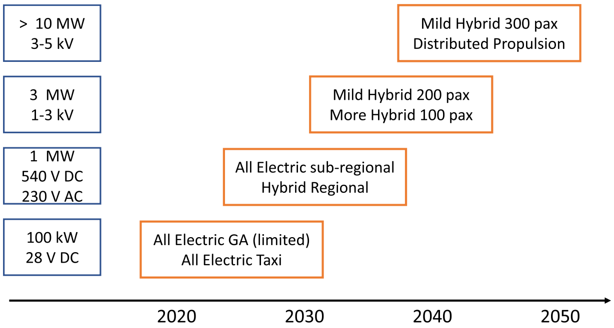


Fig. 3. ***Power requirements for the next generations of aircraft [5].***

Because aircraft electrification can start from simple subsystem electrification to thrust generation, several categories have been proposed.

1) *MEA:* Propulsion remains conventional; however, the subsystems are substituted by an electrical version.
2) *Hybrid electric aircraft (HEA):* A conventional jet engine produces electrical power through an onboard generator, and the main energy is provided by aviation fuel. Electric power is distributed throughout the aircraft, and electrical motors generate thrust that drives the propellers. Compared with MEA, the propulsion of HEA is electrified.
3) *All-electric aircraft (AEA) or full-electric aircraft (FEA):* The power for driving the propellers is supplied by onboard storage, and there is no combustion engine onboard.

The roadmap presented in [5] and presented in Fig. 3 outlines the envisaged power/voltage levels for different aircraft classes. In the short term, air taxis and general aviation can lead to the emergence of AEA. The shift to megawatt-class motors is necessary for (100–200)-passenger HEA; for larger aircraft with distributed propulsion, 10-MW engines are envisaged.

A. MEA Concept

The MEA concept advocates the electrification of aircraft subsystems to improve the efficiency and performance of the entire aircraft. The actuation system is one of the first candidates for electrification because of the immediate advantage of removing the hydraulic distribution; however, it is merely one of the aircraft subsystems powered by the main engine (see Fig. 2). Excellent power-sharing is required by the pneumatic system [for cabin pressurization (cold air)] and wing deicing system (hot air). In conventional aircraft, the pneumatic system is powered by a bleed valve that extracts high-pressure air from the main engine. However, the presence of this valve significantly deteriorates the efficiency of the main engine [6]. For this reason, to achieve maximum efficiency, the complete electrification of all systems, except propulsion, can be realized, as shown in Fig. 4. The removal of the bleed valve, however, requires electrically powered compressors, drastically increasing the number of onboard power electronics systems.

Although the objective of electrifying all subsystems may appear clear, its implementation poses challenges: power must be generated, distributed, and used.

The initial solutions conceived to provide onboard electric power suitable for low levels of electrification envisage the use of an electric machine connected to the main engine and a constant-speed gearbox for generating a constant-frequency three-phase power supply [7]. The use of a gearbox is possible only for reduced power levels, and the development of power electronics necessitates constant-frequency distribution.

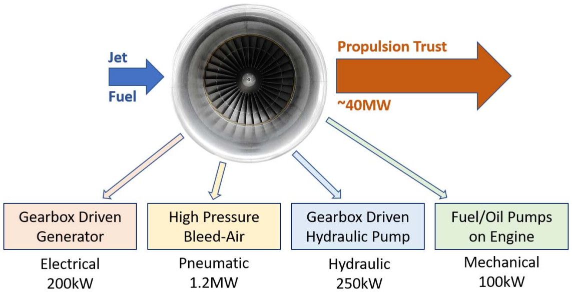


Fig. 2. ***Subsystem of a conventional aircraft.***

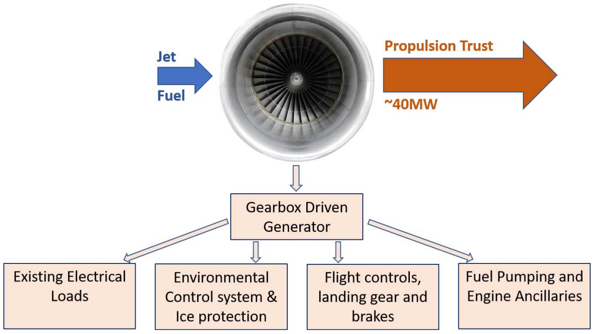


Fig. 4. ***Subsystem of an MEA.***

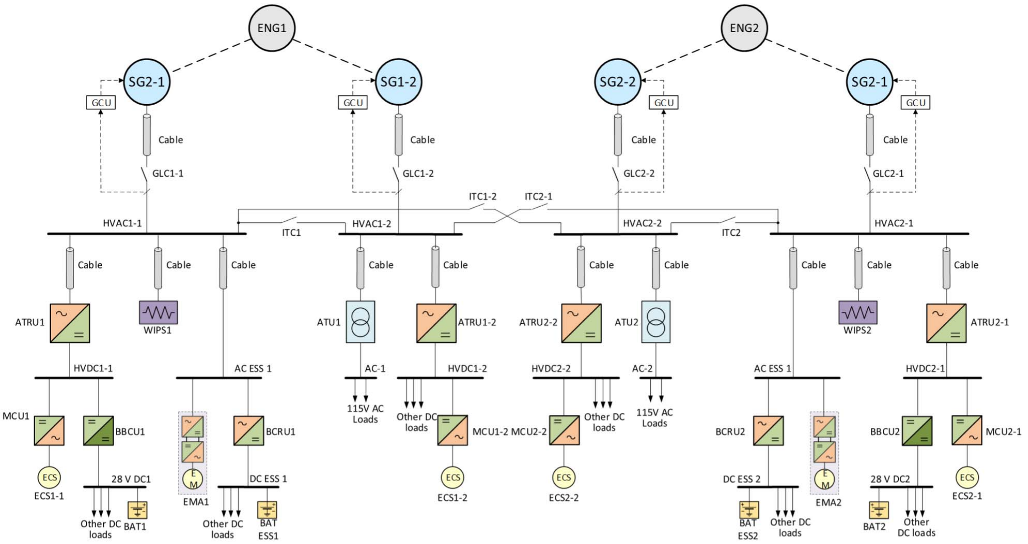


Fig. 5. ***EPDS of an MEA [9].***

Because the use of constant-speed gearboxes was quickly abandoned, the distribution shifted toward one with a three-phase variable frequency. This allowed for a more compact distribution system and paved the way for synchronous generators to be widely adopted for MEA. In fact, controlling the excitation of the synchronous machine allows for constant voltage amplitude even when the rotational speed of the main engine changes.

With the development of electrical machines and power electronics, direct-current systems have begun to be considered even for general aviation (because their use in military aircraft has already begun [8]), thus reducing conversion stages, potentially allowing the widespread adoption of power electronics.

