Electrical Power Generation in Aircraft: Review, Challenges, and Opportunities

Vincenzo Madonna, *Student Member, IEEE*, Paolo Giangrande, and Michael Galea, *Member, IEEE*

***Abstract*— The constant growth of air traffic, the demand for performance optimization, and the need for decreasing both operating and maintenance costs have encouraged the aircraft industry to move toward more electric solutions. As a result of this trend, electric power required on-board of aircraft has significantly increased through the years, causing major changes in electric power system architectures. Considering this scenario, this paper gives a review about the evolution of electric power generation systems in aircraft. The major achievements are highlighted and the rationale behind some significant developments discussed. After a brief historical overview of the early dc generators (both wind- and engine-driven), the reasons which brought the definitive passage to the ac generation, for larger aircraft, are presented and explained. Several ac generation systems are investigated with particular attention being focused on the voltage levels and the generator technology. Furthermore, examples of commercial aircraft implementing ac generation systems are provided. Finally, the trends toward modern generation systems are also considered giving prominence to their challenges and feasibility.**

***Index Terms*— All electric aircraft (AEA), aircraft electric power generation, high-voltage dc (HVdc), hybrid electric propulsion (HEP), more electric aircraft (MEA).**

NOMENCLATURE

AEA	All electric aircraft.
APU	Auxiliary power unit.
ATRU	Autotransformer rectifier unit.
ATU	Autotransformer unit.
CF	Constant frequency.
CSD	Constant speed drive.
ECS	Environmental control system.
GCU	Generator control unit.
HP	High pressure.
HVDC	High voltage dc.
IM	Induction machine.
IDG	Integrated drive generator.
LP	Low pressure.
MEA	More electric aircraft.
n	Rotational speed of the generator shaft [r/min].
N1	Rotational speed of the low-pressure spool [rpm].
N2	Rotational speed of the high-pressure spool [rpm].
p	Number of pole pairs of the main generator.
PDC	Power distribution Center.
PEC	Power electronics converter.
PM	Permanent magnet.
PMSM	Permanent magnet synchronous machine.
SiC	Silicon carbide.
SR	Switched reluctance.
SRM	Switched reluctance machine.
TRU	Transformer rectifier unit.
VFG	Variable frequency generator.
VS	Variable speed.
VSCF	Variable speed constant frequency.

I. INTRODUCTION

SECONDARY power systems allow for aircraft safe operation and ensure passengers' comfort. For conventional aircraft, secondary power systems combine pneumatic, hydraulic, mechanical, and electric power, and their energy consumption represents approximately 5% of the total fuel burned during the flight [1].

With the advent of the MEA initiative, electric power systems are progressively taking the place of pneumatic, hydraulic, and mechanical power systems [2]–[4]. Over time, this trend has led to an increase of required electric power, particularly for larger aircraft [5]–[7], as shown in Fig. 1. For instance in the B787, several loads, which were traditionally supplied by pneumatic bleed system, are now electrically driven [8]. These loads include (but are not limited to) wing ice protection, ECS and the engine starting system [9]. Therefore, an important player in all of this is the need of on-board electrical power generation. In Fig. 2, a general system-level scheme, regarding the historical evolution of on-board electrical power generation and distribution, is reported [1], [7].

The electric power demand on-board of aircraft begun with the requirement of starting the main engines. Hence, power generation on aircraft dates back to the first World War period (1914–1918), when the starting capability and also wireless telegraphy were introduced on-board of military aircraft [10]. At the time, wind-driven generators were generally preferred to batteries, mainly due to their better reliability and the

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V. Madonna and P. Giangrande are with the Power Electronics, Machines and Control Group, University of Nottingham, Nottingham NG72RD, U.K. (e-mail: eexvm3@nottingham.ac.uk; p.giangrande@nottingham.ac.uk).

M. Galea is with the Power Electronics, Machines and Control Group, University of Nottingham, Nottingham NG72RD, U.K., and also with the School of Aerospace, University of Nottingham, Ningbo 315100, China (e-mail: Michael.Galea@nottingham.ac.uk).

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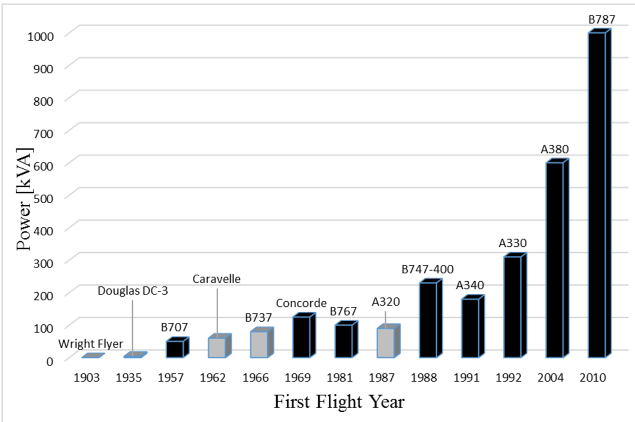

Fig. 1. Evolution of electrical power need (gray: short- to medium-range aircraft and black: medium- to long-range aircraft).

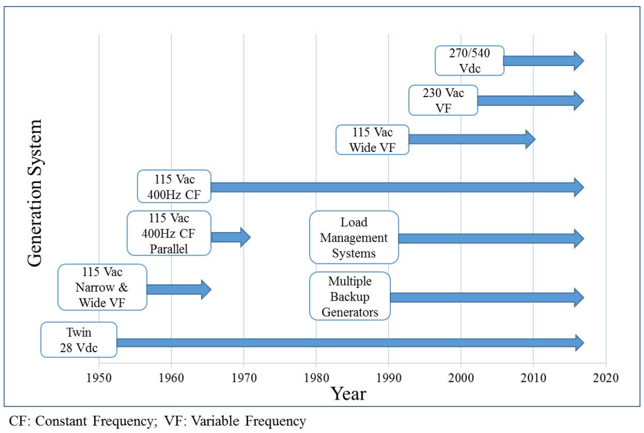

Fig. 2. Electric generation systems' evolution.

poor energy density of the available batteries in the period. Between the two world wars, electric services, such as lighting, signaling, and heating, were brought into use [3], [11], [12], and with them the power generated by the wind-driven generators escalated from 250up to 1000 W. Higher power ratings were achieved by increasing the generated voltage levels. Indeed, the 6-Vdc system (already in use in the automotive industry) was soon replaced by the 12-Vdc system, which had been upgraded to the 28-Vdc system by 1936 [13].