An advanced electrical power distribution system (EPDS) can remarkably increase aircraft efficiency and safety similar to ground-based generation/transmission/distribution systems. A higher voltage transmission system allows lighter cables (with evident weight reduction); however, the loads normally operate at lower voltages. Most distribution systems operate with hybrid alternating current (ac) EPDS and passive rectifiers to generate dc voltage levels. Although this solution is widely employed, several problems remain.

1) System complexity is high because a variable-frequency ac distribution poses several control and design challenges in terms of power quality (e.g., harmonic suppression at variable frequency is difficult) and power electronics interface.
2) The resilience of the system to faults requires numerous redundancies, increasing the weight of the system.

The foregoing paradigm is visualized in Fig. 5, which shows a modern EPDS example. Each of the two main engines powers two electric generators. Synchronous generators generate a three-phase power supply with the same rotational frequency as that of the main engine. A power electronics unit controls the excitation of the synchronous generator, ensuring that the amplitude of the voltage remains unchanged with the mechanical frequency. Accordingly, four separate high-voltage variable-frequency constant-amplitude buses were fabricated. The loads were connected to each bus (pumps, deicing systems, and so on). One of the main characteristics of ac buses is that they are isolated from each other for safety reasons. If a fault renders a bus unavailable because of physical separation, then the other buses are unaffected. The separation of different buses is currently one of the strictest design requirements to attain reliability targets.

To generate dc subsystems, transformer rectifier units (TRUs) composed of a transformer and diode bridge rectifier are used. An additional dc–dc converter can be added after the rectifier to generate a controlled dc output voltage. If galvanic isolation is not mandatory, then auto-TRUs can also be adopted to attain the same objective. For safety reasons, the generated dc rails are galvanically isolated.

A matrix of normally open switches is also present. In the case of a generator fault, this can be used to connect the ac bus to achieve an uninterrupted power supply. Note that connecting different ac buses is considered an emergency procedure; moreover, switches are normally open.

B. Electric Propulsion Aircraft

The shift from MEA to HEA (or AEA) implies realizing the propulsion system of an aircraft electrically. The same constraints for MEA apply but with two important differences.

1) The amount of available power increases from hundreds of kilowatts to tens of megawatts.

2) Electric machines become a predominant part of the system.

The foregoing introduces several consequences to the design of the electrical system as follows.

1) Due to electric propulsion, the utilization of full-size power electronics is envisaged for electric machines. Moreover, because one of the main advantages of synchronous generators is the possibility of supplying a three-phase load with a constant-voltage envelope with limited power electronics, other types of machines may become more attractive.
2) Due to the high technological maturity of voltage-source converters, the preference for dc distribution to supply the dc link of converters is possible.

This trend is confirmed by the technological choices of E-Fan X [10], in which megawatt-class motors and power electronics as well dc distribution in the kilovolt range are envisaged. Some research groups have investigated the use of permanent magnet machines for HEA and realized megawatt-class demonstrators [11], [12]. Note that the scientific debate on optimal machine topology remains open. This is because of the well-known demagnetization problem of permanent magnets at higher temperatures, rendering other types of machines, such as switched reluctance machines and extremely attractive [13], [14]. In any case, the use of a synchronous machine to supply three-phase electric grids may decline.

C. Open Challenges

Although the EPDS is a reliable system, the main open problem is the necessity of providing numerous redundancies that increase system weight, consequently decreasing power density.

Although battery technology is the main limitation of FEA [15], the power density of electrical machines and power electronics constitutes another major challenge. In addition to the electrical subsystem, the EPDS has been the subject of several investigations to improve power distribution performance. The EPDS requires high power density because it accounts for a considerable weight (approximately 1.7% of the weight of a Boeing 747 class plane [16]) and further increases with the electrification percentage. The EPDS must also guarantee continued operations even when faults occur. Furthermore, it must optimize power flow inside the aircraft with potential savings in terms of overall installed power and weight of electrical machines and power electronics [17]. A fully smart behavior of the EPDS is estimated to enable a 15% downsizing of the electric generator, resulting in enormous savings in terms of weight [18].

II. STATE OF THE ART

Sections II-A–II-D show the state of the art of power electronics for onboard microgrids. The basic components (i.e., power electronics and machines) are discussed. System-level solutions that have been proposed to overcome the limitations of conventional systems shown in Fig. 5 are also outlined.

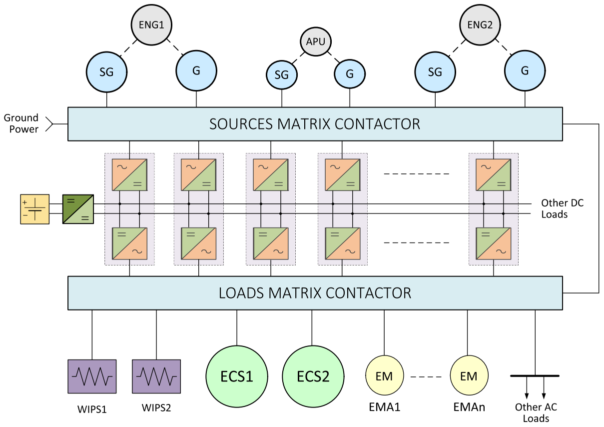


Fig. 6. *IMPEC concept [20].*

A. System Level: Interconnected EPDS

In recent years, several solutions have been proposed to improve the EPDS through modularity and increase the interconnection among different bus lines. In the integrated modular power electronics concept (IMPEC) (see Fig. 6) [19], the power distribution system is rendered more flexible by the presence of a contactor matrix for sources and loads. In reality, all sources (generators and auxiliary power units) can be connected to modular power electronics blocks, which feed a dc bus. Similarly, the dc bus can be connected to any load through a matrix of contactors.

As shown in Fig. 7, the use of several power electronic modules to implement high-power converters for the EPDS has been proposed by Fritz *et al.* [21]. The various modules comprising the power electronics interface can be connected to different buses, enabling power exchange among different sections of the EPDS. For this purpose,

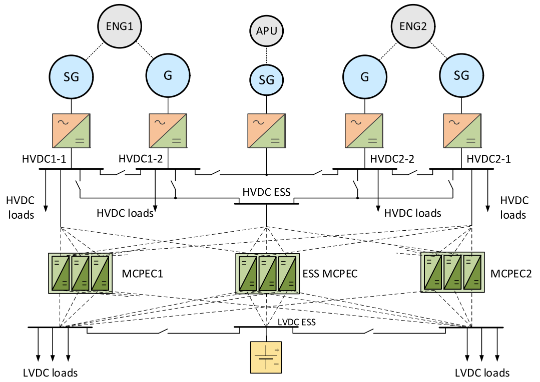


Fig. 7. *Cellular power converter concept [21].*

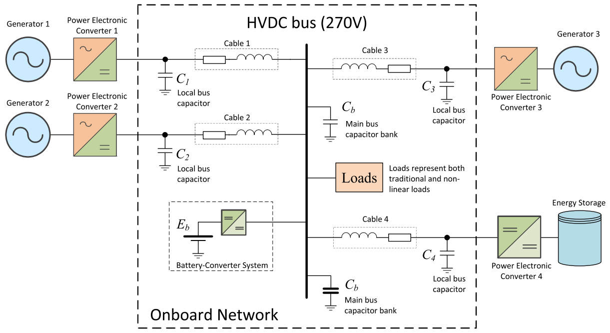


Fig. 8. ***Single dc bus EPDS [22].***

the use of single-input–single-output converters has been envisaged.

A solution that can reduce overdesign due to bus separation can indeed result in a single bus line, as proposed in [22] and shown in Fig. 8. Solid-state power controllers with extremely fast dynamics and high reliability must be added to guarantee safety in the case of faults in a single bus line. Evidently, ensuring the required level of reliability for the passenger flight of a single-bus system is extremely challenging.

The main idea to further drive the EPDS functionality is to upgrade the multibus distribution system by replacing conventional dc–dc converters with multiport equivalent converters and electric machines with multi-three-phase converters.

This represents a step toward the convergence of power electronics, electric machines, and drives because all the elements are functional in optimizing the overall power density and fault tolerance of the power system with the aim of not compromising the power density. Fig. 9 shows a possible implementation of the foregoing concept [23] in which electric machines are replaced with multiwinding machines, and the single-input–single-output dc–dc converters are replaced with multiport power electronics.

The control of the multiport dc–dc is described in [24]; an outer control loop implementing droop control is used to enable easy paralleling. A similar approach can be pursued for controlling the machine section by considering a segmented generator. The inner current loop of each segment regulates the torque demand. An outer control loop regulates the bus voltage, and the droop control loop enables the paralleling of multiple converters from different segments. This control strategy is suitable for an arbitrary connection of segments such that different buses can be supplied. This control also ensures fault-tolerant operation and automatic power-sharing in the case of faults of segments and machines.

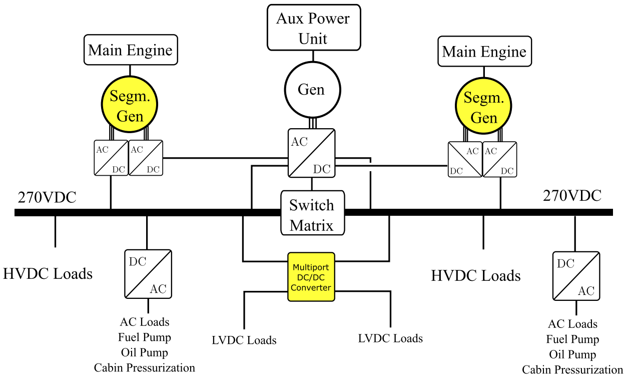


Fig. 9. ***Upgraded EPDS with multiport power electronics [23].***

This EPDS configuration combines virtually all power electronics and machines via either a transformer or an air gap of the machine that fundamentally functions as a transformer. From a functional point of view, provided that power flow does not exceed the rating of devices or machine winding, this configuration affords the advantage of a single-bus architecture (where everything is connected) while maintaining the constraint of galvanic separation among different sections of the EPDS.

The problems with such systems emanate from the control point of view, i.e., handling the power flow automatically while maintaining the voltage within limits, and from the perspective of component design such that unbalanced power flow in a modular structure may represent the normal operating condition. Finally, to be considered as a viable proposal, the segmentation of machines and power electronics must only incur a minimum power density decrease compared with traditional nonmodular designs. The work in [23] demonstrated that a slight improvement in power density can be achieved in an electric machine by shifting from a three-phase design to a multi-three-phase design. In addition to the advantages available at the machine level, the solution involving the use of a multiport dc–dc converter can offer a power density increase of up to 30% [25], rendering this latter solution even more interesting.

B. Component Level: Optimized DC–DC Converters for the Aircraft System

Isolated dc–dc converters have been adopted in several applications where the galvanic separation of sources and loads is necessary. The use of a transformer enables power transfer but requires an inverter and a rectifier power electronics stage to maintain constant input and output values.

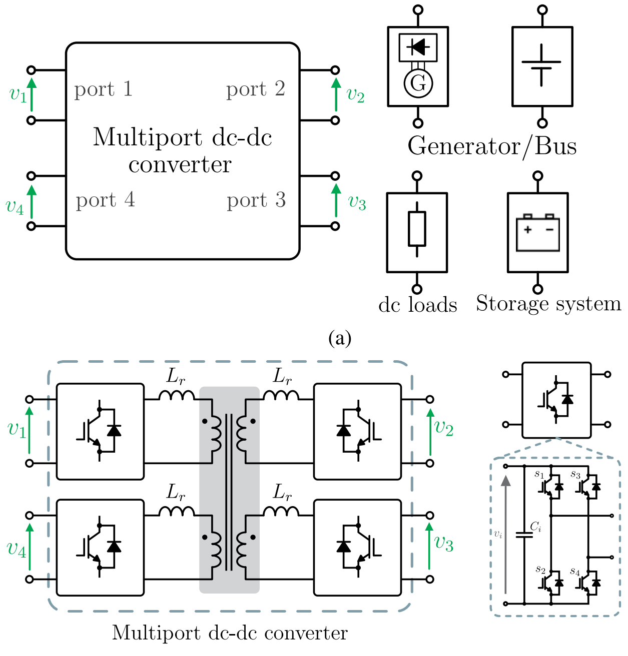
A full-bridge converter (FBC) consists of two H-bridges that operate with pulsewidth modulation to generate a sinusoidal waveform at the transformer input, whereas a secondary bridge operates as a controlled rectifier. In the case of reverse power flow, the secondary-side controller can operate as a regenerative source. The secondary bridge can eventually be replaced with a diode bridge rectifier if the unidirectional transfer is sufficient; however, this mode affects the output power quality. The major drawback of this converter is high switching losses because H-bridges operate in a hard-switching mode, and a bulky output filter is required. Solutions for the zero-voltage switching (ZVS) operation of FBCs have also been reported [26].

To increase efficiency while maintaining bidirectional power transfer, a dual-active bridge (DAB) was proposed [27], [28]. The operating principle involves the synchronous power transfer between two ac sources; the structure is the same as that of the FBC. However, power electronics are operated with phase shift modulation (PSM). The advantage of this approach is the soft-switching operation, which leads to a remarkable increase in efficiency. The possibility of implementing bidirectional power flow control without changing the operating principle is a notable advantage of this topology. Single-phase operation implies the necessity for sizeable input and output capacitors. The three-phase version has a better performance in terms of capacitor current and power density and may be well-suited for aerospace applications.