As the aircraft traveling (ground) speed begun to exceed 280 km/h (around 1934), the drag forces related to wind-driven generators started to become a significant issue [14]. For this reason, wind-driven generators were superseded by engine-driven generators. During second World War (1939–1945), engine-driven generators were improved, in terms of power/weight ratio and reliability; however, generation was still in dc. In the 1940s and 1950s, twin 28-Vdc engine-driven generators became a standard on-board of many aircraft. Apart from its main two 12-kW engine-driven generators, it employed one or two batteries (as emergency power source) and a power converter, which fed the ac electric loads [14]. In the 1950s, three-phase generators were mounted on British V-Bombers. These military aircraft used four ac generators providing about 40 kVA each, at 400-Hz frequency and 115/200-Vac voltage [1]. At that time, V-Bombers were one of the first aircraft to implement parallel ac generators [15]. Thirty years later, the V-Bombers were decommissioned; however, their power generation system is still in service today on the VC10 air-to-air refuelling tankers. Generating ac voltage at CF required a coupling mechanical gearbox between the VS prime mover (i.e., engine shaft) and the generator [16]. This complex hydromechanical unit introduced reliability issues, due to increased component count (with several moving parts), which needed frequent maintenance [17]. In the early 1990s, the need for more energy-efficient aircraft promoted the MEA concept, which was already known since the 1940s. As a result of this trend, commercial aircraft implementing more electric features are nowadays available and some examples are the A380 and the B787 [3].

Starting from the dawn of aviation, this paper presents a survey on the evolution of electrical power generators for aerospace applications. In particular, dc power generation is discussed in Section II, where the technologies implemented pre- and post-World Wars are examined. In Section III, the ac power generation technologies, such as CF and VSCF systems, are described and their main advantages and drawbacks are highlighted. Section IV deals with "unconventional systems," such as SRM-based systems, for generating electric power on-board of military aircraft. Recent achievements and today's generation systems employed in MEA are considered in Section V. The challenges and forthcoming developments regarding the power generation on the future aircraft (i.e., multispool generation and HVDC systems) are briefly reviewed in Section VI. Finally, Section VII provides a summary through more than a hundred years of electric power generation on-board of aircraft.

II. DC GENERATION

In the early days, electric power on aircraft was mainly used for communication and ignition systems. Indeed, the first dc generators were typically rated for less than 500 W and usually adopted 6- and 12-Vdc voltage levels [11], [12]. As previously mentioned, the installation of lighting, signaling, and heating systems increased the electric power requirements. Hence, the generator capacity rose up to 1 kW (value retained till the beginning of World War II [18]), as well as the voltage level, which was increased to 28-Vdc. Higher generated voltage allowed for savings on cables and commutators weight [13], [19], [20].

A. Pre-World War II

The majority of the first dc generators relied on wind-driven technologies [19]. This topology of generator was most commonly mounted externally on the aircraft's landing gear strut. However, as aircraft speeds increased, requirements for more refined flight dynamics started to push toward fully retractable landing gear, and thus, wind-milling generators became obsolete. The era of engine-driven generators thus began [21]. Table I shows the combination of the two "families," i.e., wind-driven and engine-driven generators, and reports the main characteristics of some of these early

TABLE I
EARLY DC GENERATORS FOR AIRCRAFT

DC Generator	Electrical parameters	Speed [*krpm*]	Weight [*kg*]	Approx. date	Power density [*kW/kg*]
Wind Driven	$12V$, $250W$	3.5	5.5	1924	0.05
	$12V$, $500W$	4.5	6.4	1924	0.08
	$12V$, $1kW$	3.5	12.3	NA	0.08
Engine Driven	$12V$, $500W$	3.8 to 6	9.8	1934	0.05
	$28V$, $1kW$	3.8 to 6	16.3	1936	0.06
	$28V$, $1.5kW$	3.3 to 6	15.4	1941	0.10
	$28V$, $3kW$	3 to 6	27.2	1943	0.11
	$28V$, $6kW$	3.25 to 4.8	25.4	1944	0.24
	$28V$, $11.2kW$	6	NA	1953	NA
	$112V$, $22.5kW$	2.9-10	63	1956	0.36

Fig. 3. 1 kW at 28-Vdc engine-driven dc generator, stored in the Shuttleworth Museum, Biggleswade, U.K.

dc aircraft generators [11], [12], [19], [21]. Engine-driven dc generators were designed for speeds between 3200 and 6000 r/min, according to the prime mover speed, and allowed for short-time overloads [19]. The overload capability was usually aimed at 50% of the rated power. In order to ensure lightweight, the generator housing and its accessories, such as supporting brackets, were typically made of magnesium alloys [20], [22]. Indeed, these alloys were preferred to aluminum alloys, because their mass density is about two thirds of the aluminum ones.

Fig. 3 shows an example of an early engine-driven dc generator rated 1 kW at 28 Vdc. In terms of the cooling system, dc generators were usually air cooled through a fan (installed on an engine shaft extension), whose material might vary according to the mechanical damping required by the engine [20]. Magnesium or aluminum was usually employed; however, heavier metals were used if an additional flywheel effect was needed by the engine. The main components of a typical dc aircraft generator are reported in Fig. 4, where the generator exploded view is depicted [20], [23].

B. Post-World War II

After World War II, the trend in aircraft power generation was to move toward ac generation systems. Nevertheless, dc generators still continued to be developed and used, mainly

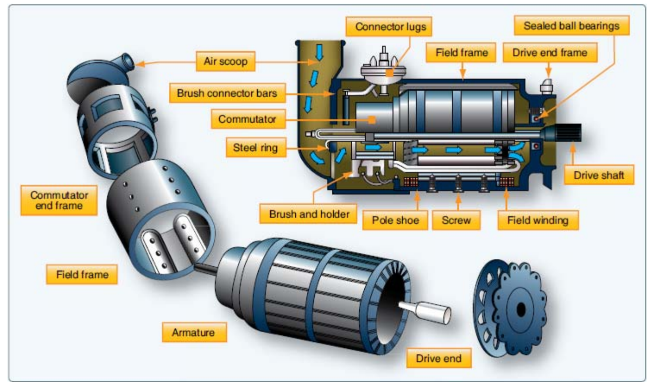

Fig. 4. Exploded view of a typical 28-Vdc aircraft generator [23].

based on the knowledge and expertise gained by their adoption in the previous years. In the early 1950s, a customized dc starter generator was built for the Republic F-84 Thunderjet.

This starter generator was able to continuously operate at 7500 r/min, while providing a current of 400 A [24]. In order to reduce the cabling weight, dc generators operating at 120 Vdc were also introduced on some aircraft [13], since higher voltage implies lower current for a given power. However, higher voltage systems always presented (and still do) significant concerns related to safety and risk, especially for dc systems dependent on electromechanical commutation. Indeed, based on the Paschen's law, the breakdown voltage between two electrodes, at a fixed distance in air, decreases with increasing altitude (i.e., decreasing pressure) [25].

As a consequence, at high altitude, a lower voltage (with respect to ground level) is necessary to sustain electric arcing, which is the cause of premature brushes/commutator wear out and reliability issues. For most small- and medium-sized aircraft, generation at 28 Vdc still represents a feasible operating system [13]. However, low-voltage dc systems, which have been so successful in the past, are no longer sufficient for the higher amount of electric power demanded today [26], especially in the case of larger aircraft. For example, the modern Airbus A380-800 (which operates at 115 Vac) counts a total wire length of about 470 km, with a total weight of 5700 kg [27]. This weight would be more than tripled, if the aircraft electrical distribution system voltage was 28 Vdc [28]. Nowadays, many small modern aircraft make use of dc generators for both main and backup generation systems. Some examples of civil aircraft employing 28-Vdc starter generators are: 1) ATR-600; 2) Dornier 328; 3) Gulfstream G280; and 4) Falcon 2000. A number of military aircraft using 28-Vdc starter generators include: 1) the Alpha jet; 2) the C295; 3) the CN235; and 4) the IJT-36 [29]. In Table II, the main features of the modern dc generators are listed.