Exploiting the possibility of zero-current switching (ZCS) was performed for the series resonant converter in which a capacitor is added in series with the transformer to create a resonant tank. If the H-bridge is operated at a frequency below the resonant frequency of the tank, then the converter operates in the ZCS, ensuring a high-quality current waveform and extremely high efficiency [29]. The main problem with this topology is the difficulty in controlling power and the necessity for the operating mode to switch to the regenerative mode.

Although a high level of optimization has been achieved for all of the abovementioned topologies, and they all retain a specific application field, a better contextualization of the aircraft system is required. Research on different topologies specific to aircraft applications remains extremely active. In [30], the active-bridge active-clamp converter was optimized for MEA applications. The operating principle is similar to that of DAB; however, it offers a reduced capacitance requirement compared with that of the single-phase DAB. A modification of DAB with interleaved buck–boost converters on the low-voltage side was adopted in [31] along with triple PSM to relieve the current stress and reduce the reactive power circulation. Different concepts, such as inductor-less dc–dc converters, have been investigated for increased power density and radiation hardness [32].

In applications, such as smart grid systems, where multiple loads and/or sources must be interconnected, multiple dc–dc converters are used. However, to avoid the use of several converters and the necessity for communication and synchronization among them, a centralized solution based on a multiport converter can be adopted. Fig. 10(a) shows a generalized block diagram of a multiport converter, and the possible sources and loads connected to the ports. In particular, a multiport converter based on multiple active bridges was proposed in 2007 in [33] and [34] to interface a fuel cell generator, the battery storage system, and passive loads.



(a)

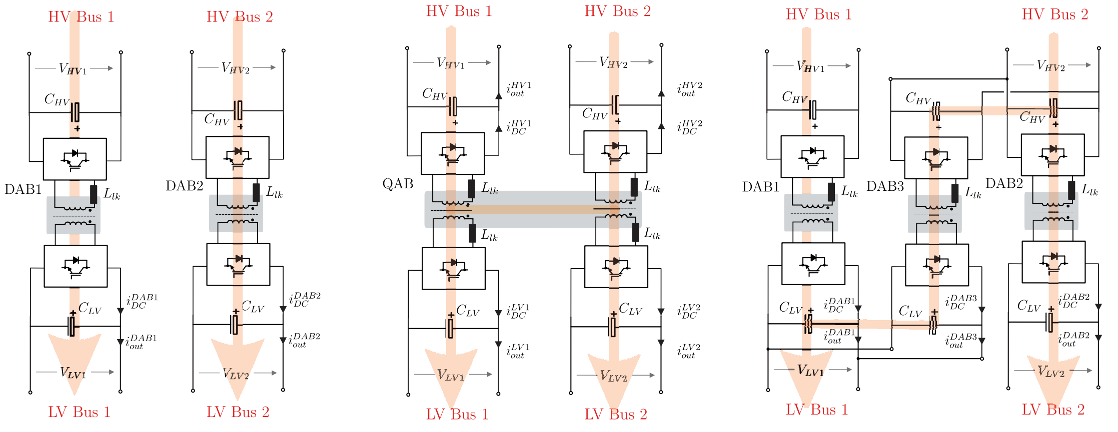
(b)

Fig. 10. ***Isolated multiport dc–dc converters [37]. (a) Block diagram of a multiport converter with the typically sources connected to the ports. (b) Topology of the QAB converter.***

The above converter is an extension of the DAB converter and has three active bridges connected to the same high-frequency multiwinding transformer. Because of having three active bridges, it was named the triple-active bridge converter [35]. Similarly, an extended version with four active bridges, called quadruple-active bridge (QAB), as depicted in Fig. 10, has been proposed in [36] to integrate a distributed generation system and storage system into a solid-state transformer.

Another key factor that becomes important in architectures featuring a high number of dc–dc converters is that the QAB reduces the number of converters and conversion stages compared with single-input–single-output solutions. This is depicted in Fig. 11, where a four-port system is realized using multiple single-input–single-output converters. This configuration represents a typical case in which two high-voltage lines (HV bus 1 and HV bus 2) are interfaced with two low-voltage lines (LV bus 1 and LV bus 2). If the power exchange among different buses is not required, then the solution shown in Fig. 11(a) represents the easiest approach. Two conventional converters (e.g., DABs) can be used for this purpose. The same goal can be achieved using a four-port power converter [see Fig. 11(b)]. The number of power electronic devices is the same as that in the previous solution, whereas the amount of magnetic material (the transformer is comparatively smaller) is reduced with the control logic. In contrast to the previous case, power can be routed to all buses.

Power exchange can be realized by utilizing multiple DAB converters to connect all inputs and outputs; the evident drawback is power density reduction. The possibility of reducing the deterioration of power density is shown in



(a) (b) (c)

Fig. 11. *Different possibilities to realize a four-port module: (a) two single-input–single-output power converters, (b) four-port power converter, and (c) three single-input–single-output power converters [40].*

Fig. 11(c) where only an additional DAB is adopted. If the power exchange among the HV lines or among the LV lines is required, then multiple conversions are also necessary, with a distinct decrease in efficiency. Whether the QAB can achieve the same efficiency as the dual-DAB solution remains under dispute; however, a maximum efficiency rate of 97.5% has been achieved by a 20-kW QAB converter in [38]. In [39], only a slight difference between the symmetrical and asymmetrical operations of the QAB was measured. Although the foregoing is promising, the result remains lower than that of optimized DAB converters. However, if power exchange among multiple buses is required, then the QAB solution outperforms the multiple DAB solution in terms of efficiency and power density.

Because the actual EPDS still features a considerable amount of ac loads and the supply of legacy ac remains expected in future electric aircraft, a multiport bidirectional dc–ac converter for replacing old TRUs has been investigated. In fact, a reduced-scale fault-tolerant smart transformer as a power interface between multiple dc and ac buses on MEA can be advantageous to ensure the safety of the power supply and galvanic separation of dc rails.

A possible topology for such a device is proposed in [41]; its basic structure is shown in Fig. 12. This converter features a QAB that interfaces with a cascaded H-bridge (CHB) converter. The QAB handles the power transfer among different points, whereas the CHB outputs a low-distortion sinusoidal voltage. Because of the possibility of CHB interleaving the carriers even with a low carrier frequency, an extremely high apparent switching frequency can be obtained [42].

C. Component Level: Variable Speed Drives for MEA

Variable speed drives (VSDs) represent a major share of the world's electrical power consumption. In MEA and other concepts of highly electrified aircraft models, electric power is produced via generators coupled to the main engines and utilized by compressors, pumps, and actuators. This means that a substantial share of the power is generated by an electric machine and used by another electric machine.