Comparing the results of Tables I and II, the higher power density (ratio power/mass) of modern dc generators is immediately observable. In fact, its value has more than doubled.

III. AC GENERATION

As mentioned earlier, most aircraft were still dc powered even after World War II. However, from the 1960s' onward,

TABLE II
CHARACTERISTICS OF MODERN ENGINE-DRIVEN DC GENERATORS FOR AIRCRAFT (COURTESY OF THALES GROUP) [29]

Electrical parameters	Speed [k*rpm*]	Weight [*kg*]	Approx Date	Power Density [*kW/kg*]
28*V*, 4.8*kW*	8-12.15	7.8-8	2014	0.6-0.62
28*V*, 6*kW*	7-12.15	9-11	2014	0.54-0.67
28*V*, 9*kW*	4.5-12.3	16-21	2014	0.43-0.56
28*V*, 12*kW*	7-12.8	17-19	2014	0.63-0.71

increasing speeds and aircraft size led to an unprecedented increase of required electric power. Furthermore, specifications, such as reliability and power density, became ever more critical. For these reasons, a general worldwide move toward ac generation was observed [13], [30], which reveals several advantages compared to dc generation. First of all, a significant improvement is achieved in terms of power density (i.e., ac generators are lighter and smaller in comparison to equal rated power dc generators). In the 1950s generators, the power density for the dc topology was generally below 0.5 kW/kg [13], [22]. Their ac counterparts ranged from 0.66 to 1.33 kVA/kg [13], [18], [22], thus highlighting the significant benefits of producing electric power in ac. A relevant advantage is the potentially much higher operating voltage. In particular, a considerable cabling weight reduction was accomplished by increasing the operating voltage (i.e., decreasing the current for the same power) [13]. From a reliability perspective, the absence of commutators on ac generators improved maintenance and lifetime performance [22], despite the higher voltage and power levels.

However, the advent of ac generators also introduced new challenges, mainly due to: 1) the parallel operations; 2) the need to manage reactive power; and 3) the choice of an appropriate frequency. Indeed, ac generators can be operated in parallel, when the developed voltages have the same amplitude, phase, and frequency. Conversely, only the same voltage amplitude is needed for dc generators. Furthermore, unlike ac systems, the dc ones do not involve reactive power; hence, the related issues (e.g., power factor correction) are avoided.

Several frequency values (60, 180, 240, 360, 400, and 800 Hz) were initially considered [13]. A frequency of 240 Hz was suggested at the beginning of the 1940s, for keeping motors and transformer weight to a practical minimum [30]. Obviously, this choice was also dictated by the magnetic materials available at that time. Nevertheless, the frequency selection must take into account also the generator operating speed [22]. Considering this aspect, suitable frequency values were 400 and 800 Hz. Based on respective needs and requirements, the Army Air Corps in 1943 chose 400 Hz as the standard frequency, since it appeared to be more feasible for the generator speed (e.g., 12000 r/min for four-pole machines) [30], [31]. This “standard” of 115/200 V at 400-Hz frequency has been made mandatory for use by the US Air Force in 1959 (MIL-STD-704) and has remained with us to this day.

The voltage level of 115/200 V was deemed high enough to transmit high power over a convenient distance, while still low

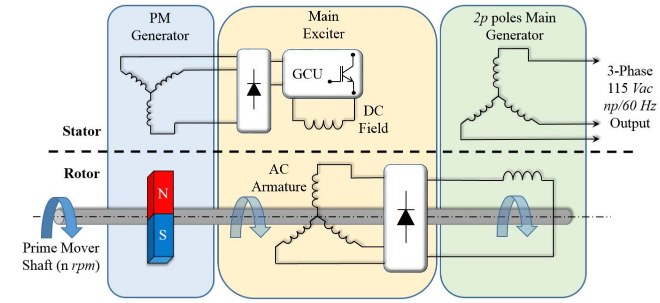

Fig. 5. Architecture of the three-stage wound-field synchronous generator.

enough to avoid the devastating phenomena associated with corona effects at altitude [11], [12], [19], [21]. An important step toward the ac generation was made in 1949 with the entry into service of the Convair B 36, which was equipped with four 30-kVA synchronous generator (one per engine) [21], [32]. In the following subparagraphs, the most common ac electric power systems are discussed and analyzed.

A. AC Constant Frequency Systems

The three-stage wound-field synchronous generator is the most popular ac generator used on aircraft [33], [34]. This popularity is due to its inherent safety, since the excitation can be instantaneously removed by deenergising the machine through direct control of the field [35], [36]. In Fig. 5, a schematic of a three-stage wound-field synchronous generator is depicted, where the three principal stages, namely: 1) the PM generator; 2) the main exciter; and 3) the main generator, are shown [37]. The generation system is powered by the PM generator (first stage), whose moving PMs induce a three-phase voltage in its stationary armature. This ac voltage is then rectified and used for suppling stationary field circuit (i.e., dc field) of the main exciter (second stage), by means of the GCU. The GCU fulfills two essential tasks on the dc field: 1) controls the dc voltage amplitude, for regulating the excitation current of the main generator (third stage) and 2) deenergises the dc circuit in case of anomalous operations (e.g., excessive overload and short-circuit faults) [5], [38]. The dc field induces a three-phase voltage in the moving armature of main exciter. Such ac voltage is subsequently converted into dc, for feeding the moving field circuit of the main generator. The ac to dc conversion is performed by a rectifier, which is rotating synchronously with the prime mover shaft. Finally, the three-phase voltage is available at the output of the main generator armature. Its frequency depends on: 1) the main generator number of poles pair (p) and 2) the mechanical rotational speed of the prime mover shaft (n). Thus, the frequency is closely reliant on the speed of the prime mover.

For on-board power generation, the prime mover is usually the main aircraft engine, whose speed varies across a wide range, from idle to full power. Hence, the prime mover VS represented the main challenge in the adoption of the three-stage wound-field synchronous generator and actions were required for addressing this issue. Therefore, the engine

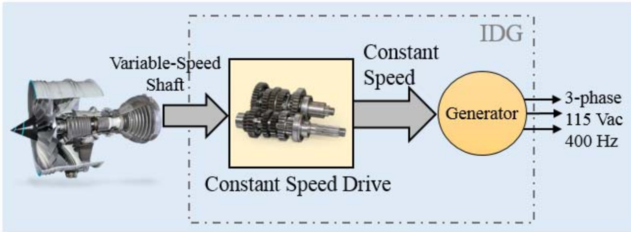

Fig. 6. CF IDG system.

TABLE III
POWER RATING FOR AC CONSTANT FREQUENCY SYSTEMS

Aircraft Model	First year of service	(Approx.) Passenger capacity	Main Generators Power (Excluding APU)
Convair B-36	1949	(Military)	4x30*kVA*
Boeing B-52H	1955	(Military)	4x60*kVA*
Boeing 707	1958	219	4x30*kVA*
Boeing 727	1964	189	3x38*kVA*
Vickers VC10	1964	151	4x40*kVA*
Boeing 737 (NG)	1968 ('97)	210	2x90*kVA*
Airbus A320	1987	220	2x90*kVA*
Boeing 747-800	1988	660	4x90*kVA*
Boeing 767-300ER	1988	258	2x90*kVA*
Airbus A340	1991	375	4x90*kVA*
Airbus A330	1992	335	2x115*kVA*
Boeing 777	1994	396	2x120*kVA*
Boeing 717	1999	100	2x40*kVA*
Boeing 767-400ER	2000	256	2x120*kVA*

and the three-stage generator shaft were mechanically coupled through a variable-ratio transmission gearbox referred as CSD [39], as schematically illustrated in Fig. 6. The CSD converts the input VS to the output constant speed, which is used to drive the ac generator. By using CSDs, the challenge of VS was eliminated, at the cost of a bulky, expensive and component count enhancing, extra gearbox. CF generation systems adopting CSDs and producing 115/200 V at 400 Hz have been widely used in aircraft since the 1960s [40].

The 1970s saw a move toward integrating the generator stages and the CSD into a single unit, in order to achieve weight reduction, as well as enhanced reliability [40], [41]. In that period, CSDs had far longer mean time between failures with respect to generators [40]. Consequently, the integration into a common housing improved the overall system-level reliability [39]. Considerable reduction in weight and size was obtained by designing a common oil system for both generator cooling and CSD lubrication [42]. This compact unit was named IDG and allowed a power density improvement from 0.88 (typical value for CSD + generator systems) to about 1.5 kVA/kg [35], [43], [44]. IDG systems were very popular for over 20 years, due to their efficiency and power density values. Indeed, a number of aircraft, such as the A320, A330, A340, B747, B757, B767, and B777, implemented IDG systems [6], [14]. The block diagram of an IDG system is shown in Fig. 6 [16], while civil and military aircraft employing traditional ac CF systems are listed in Table III [3], [45]–[48]. IDGs usually have a short-time

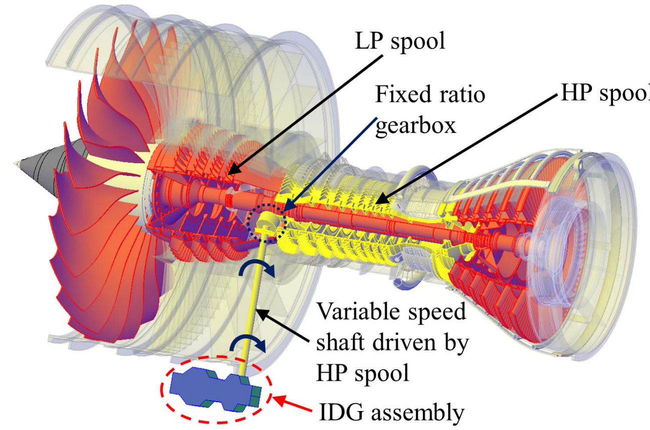

Fig. 7. Typical dual-spool turbofan engine [50], [53].

overload capability of approximately 185% of the rated power [49]. For example, the 120-kVA IDG of the B777 can safely deliver up to 226.8 kVA for 5 min, every 1000 h of operation [49].

On civil aircraft, dual-spool turbofan engines are commonly installed. According to the operating pressure, these engines are characterized by two main sections: 1) the LP sector, which includes the fan, the LP compressor, and the LP turbine and 2) the HP sector, which comprises the HP compressor and the HP turbine [50]. In dual-spool turbofan engines, the IDG is driven by the HP spool (i.e., HP shaft) through a fixed-ratio accessory gearbox, as schematically reported in Fig. 7 [34], [50], [51]. Considering the GE90 engine mounted on the B777, the rotational speed of the HP spool is equal to 9333 r/min, while the IDG is driven by a gear-to-core ratio of 0.79:1 [49]. For the sake of clarity, the speed of 9333 r/min (100%) represents the "normal" operating speed, which in some cases (e.g., during take-off) can be exceeded by some percentage [52].

B. AC Variable Speed Constant Frequency Systems

The CSD adopted for ac CF systems required maintenance and contributed in a significant way to both weight and size of the system. For these reasons, new approaches for generating ac power at CF were introduced in the 1980s [54] and they took hold in the 1990s. Indeed in the 1900s, power electronics and microprocessor technologies were by then mature enough to allow the significant progress in electrical drives to be employed also in aerospace [43], [55]–[57]. The VSCF system works without the heavy CSD, whereby the three-stage synchronous generator can be directly coupled to the main engine shaft. In this case, the frequency of the generated voltage is variable, so in order to provide CF voltage, two approaches are adopted. The first method consists in implementing a dc link between the ac generator and the ac loads, by means of a rectifier and an inverter [40], [55]. The block diagram of the VSCF system with dc link is shown in Fig. 8 [38]. The VSCF system using a dc link was mounted on the MD-90 until 2000 and it is still used on the B777, for the two 20-kVA backup generators [43]. These backup power

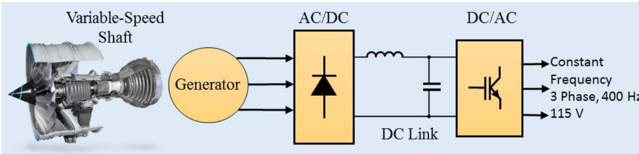

Fig. 8. VSCF system using dc link.

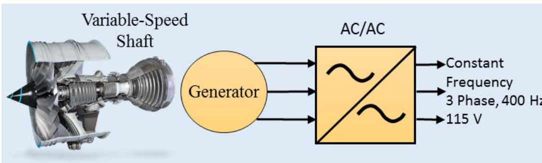

Fig. 9. VSCF system using ac/ac converter.

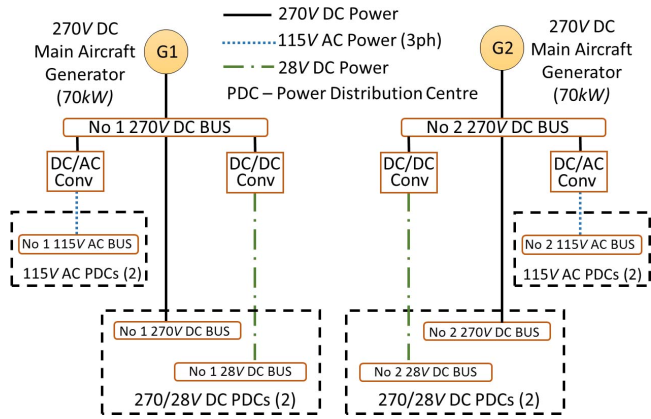

Fig. 10. F-22 power generation and distribution system [58].

sources generators are driven by the engine HP spool through a 2.41:1 fixed-ratio accessory gearbox [49].

Another method for generating CF voltage involves an ac/ac converter (e.g., cycloconverter or matrix converter), which is placed between the ac generator and the ac loads. Fig. 9 reports the block diagram of the VSCF system with ac/ac converter [39]. This architecture is mainly implemented on military aircraft, such as for the F-18 fighter aircraft, the F-117A stealth attack aircraft, and the V-22 ultrahigh altitude reconnaissance aircraft [14], [58].