In particular, the starter/generator has represented a major technology breakthrough for MEA [43] because it enables a complete electrical start of the main engine without the necessity for an external power unit. An electric machine, usually a synchronous generator [44]–[46], is coupled to the main engine to accelerate the rotor from a standstill until the start velocity (ω_{start} in Fig. 13) is attained (other machines, such as induction [47], [48] and switched reluctance machines [13], [49] with bidirectional power electronics, are also linked). Once the engine reaches the appropriate velocity, self-sustaining combustion can occur. Moreover, the power electronics shift from the starting mode to generator mode following the operation as the rotational speed increases from the minimum ($\omega_{\min}$) to the maximum ($\omega_{\max}$) velocities, as shown in Fig. 13.

With this type of system, the challenge is the minimization of the weight of the electrical machine; otherwise, a high rotational speed is necessary. To cope with the

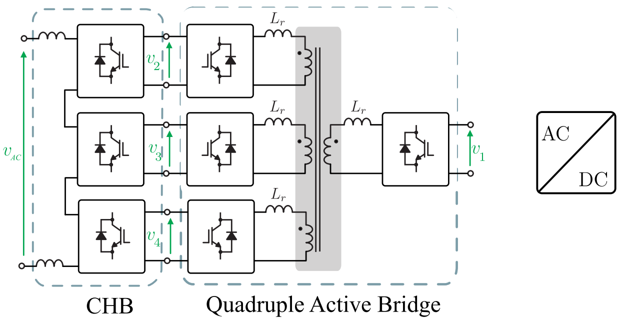


Fig. 12. *Two-port modular smart TRU [41].*

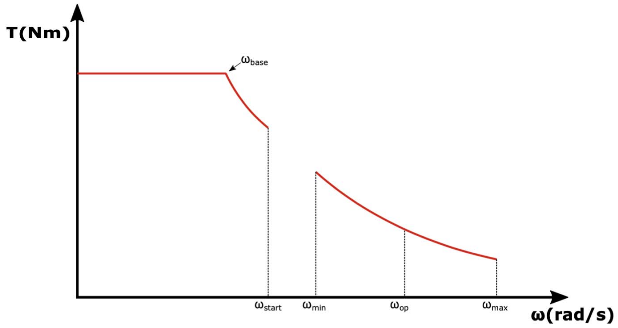


Fig. 13. ***Torque–speed characteristic of a starter/generator system for the MEA [50].***

high fundamental frequency and high power, multilevel converters or wide bandgap devices can be used.

One of the main trends for generation systems is the adoption of a three-level converter (see Fig. 14) to increase the effective switching frequency for control purposes and to obtain a better current waveform for the machine [51]. With the trend of increasing dc voltage and the use of multilevel converters for high-power aerospace applications, systems seemingly become more susceptible to random failure due to cosmic rays at high altitudes [52], rendering modular systems necessary.

Another important area of electrical machine utilization is electrohydrostatic actuators. In contrast to purely hydrostatic actuators, which require a conventional distribution system with a central hydrostatic pump, the HEA (see Fig. 15) consists of a VSD, hydrostatic pump with a local reservoir, and hydrostatic actuator. Compared with the traditional hydraulic solution, this approach does not require pipes or centralized distribution. The actuator can operate provided that electric power is supplied to the VSD. A study [53] estimated that the HEA can achieve 40% of the power density compared with the analog actuator. However, the mass of the hydraulic supply and the maintenance cost of the analog version must be considered.

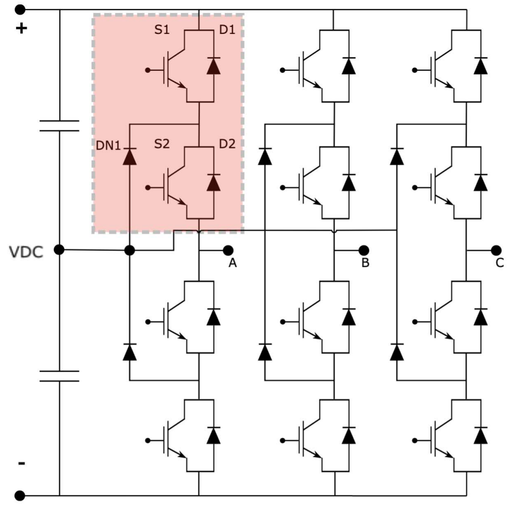


Fig. 14. ***Neutral point active rectifier for a starter generation system [50].***

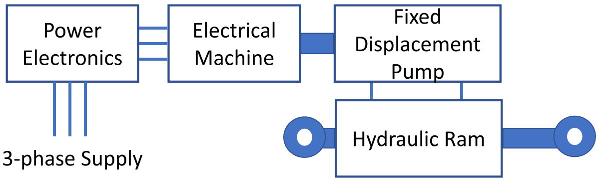


Fig. 15. ***Electrohydrostatic actuator concept.***

Given their reduced power rating compared with starter/generator systems, HEAs have leveraged wide bandgap semiconductors [53].

It is safe to state that, given the current technology, a higher degree of modularization can open the opportunity for fault-tolerant systems and the perspective of power electronics and machines. Accordingly, researchers have investigated different machine topologies with more than three phases.

The main difference between a multiphase machine and a three-phase machine is that the number of phases (m) of the former exceeds 3. This has profound consequences for the design of electric machines and power electronics. In particular, the main design choice is represented by the degree of modularity in terms of converter design. A single converter with a single dc-link can supply all phases of the machine, or multiple power converters (three-phase, H-bridge, and single legs) can be used to feed either the individual coils or groups of coils.

With respect to machines, the choices are winding topology (symmetrical and asymmetrical), the presence of phase displacement among the phases, and the starting point of connections. Each choice influences fault-tolerance capability and control. The number of phases represents the main means to split the power of the machine, allowing the power rating of power electronics to be matched with that of individual phases. Indeed, one of the main advantages of a multiphase machine is the realization of a high-power drive with lower power semiconductors. By increasing the number of phases and affording individual current control, finer control of the airgap flux with possible advantages in terms of machine efficiency and operation can be achieved. The principle behind a multiphase drive is the same as that of a multilevel power converter. In the multilevel converter, the voltage levels are added together to reduce the distortion of the output waveform. In contrast, in the multiphase machine, the airgap flux density levels due to individual phases are added together to reduce the distortion of the overall airgap flux.

An additional degree of freedom that is provided by multiphase machines is the winding topology. Although traditional machines already have different types of winding configurations (concentrated, distributed, single/double layer, and so on), they are consistently in the configuration of a balanced three-phase system with 120 electrical degrees of phase-shifted back EMF. In particular, the electrical phase shift among different three-phase systems can be exploited for airgap flux optimization [54]. Another possibility is to have a different three-phase system wound in various parts of the stator to realize a multisectored [55] machine.