The VSCF systems, apart for some noteworthy exception previously mentioned, did not get the same level of diffusion of IDG systems. This can be safely attributed to the role played by the PEC (either ac/dc or ac/ac), which processes all the generated power and represents a single point of failure. Therefore, the PEC needs to be designed for the full-power rating and with high reliability requirements [38]. In addition, several aircraft energy-consuming loads (e.g., wing ice protection, galley ovens, and cargo heaters) are frequency insensitive (i.e., resistive loads) [9]. Thus, they can be directly supplied by the VFG, without the need of PECs. This feature led to the variable frequency systems that are discussed in Section V.

C. Concluding Remarks

In general, VSCF systems are more flexible than constant-speed CF systems (i.e., IDG systems), due to the inherent distribution of components throughout the aircraft [55]. Indeed, the IDG systems make use of the CSD, which must be placed close to the main engine, while the PECs of the VSCF system can be either installed close to the engine or in a different location (e.g., close to the electric loads), allowing aircraft weight distribution optimization. Despite their advantages, the VSCF systems remain a rare choice for civil aircraft, due to the reliability level of PECs. In fact, the PECs have not yet reached a proper reliability level for making the VSCF systems a viable option [38].

IV. Unconventional Systems

In terms of dc generation, the majority of aircraft employ 28- or 120-Vdc generators, while the three-stage synchronous generator producing 115/200 V at 400 Hz is the common solution in case of ac generation. However, some exceptions to these widespread solutions can be found in military applications. These particular generation systems are also known as "unconventional systems" and the more important are considered in this section.

SRMs have been in use since the nineteenth century [59], but their need for custom-built power electronics and control algorithms prevented a more extensive implementation. Regarding the SRM structure, its stator is equipped with concentrated windings wound around the stator poles, while the rotor is a totally passive salient-pole geometry (i.e., solid or laminated electrical steel without any PMs or field windings). The SRM working principle is based on the natural tendency of any system to come to rest at the "minimum-energy" position. The stator poles (when excited) attract the nearest rotor poles (i.e., position of minimum reluctance for the magnetic flux) [60]. In order to operate the SRM as a generator, the phase must be excited as the rotor poles move through the aligned position [60]. Precise rotor position monitoring, as well as, accurate control algorithms are necessary for optimal power generation.

Due to developments of both power electronics and design procedures, SRMs have become suitable candidates for integrated starter generators [61]–[66]. The success of the SRM relies on its inherent fault-tolerance capability and rotor robustness [67]–[71]. Indeed, adopting a multiphase design, together with the power segmentation approach (i.e., each machine phase is supplied by an independent PEC), allows to safely operate the machine even under electromagnetic and/or PEC faults [72]. The absence of PMs reduces the risks associated with machine winding faults [71] and favors operations in harsh environments, where PMs could be subject to demagnetisation or performance derating. Finally, the salient-pole one-material rotor is easy to manufacture and makes the SRM convenient for high-speed applications [70]. These features have contributed to the SRMs employment, mainly on military aircraft. In 2005, the Lockheed Martin F-22 came into service. This is a modern two-engine combat aircraft, using as many SR generators. Although the electric power is generated at 270 Vdc, the F-22 is fit with electric loads requiring 115 Vac and 28 Vdc, which are supplied through PECs [14]. Fig. 10 shows the F-22 power generation and distribution systems [14]. A similar architecture has also been implemented on the Lockheed Martin F-35 (i.e., single engine combat aircraft), that was launched in 2015. For redundancy purposes, an 80-kW double channel SR generator is adopted [73], [74].

Considering voltage level, reliability, efficiency, and fault-tolerance capability, traditional brushed dc machines cannot reach the same performance of SRMs. Thus, SRMs are suitable for generating dc power at high voltage, avoiding the electric arcing issue typical of the brushes/commutator system. SRMs are characterized by indisputable advantages (i.e., rotor robustness and inherent fault-tolerance capability), notwithstanding their drawbacks (i.e., uncustomary PECs and complex control algorithms) restrict a wider adoption. In fact, while very popular for military aircraft due to the lower power generation requirements, as the demanded power increases (i.e., in civil aircraft), ac generation is then generally preferred, for the reasons discussed in Section III.

V. More Electric Aircraft ERA

The above is all related to existing and consolidated systems for on-board electrical power generation. However, as previously mentioned, a considerable shift toward more electric systems is in play today. The MEA concept revolves around the idea of replacing most of the aircraft secondary systems, currently operated by mechanical, hydraulic, and pneumatic power, with systems powered by electricity [38], [75]. Some early examples of the MEA concept go back to the mid-1950s with the Vickers Valiant V-Bomber and the Bristol Brabazon 167 [1]. Albeit the feasibility and availability of the MEA concept is debatable and is still in question today, a revamped interest in the MEA initiative started in the early 1990s, when the US Air Force began several research programs concerning MEA. In particular, these programs focused on improving reliability, fault-tolerant capability, and power quality of existing MEA systems, with the final purpose of reducing both fuel burn and weight of aircraft secondary power systems [2]. An immediate consequence of the MEA concept is the significant increase (in the absolute numbers) of the required electric power. For this reason, today, electrical power generation is a major game-changing factor across the whole industry.

A. Modern MEA Programs

A number of aircraft have been claimed to incorporate MEA designs, nevertheless, it is widely acknowledged that the two programs, which have really and seamlessly integrated the MEA concepts, are the long-haul, wide bodied commercial aircraft known as the Boeing 787 and the Airbus A380 [38]. These aircraft are characterized by an intensive electrification, since services like the ECS (for B787) and flight-control electro hydrostatic actuators (for A380) are electrically powered. Consequently, their electric generation capability is roughly of an order of magnitude greater than all other aircraft. Both the B787 and A380 have replaced the traditional generation system employing IDGs, by VFGs directly coupled to the engines. The B787 main electrical power generation relies on four 250-kVA VFGs (two per each main engine), while the A380 uses four 150-kVA VFGs (one per engine), as reported in Table IV [3].

TABLE IV
Power Generation Capabilities for Some Modern Aircraft

	Boeing 787	**Airbus A380**
No. of engine	2	4
No. generator per engine	2	1
Generator rating	$250kVA$	$150kVA$
Generating output voltage	$230VAC$	$115VAC$
No. generator per APU	2	1
Generator rating per APU	$225kVA$	$120kVA$

The implementation of the so-called bleedless architecture permits to electrically supply services (e.g., ECS and wing ice protection), which were pneumatically operated on conventional aircraft. In bleedless technology, no HP air is extracted from the engines (i.e., no-bleed air), allowing more efficient thrust production and engine operations [7], [8], [76]. Indeed, in most conditions, conventional pneumatic systems withdraw more power than needed, causing excess energy to be dumped overboard [8].

The bleedless architecture of the B787 reduces the fuel consumption by 2% (at cruise condition) with respect to a similar-sized traditional aircraft (e.g., B767) [8]. Nonetheless, removing the pneumatic system increases the complexity of the electric power distribution network [9]. This aspect is highlighted in Fig. 11, where the B787's distribution system is schematically compared with that of a traditional aircraft, together with some examples of electrically operated loads [9], [43]. As mentioned earlier, several energy-consuming loads are frequency insensitive. Therefore, they are directly supplied by the VFGs, without the need of PECs (see Fig. 11, B787 diagram). The other loads (operating at 115 Vac, 270 Vdc, or 28 Vdc), are connected to the VFGs through transformers and/or PECs, implementing the so-called hybrid distribution system.

The transition to a more electric architecture, the adoption of energy-efficient engines and the intensive use of lightweight composite materials have contributed to a considerable reduction of the B787's operating cost with respect to its predecessor the B767-300/ER [77], [78]. In particular (based on airlines' data), the block hour operating cost reduction is about 14% [78]–[80].

B. Modern Developments at Component Level

Currently, three-stage wound-rotor generators are used as VFGs. However, PM generators can and are being considered as alternative, thanks to their higher power density (from 3.3 to 8 kVA/kg) [61]–[63]. Variable frequency generation systems do not require the CSD between ac generator and main engine, since they are directly coupled (i.e., direct-drive application), as sketched in Fig. 12.

The absence of a gearbox improves the system-level reliability, due to the reduced component count, whilst other advantages are associated with the weight and size of the system [47]. As a consequence of the shaft VS, the VFG output voltage is variable in amplitude and frequency. Considering the

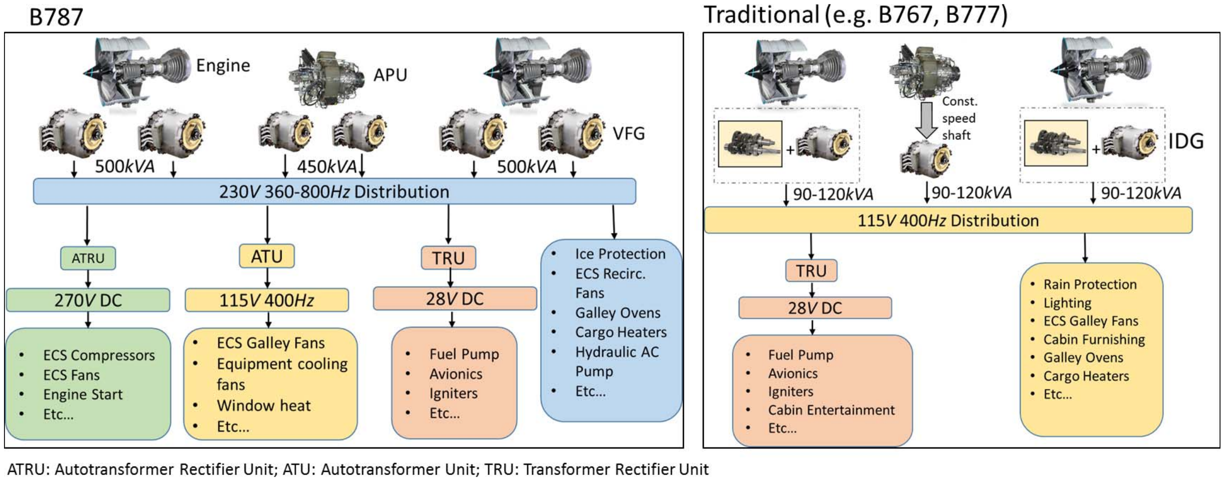

Fig. 11. Simplified diagrams of electric distribution systems for both B787 and traditional aircraft.

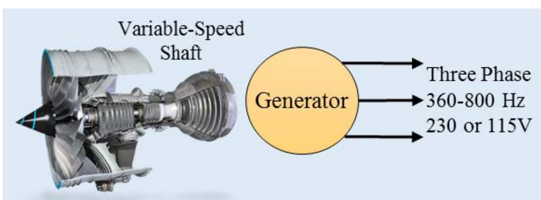

Fig. 12. VFG systems.

case of a three-stage wound-rotor generator used as VFG, the output voltage amplitude is regulated by acting on the field current through the GCU, as mentioned in Section III. Conversely, reactive power is injected into the armature circuit (by using a PEC), when a PM generator is employed as VFG [81]. According to the aircraft mission profile, the output frequency varies from 360 to 800 Hz during takeoff and landing, while it is almost unchanged for the rest of the flight (about 80%–90% of the total flight duration). Challenges related to the VFGs adoption are the cooling system and the mechanical design. In effect, the proximity to the main engine imposes a careful thermal management. Besides, the direct-drive application subjects the rotor to high accelerations, which must be accounted during the mechanical design [82].

C. Overall Power Generation

An overall view of how the MEA initiative is influencing the required ratings of on-board electrical generators is summarized in Fig. 13. For the years from the 1940s to the 2010s, Fig. 13 shows the trend of the generated power on some of the more common aircraft, where the absolute power (in terms of total electrical power generation) is translated to the rating requirements of the single component [45]–[48]. As highlighted in Fig. 13, the global rated power has significantly increased, in the last 10 years. It is perceived that this tendency is mainly caused by the move toward the MEA concept. Indeed, for the 20 years prior to the MEA era (from the 1970s to the 1990s), the main generator rated power remained unchanged and equal to about 90 kVA [1], [52].

VI. Future Trends Beyond the MEA

While the aerospace community is still debating the feasibility and implementation of the MEA, a new movement, that has taken hold over the last couple of years and is creating a lot of excitement, is represented by both the hybrid gas/electric propulsion and the AEA. Although in recent years, the price of Jet-A fuel has considerably dropped, forecasts suggest a turnaround during the next decade [83]. At the same time, year-over-year, the passenger-travel growth has averaged 6.2%, from 2012 to 2017, and it is expected an even higher growth rate in the next 20 years [83], [84]. The two aforementioned factors, together with the airlines' need for reducing aircraft operating cost, are encouraging aerospace industries in developing more energy efficient means of air transportation [85]–[89]. The hybrid gas/electric propulsion and/or the AEA concept aim at lowering or completely removing the traditional air-breathing engines, which depend on the Jet-A fuel, as a main energy source [87], [90]. In Sections VI-A–VI-C, the main ideas that go beyond the conventional MEA initiative are introduced and examined.

A. Multispool Generation and HVDC Systems

Currently on modern large aircraft, turbofan engines are generally employed for propulsion. The main electrical power generator is usually driven by the HP spool (as shown in Fig. 7 and discussed in Section III), principally because the higher speed of the HP spool allows smaller size generators. Furthermore, assuming $N1$ and $N2$ as rotational speeds of the LP and HP spools, respectively, $N2$ varies in a narrower range (from idle to full power) with respect to $N1$ [50], [52]. For these reasons, no generation activity was traditionally done on the LP spool (i.e., low speed). In conventional turbofan engines, the electric power extracted from the HP spool is a small fraction of the total engine power. However, the trend toward (and beyond) the MEA is resulting in an ever-growing demand for more on-board electric power; thus, any potential source of power needs to be fully utilized. Therefore, generating through multiple spools (i.e., exploiting both HP