D. Component Level: Wide Bandgap and Highly Integrated Power Electronics

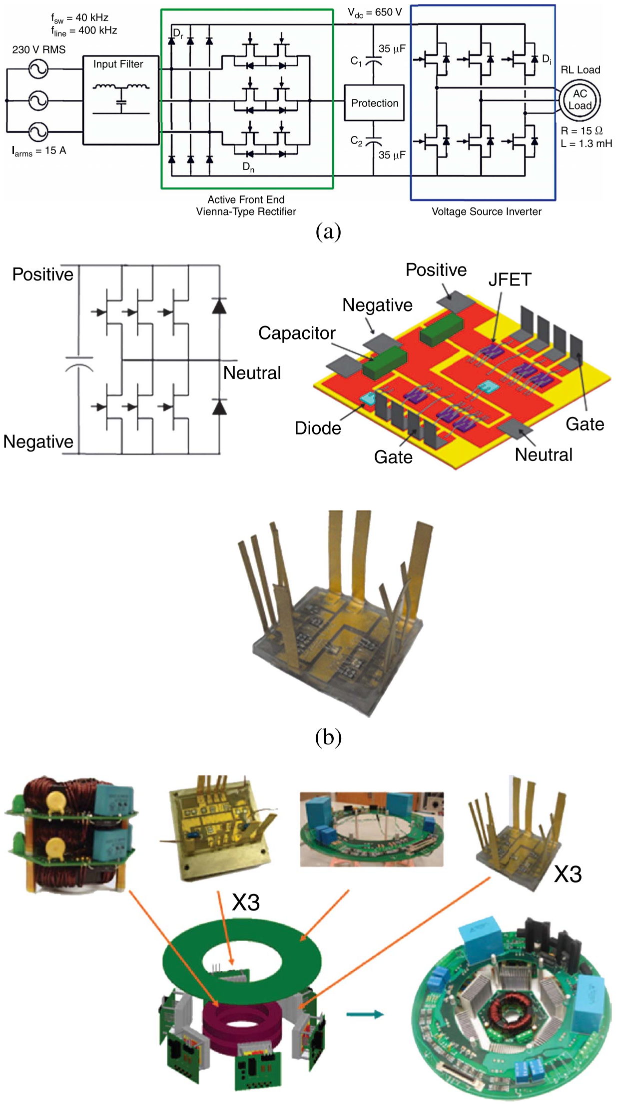
To pursue the extreme power density requirements of the next generation of electrified aircraft, researchers have studied advanced integration, packaging, cooling, and power electronics techniques [56], [57].

The various trends observed can be summarized as follows:

1) reduction in the losses of the power electronics stage;
2) reduction in the size of passive components;
3) improvement in the cooling system;

All of the abovementioned characteristics contribute to the increase in the power processing capability with the same weight/volume at the power electronics stage. Of particular interest in this area is the adoption of wide bandgap semiconductors, which enables increased operating frequency (reduction in the size of passive components). They reduce losses compared with their Si counterparts and have higher operating temperatures (allowing the flow of higher magnitude current under the constraint of maximum operating junction temperature). In this framework, integration and advanced cooling are the keys to push the limits of wide bandgap devices. For example, in [58] and [59], a Peltier element was used to optimize the cooling of SiC semiconductors, allowing them to operate at a maximum junction temperature of 175° and an ambient temperature of 120°. In [60], a SiC junction field-effect transistor current-source converter was realized with an extremely high frequency, which allows a significant reduction in the dc-link inductor size. In addition, the use of planar magnetics [61], [62] and 3-D printing [63] has been investigated to further improve the power density. For electric actuator applications, power electronics can also be integrated into an electrical machine, allowing for optimized cooling and 30

As a case study, the design of an integrated ac–dc–ac full-SiC power electronics for aerospace applications [65] is described as an example of convergence of multiple targets. The topology of such a converter, which is based on the Vienna rectifier, is shown in Fig. 16(a). The impact of all design parameters, such as switching frequency, modulation scheme, and passive component values, on the control bandwidth and losses is considered. The cooling system was split among different individual heatsinks with forced air cooling for each half-bridge module [see Fig. 16(b)], which also integrates the dc link and gate drive circuit. The finite element method simulations allowed the individuation of the optimal cooling technique and component placement [see Fig. 16(c)]. The operation at a higher temperature value allowed a 25% weight reduction between the 250° and 175° versions of the 10-kW prototype.



(a)

(b)

(c)

Fig. 16. ***Integrated high-temperature ac–dc–ac converter developed in [65]. (a) Topology of the integrated high-temperature ac–dc–ac converter. (b) Layout of the inverter model. (c) Picture of the assembled converter.***

III. CASE STUDY: HIGH-POWER ELECTRIC DRIVE FOR HYBRID PROPULSION SYSTEM

To demonstrate the feasibility of hybrid propulsion systems based on high-performance PMSMs and advanced power electronics topology, a 4-MW demonstrator

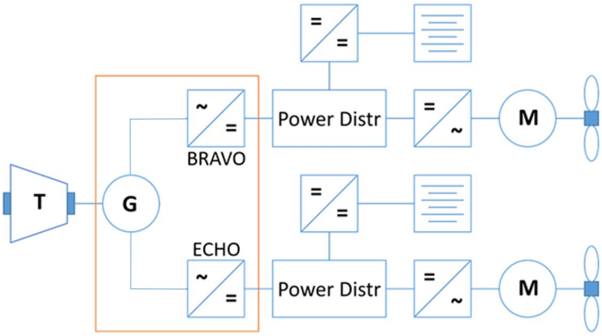


Fig. 17. ***Block scheme of the hybrid propulsion system used as the test case [11].***

featuring generator and rectifier systems was fabricated in [11] and [12].

The structure of the system is shown in Fig. 17. It is coupled to a high-power density high-speed multiphase permanent magnet generator, which feeds two separate power electronic converters: BRAVO and ECHO. These two converters regulate two dc rails at 3 kV, which are connected to the rest of the distribution and electrical propulsion systems. Because operation at high frequencies is necessary due to the high-speed operation of the machine, a tradeoff analysis was performed for the optimal choice of power electronics. Because the availability of components at the time of the design is necessary to achieve a relatively high switching frequency (15 kHz) with sufficient current-carrying capability, a series NPC solution that allows the use of 1.2-kV devices to realize the basic converter is adopted (see Fig. 18). Such an application requires power-sharing and fault tolerance; hence, the single rectifier (BRAVO or ECHO) is composed of two series-connected NPC converters in parallel for a total of 24 phases of the machine.

Pictures of the realized power electronics converters and the developed generators are shown in Fig. 19. The tests performed at a recirculating power level of 1 MW showed that the efficiency of the entire system was 92.5%, which was in perfect agreement with the theoretical analysis. The demonstrator also showed how the design techniques for the control of power electronics and electrical machines enabled the prediction of the performance of an extremely complex system.

IV. OUTLOOK

Different types of aircraft have different electrification requirements, as outlined in the NASA Roadmap for aircraft electric propulsion [66]. Hundreds of kilowatts are envisaged for general aviation and small passenger aircraft. Megawatt-class motors are envisaged for regional aircraft, whereas, for 737-class aircraft, electrical motors of more than 10 MW are deemed necessary.

Currently, various aircraft electrification technologies have different readiness levels. Major industry players worldwide are actively investigating various topics and developing solutions to problems in the aforementioned technology [67]. For several years, MEA has been marketed as a commercial product.

The 787 Dreamliner of Boeing was designed to reduce fuel consumption by 20%, CO_2 emission by 28%, NO_x emission to less than the 2008 industry limit, and noise to be 60% lower than that of Boeing 767 [68]. One of the main improvements in the 787 Dreamliner is the no-bleed engine. Compared with the traditional structure, the no-bleed structure provides most onboard subsystems with power in an electrical form rather than a pneumatic form via shaft-driven generators. It was reported in [**?**] that the elimination of pneumatic bleed reduces the overall power level of aircraft and then optimizes the engine efficiency with a 1%–2% reduction in fuel consumption under cruise conditions. In addition, the centered hydraulic system of Boeing 787 is powered by two electric motor-driven hydraulic pumps rather than the air turbine-driven hydraulic pumps of traditional systems. Moreover, the environmental control system is also improved by applying adjustable-speed electrical motors and avoiding excessive energy usage due to cabin pressurization compressors. With these benefits and other aspects, such as the new low-weight composite fuselage,

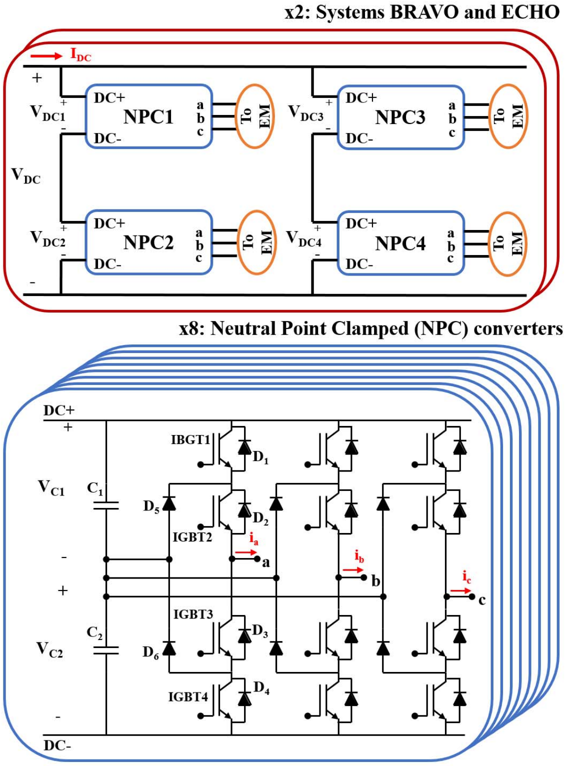
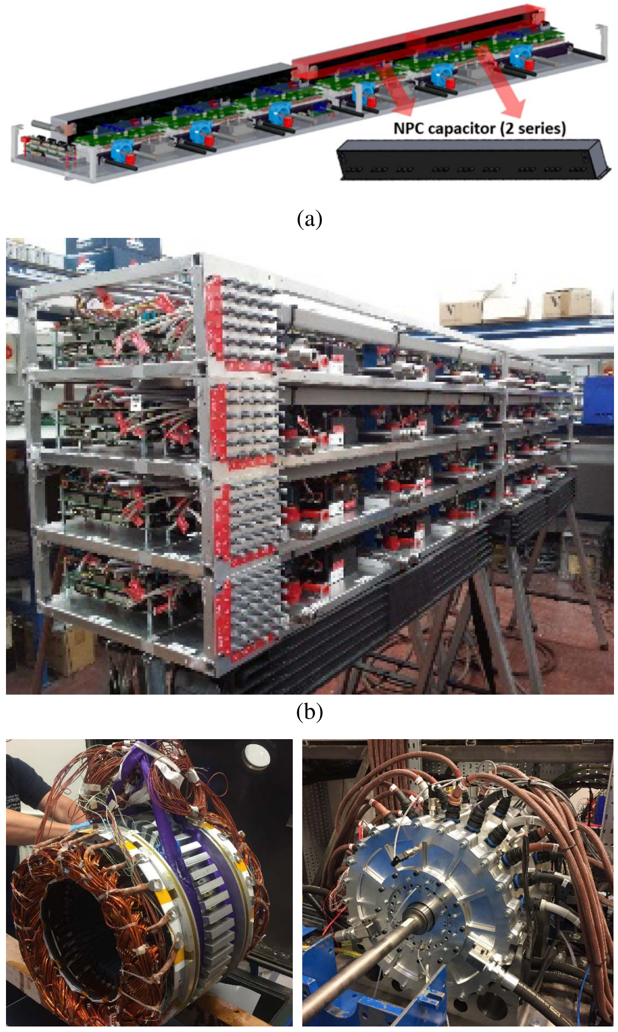


Fig. 18. ***Block scheme of the power electronics used in [11].***



(a)

(b)

(c)

Fig. 19. ***Prototypes of the power electronics and electric machine for hybrid propulsion aircraft [11], [12]. (a) Single NPC series. (b) Picture of the four NPC series. (c) Stator assembly and developed generator.***

Boeing claimed that, in 2020, the 787 Dreamliner saved 48 billion pounds of fuel since 2011 and significantly reduced CO_2 emissions compared with the airplanes that they replaced [69]. Moreover, Airbus launched a “more-electric” architecture for A380 and A350 [70]. Both models adopt a 2H/2E scheme for flight controls where the third hydraulic actuator existing in previous models was replaced with an electrohydrostatic actuator [71]. This replacement leads to less weight and a fuselage with higher reliability; this means less fuel consumption and lower maintenance costs. Combined with the innovations from other aspects, Airbus announced in 2020 that A350 achieved a 25% reduction in fuel consumption compared with that of the Boeing 777, a maximum NO_x emission that is 23% below CAEP/8 International Civil Aviation Organization (ICAO) standards, and noise footprint that is 21.4% below the ICAO standards in Chapter 4 [72]. At the same time, the ICAO updated the CO_2 standard for aircraft production starting 2023 [73]. In the updated standard, the CO_2 emission metric is set as the reference value [74], as follows:

$$\mathrm{CO_2\ EMV} = \frac{1}{\mathrm{SAR} * \mathrm{RGF}^{0.24}} \tag{1}$$

where SAR is the specific air range and RGF is the reference geometric factor. According to the new standard, aircraft models that can satisfy the requirement with a specific margin are anticipated to remain in production until 2023 when the standard takes effect. It was disclosed in [73] that the newest versions of Airbus A350 and Boeing 787 can fully satisfy the requirement with negative exceedance. As for Airbus A380, the prospect is actually not optimistic because the fuel consumption remains high due to the large size of the fuselage and extremely high maximum takeoff weight. Moreover, the CO_2 emission per passenger is considerably high because of the low seat occupation rate of each flight during the postpandemic period.