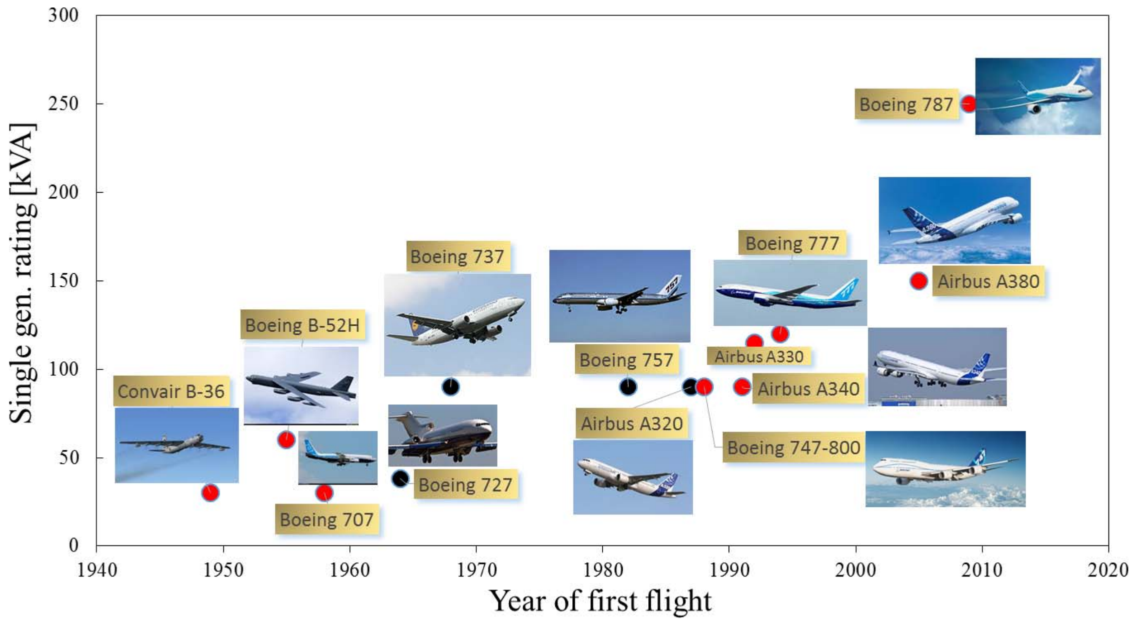

Fig. 13. Power rating of the main generators of some common aircraft (red: medium- to long-range aircraft and black: short- to medium-range aircraft).

TABLE V
SHAFT ROTATIONAL SPEEDS FOR COMMON DUAL-SPOOL TURBOFAN ENGINES

Engine Series	Aircraft (example)	N1(100%) [rpm]	N2(100%) [rpm]	$\frac{N1_{Max}}{N1_{min}}$	$\frac{N2_{Max}}{N2_{min}}$
GP7200	A380	2467	10998	6.1	1.9
CFM56	B737	5175	14460	5.2	1.8
GEnx-2B67	B747-8	2560	11377	6.7	2.3
PW1100G	A320neo	NA	NA	5.7	1.8
CF34-8C1	Business Jet	7400	17820	NA	1.8
V2500	A320	5650	14950	4	NA
PW300	Business Jet	10608	26956	NA	1.6
GE90	B777	2261	9331	6.1	1.7

and LP spools, as prime mover for electrical generation) is fastly becoming justifiable [34], [65], [91], [92]. The main challenge rising from using both HP and LP spools [5], [93] consists in the particular design attention required by the LP spool driven generator, due to the wider speed range and harsher operating conditions [67]. Indeed, $N2$'s full power to idle ratio ($N2_{\text{Max}}/N2_{\text{min}}$) is usually around 2:1, whereas $N1_{\text{Max}}/N1_{\text{min}}$ can be more than 6:1 for high bypass ratio engines [52]. For the sake of completeness, full power to idle ratios are reported in Table V for some common dual spool turbofan engines, together with the "normal" operating speed of $N1$ and $N2$ [52].

With regard to the electrical machine topology, PMSMs, IMs, and SRMs are possible candidates for the LP spool generators [68], [94], [95]. Nevertheless, each of these machines reveals advantages and disadvantages. The principal benefits of PMSMs are: 1) excellent power density; 2) high efficiency; and 3) well-established control strategies, while their drawbacks are as follows:

1) high cost;
2) inability to operate at elevated temperatures;
3) dependent on power electronics; and
4) medium reliability and fault-tolerance capability.

As matter of fact, the excitation field produced by the PMs is practically uncontrolled and can supply winding faults [96]–[98]. On the contrary, a good level of reliability and fault-tolerance capability is ensured by IMs, which, however, do not "enjoy" the power density levels of their PM counterparts. SRMs cannot compete with PMSMs in terms of power density and control strategy, albeit their rotor robustness makes SRMs suitable for working in harsh environments [72], [99], [100]. Finally, SRMs are also intrinsically fault tolerant, for the reasons discussed in Section IV.

Aside from incrementing the generation capability, future aircraft concepts aim to improve the overall electrical power system and its architecture. In the next generation aircraft, a significant weight saving could be achieved by increasing the distribution voltage [33], [101]. As previously mentioned, considering the same transmitted power, a higher voltage (for the distribution system) will result in smaller cable cross-sectional area. Furthermore, raising the voltage will allow greater line voltage drop [101]. In fact, the minimum allowed voltage is 108 Vac, for distribution system at 115 Vac, instead 250 Vdc are accepted on 270-Vdc systems (as per MIL-STD-704F) [100]. For these reasons, HVDC distribution systems at 270 and 540 Vdc are under investigation [101], [104]. Regarding the HVDC systems, the most obvious concerns are safety and the increased risk of electrical system failures, caused by the LP phenomenon, such as corona effects and insulation breakdown.

The migration to HVDC systems, together with the implementation of LP spool generators, will also influence the design of PECs. In this area, some of the main challenges are imputable to: 1) higher operating voltage; 2) elevated amount of power to be handled; and 3) wider generators' operating (fundamental) frequency (for LP spool generation). Wide bandgap semiconductors, such as SiC, are recognized, by the scientific and industrial communities, as a technology enabler [105]–[107].

The major features (particularly convenient for aerospace application) of SiC-based PECs, over traditional silicon-based PECs, are as follows:

1) lower losses;
2) better temperature tolerance;
3) higher operating voltage; and
4) faster switching capability [105]–[107].

Reduced losses and high temperature tolerance help to decrease thermal management specifications [106], hence smaller and less expensive cooling systems are necessary for SiC-based PECs. Furthermore, high operating voltage and fast switching capability lead to a potential decrement of both PECs' weight and size [107]. In particular, higher switching frequencies contribute to the reduction of filtering passive component size [107], while less series-connected modules (than traditional silicon-based counterpart) would be adopted for managing higher voltages [106].