With Airbus E-fan X, which was canceled in 2020, HEA was at the demonstration level for medium-haul aircraft [75]. To improve turbo engine performance during the cruise for improving fuel economy, the Boeing/NASA Subsonic Ultra Green Aircraft Research (SUGAR) has individuated the SUGAR Volt concept [76], which is a twin-engine hybrid aircraft with electrical propulsion and onboard storage. Smaller HEA, such as Faradair BEHA M1H [77], is also under development. The turboelectric NASA N3-X aircraft, although still a concept [76], demonstrates the point at which the technology can be further developed with the implementation of distributed propulsion in the wings (improved aerodynamics, as already demonstrated in NASA X-57 Maxwell [78]) and the use of superconductive material (for power density improvement). Other researchers have proposed products for small HEA (Smartflyer SFX1 [79] and Ampaire EEL [80]). In terms of semiconductors, GE Aviation [81] has been working on megawatt-class full-SiC power electronics for future HEA. Although the development of HEAs is slow, the potential of HEA continues to interest many researchers and manufacturers. One the main potentials is distributed propulsion, which can open new opportunities for aircraft design. Compared with the conventional structure, the hybrid electric distributed propulsion structure has the advantages of better aircraft control performance, short takeoff and landing, lower noise, and lower complexity of propeller replacement [82]. Rolls-Royce introduced several hybrid electric patterns, such as turboelectric structure, series hybrid structure, and parallel hybrid structure [83]. With such structures, the power generated by the gas turbine is converted to electrical power for longer distance transmission, whereas the motor-driven fans or propellers can be distributed to the wings and rear of the fuselage; moreover, they can be independently controlled by power electronic devices. However, all these patterns must be investigated further in terms of several aspects, especially the energy density of batteries, the efficiency of electrical machines, and optimization of the powertrain structure [84]. Boundary layer ingestion (BLI) is another potential HEA. The boundary layer of the aircraft is known as a layer of slower moving air along the skin of the fuselage and wings during flight, creating an additional drag force acting on the aircraft and indirectly increasing the fuel consumption. The concept of BLI was proposed to reduce the drag force by utilizing the air flowing over the fuselage as a part of the air entering the engine [85]. To enable BLI, the engines are located in the path of the boundary layer, such as at the rear of the fuselage, during cruising. Hence, BLI can be regarded as an additional advantage of the distributed propulsion structure in aircraft design [86]. However, adding or changing the location of engines results in challenges in dealing with the weight and distorted airflow at the engine-located parts for which more research works must be implemented.

The HEA concept is applied by FEA a step further. The potential advantages of FEA are similar to those of HEA; however, they are more significant. The challenges are more difficult because the fuel cells are to be replaced with batteries, consequently reducing the energy density and increasing the EPDS mass. To date, several companies have invested in FEA products, such as Bye Aerospace eFlyer 800 [87] (eight-seater), Eviation Alice [88] (nine-seater), and magniX [89] (with a line-up of electric propulsion drives). The Pipistrel Alpha-Electro is already certified by the Federal Aviation Administration [90].

With the electrification of onboard source and load subsystems, the EPDS structure becomes more complex, along with potential risks, such as partial discharge, which is attributed to high power, high voltage, and low pressure. So far, some relevant studies have been conducted to assess the risk of partial discharge of onboard electrical components. It was reported in [91] that electrical machines for actuating primary flight control surfaces have a higher risk of partial discharge. A comprehensive study of partial discharge in onboard electrical machines was conducted, and possible solutions ranging from electrical machines to power electronic devices were provided in [92]. In addition, the effect of partial discharge on high-temperature insulation materials for dc cables was studied and presented in [93]. The partial discharge phenomenon in the next generation of aircraft has evidently attracted the interest of an increasing number of researchers.

In addition, considering that the combustion engines are supposed to be replaced with power electronic devices and electrical machines on HEA and FEA, the thermal management system can be another main concern because power electronic devices tremendously increase temperature. Moreover, they are all inside the aircraft; this differs from conventional aircraft in which the combustion engines are outside and can directly release heat to the atmosphere [84]. To deal with heat dissipation inside the aircraft, Meredith [94] reported that the correct design of the radiator can benefit aircraft propulsion by utilizing waste thermal energy to offset the radiator drag or the Meredith effect. In addition, Freeman *et al.* [95] reported that this waste heat energy can be considered for wing deicing, cabin heating, fuel cell preheating, battery temperature control, and so on.

In general, the aircraft industry has intensified its efforts worldwide to reduce the environmental impact and increase aircraft efficiency. For example, in the next China Civil Aviation five-year plan, a considerable thrust toward greener airports and electrical technologies is envisaged [96] to reduce the environmental impact of aviation and guarantee the growth rate necessary to satisfy the increasing air transportation demands.

V. CONCLUSION

Aircraft electrification is a concept that has been considered for several decades, and considerable efforts have been devoted to improve aircraft performance in response to increasing air traffic. To achieve the extreme targets of power density and availability required by aircraft applications, the following multiple realms of engineering knowledge had to converge: power electronics, electric machine design, control system, thermal and manufacturing engineering, and new magnetic and semiconductor materials. Evidently, when the performance requirement increases, the optimization of individual components and the assembly of the system thereafter are inadequate. However, a paradigm shift, which consists of a holistic approach to system design, is necessary. Given the extremely close relationship between power electronics and thermal design, the manufacturing and integration aspects must be considered in the initial design stages. Similarly, the availability of EPDS conditions the choice of the power electronics topology for the distribution of system electronics. At present, MEAs are consolidated products that serve thousands of long-distance flights. Moreover, FEA products have started to be certified and commercialized. The main industry players and universities have also proposed solutions for high-power drivetrains for power generation and electric propulsion to satisfy regional aircraft requisites. It is now evident that what started as simple electrification of selected subsystems in conventional aircraft will soon lead to the widespread use of electric aircraft as part of everyday reality. ■

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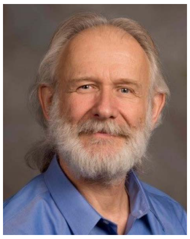

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