B. Future Aircraft Concepts

Some of the most attractive concepts for future aircraft are represented by hybrid electric (e.g., Pipistrel Hypstair) [108], [109], distributed electric (e.g., NASA-DEP) [110], turbo-electric (e.g., Rolls Royce/Airbus E-Thrust) [111], and fully electrical (e.g., Airbus E-Fan) aircraft [112]. All these configurations are characterized by an intensive electrification, since electric power is not only used for secondary systems, but also for propulsion purposes. For instance, the Airbus/Siemens/Rolls Royce *E-Fan X hybrid-electric technology demonstrator* is anticipated to fly in 2020 [85]. This program has two objectives, such as: 1) replacing one of the four gas turbine engines of a traditional British Aerospace 146 (as well-known as BAe 146) with a 2-MW electric motor and 2) introducing a 2-MW generator (in the classical turbo-electric system style), powered by a Rolls-Royce AE 2100, which is used as an APU [85]. The success of these concepts, besides from relying on high-performance electrical machines and PECs, will be strongly dependent on the technological development of energy storage systems. Modern electrochemical batteries have proven to be suitable for powering unmanned aerial vehicle and hybrid/electric light aircraft, for short-endurance missions [90], [109], [113], [114]. Nonetheless, for energizing a fully electric, short-haul civil aircraft, the energy density of the currently available battery technologies needs to improve by at least eight or tenfold.

C. Electrical Systems and Subsystems in the Future Aircraft

As previously pointed out, high power density and reliable electrical machines and PECs will be the key enabling technologies, in the future aircraft systems. Significant work across a range of aviation authorities has recently gone into defining roadmaps for the technology requirements of such systems [86], [87], [115].

TABLE VI
ELECTRICAL MACHINE POWER DENSITY SPECIFICATIONS FOR FUTURE AIRCRAFT

Timelines	Predicted Power Density	Enabling Technology
By 2025	10*kVA/kg*	Liquid cooling, Low Loss Steel, High Breakdown-Strength Insulating Materials, Additive Manufacturing, Nanocomposite-Based Magnetic Materials [86, 116, 118, 119]
By 2035	20*kVA/kg*	
By 2050	40*kVA/kg*	All the above + Superconducting materials

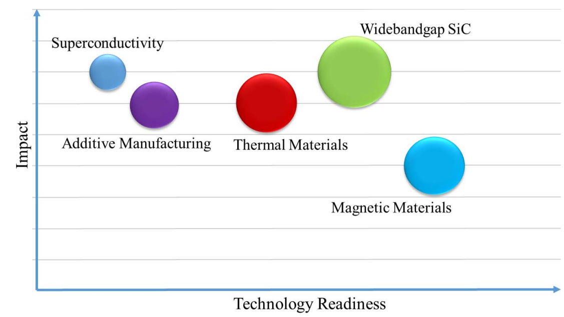

Fig. 14. Enablers: impact versus readiness.

1) High Power Density Specifications: For electrical systems, it is clear that today's state of the art is still not at the demanded power density levels for future aircraft, comprising all electric and hybrid-electric propulsion. A quantitative analysis, whose results are compiled in Table VI, indicates the predicted electrical machine power density specifications for the short-, mid-, and long-term future [86], [117]. Considering the analysis outcomes, the long-term goal is only achievable by the practical application of nonconventional technologies, such as superconductivity; whereas, the short- and mid-term targets are feasible using more conventional technologies strengthened by a high level of innovation. Indeed, electrical machines with power densities higher than 10 kVA/kg have already been manufactured and tested [117], and an example is reported in Section VI-C2.

2) Enabling Technologies: In order to reach such performance, a number of technology enablers are today being studied and investigated by research communities. These include new magnetic and electrical materials [118], [119], advanced modeling [120], [121] and manufacturing processes [122], [123], new thermal management techniques [124]–[126], high-speed systems [116], and better understanding of failure mechanisms [127], [128]. The latter involves advancements in power electronics (e.g., wide bandgap devices), machines (e.g., new, high strength, and low losses steels), and controllers (e.g., high bandwidth control algorithms). The relationship between the technology impact of the enablers on the drive (or its components) general performance and the technology maturity is illustrated in a visually representative manner in Fig. 14.

A power generation system for a more electric business jet, implementing some of the aforementioned features, is the electrical machine described in [129]–[131], which was

Fig. 15. State-of-the-art PM generator developed at the University of Nottingham.

developed within the authors' organization. This generator is a 45-kVA surface mount PMSM, capable of working also as engine starter (i.e., starter generator), and it is shown in Fig. 15.

Some of the innovative attributes characterizing this machine are as follows:

1) a carbon fiber PMs retention mechanism;
2) low losses, high grade, and nonoriented silicon steel;
3) novel thermal management involving the use of direct oil cooling of the stator core;
4) advanced high energy density PMs;
5) multilevel PEC design configuration; and
6) the use of higher voltage rating materials, that allows operation at the new 540 V HVDC buses, being considered for future aircraft.

These characteristics have contributed to achieve a power density higher than 16 kVA/kg, confirming the high impact of some of the technology enablers reported in Fig. 14 and highlighting the way toward the future of the aircraft industry.

VII. CONCLUSION

This paper provides a "journey" along the evolution of electric power generation on-board of aircraft, by addressing the main technologies adopted over more than a hundred years' time span. The advantages and disadvantages of the most common generation systems are analyzed. The aircraft power requirements and the generation power trends are reported and discussed. The level of generated power was first affected by the transition from dc to ac generation. Then a constant growth rate is highlighted until the recent implementation of the MEA concept. In fact, the migration to ac variable frequency generation systems represented an important step toward modern aircraft. The state of the art and the major challenges of the MEA concept are also reviewed, keeping in mind the role played by electrical machines, in terms of power density and technology. Finally, some considerations related to future aircraft are drawn.

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Vincenzo Madonna (S'17) received the B.Sc. degree in electronic engineering from the University of Calabria, Rende, Italy, in 2012, and the M.Sc. degree in electrical engineering from the University of Bologna, Bologna, Italy, in 2016. He is currently pursuing the Ph.D. in electrical machine design with the University of Nottingham, Nottingham, U.K.

In 2012, he joined KU Leuven, Leuven, Belgium, as an Exchange Student. In 2015, he joined the University of Nottingham, as a Visiting Researcher, where he is currently a Marie Curie Researcher with the PEMC Group and the Institute for Aerospace Technology. His current research interests include design, thermal management, and lifetime prediction modeling of electrical machines.

Mr. Madonna received the qualification of Italian Chartered Engineer in 2016.

Paolo Giangrande received the bachelor's (Hons.), master's (Hons.), and Ph.D. degrees in electrical engineering from the Politecnico of Bari, Bari, Italy, in 2005, 2008, and 2011, respectively.

In 2008, he joined the University of Malta, Msida, Malta, as a Marie Curie Intra-European Fellow. Since 2012, he has been a Research Fellow with the Power Electronics, Machines and Control Group, University of Nottingham, Nottingham, U.K., where he has been the Head of the Accelerated Lifetime Testing Laboratory, Institute for Aerospace Technology, since 2017. His current research interests include sensorless control of ac electric drives, design and testing of electromechanical actuators for aerospace, thermal management of high-performance electric drives, and reliability and lifetime modeling of electrical machines.

Michael Galea (M'13) received the Ph.D. degree in electrical machines design from the University of Nottingham, Nottingham, U.K.

He was a Research Fellow with the University of Nottingham. He is currently the Head of the School of Aerospace, University of Nottingham, Ningbo, China, where he is also the Director of aerospace. He currently lectures in electrical drives and in aerospace systems integration and manages a number of diverse projects and programs related to the more/all electric aircraft, electrified propulsion, and associated fields. His current research interests include design, analysis, and thermal management of electrical machines and drives, the more electric aircraft, and electrified and hybrid propulsion.