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High-Power Machines and Starter-Generator Topologies for More Electric Aircraft: A Technology Outlook

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ABSTRACT More electric aircraft (MEA) architectures consist of several subsystems, which must all comply with the settled safety requirements of aerospace applications. Thus, achieving reliability and fault-tolerance represents the main cornerstone when classifying different solutions. Hybrid electric aircraft (HEA) extends the MEA concept by electrifying the propulsive power as well as the auxiliary power, and thereby pushing the limits of electrification. This paper gives an overview of the high-power electrical machine families and their associated power electronic converter (PEC) interfaces that are currently competing for aircraft power conversion systems. Various functionalities and starter-generator (S/G) solutions are also covered. In order to highlight the latest advancements, the efficiency of the world's most powerful aerospace generator (Mark 1) developed within the E-Fan X HEA project is graphically represented and assessed against other rivaling solutions. Motivated by the strict requirements on efficiency, power density, trustworthiness, as well as starting functionalities, supplementary considerations on the system-level design are paramount. In order to highlight the MEA goals and take advantage of all potential benefits, all subsystems must be treated as a whole. It is then shown that the combination of PECs, aircraft grid and electrical machines can be better adapted to benefit the overall system. This survey outlines the influence of these concerns and offers a view of the future technology outlook, as well as covering the present challenges and opportunities.

INDEX TERMS Aerospace generators, more-electric aircraft (MEA), hybrid-electric aircraft (HEA), power electronic interfaces, matrix converters, three-level converters, wound-rotor synchronous machines, induction machines, permanent magnet machines, reluctance machines.

AEA	All Electric Aircraft
MEA	More Electric Aircraft
HEA	Hybrid Electric Aircraft
S/G	Stater/Generator
EM	Electrical Machine
PMM	Permanent Magnet Machine
IM	Induction Machine
RM	Reluctance Machine
WFSM	Wound-Field Synchronous Machine
AE	Asynchronous Exciter
PD	Partial Discharges
VSVF	Variable-Speed Variable-Frequency
VSCF	Variable-Speed Constant-Frequency
CSCF	Constant-Speed Constant-Frequency
PEC	Power Electronic Converter
2LC	Two-Level Converter
3L-NPC	Three-Level Neutral Point Clamped Converter
3L-TTC	Three-Level T-Type Converter
DMC	Direct Matrix Converter
IMC	Indirect Matrix Converter
DQC	Dual Quadrant Converter
CSC	Current-Sourced Converter
VSC	Voltage-Sourced Converter
HVDC	High Voltage Direct Current
WBG	Wide Band-Gap
SiC	Silicon Carbide

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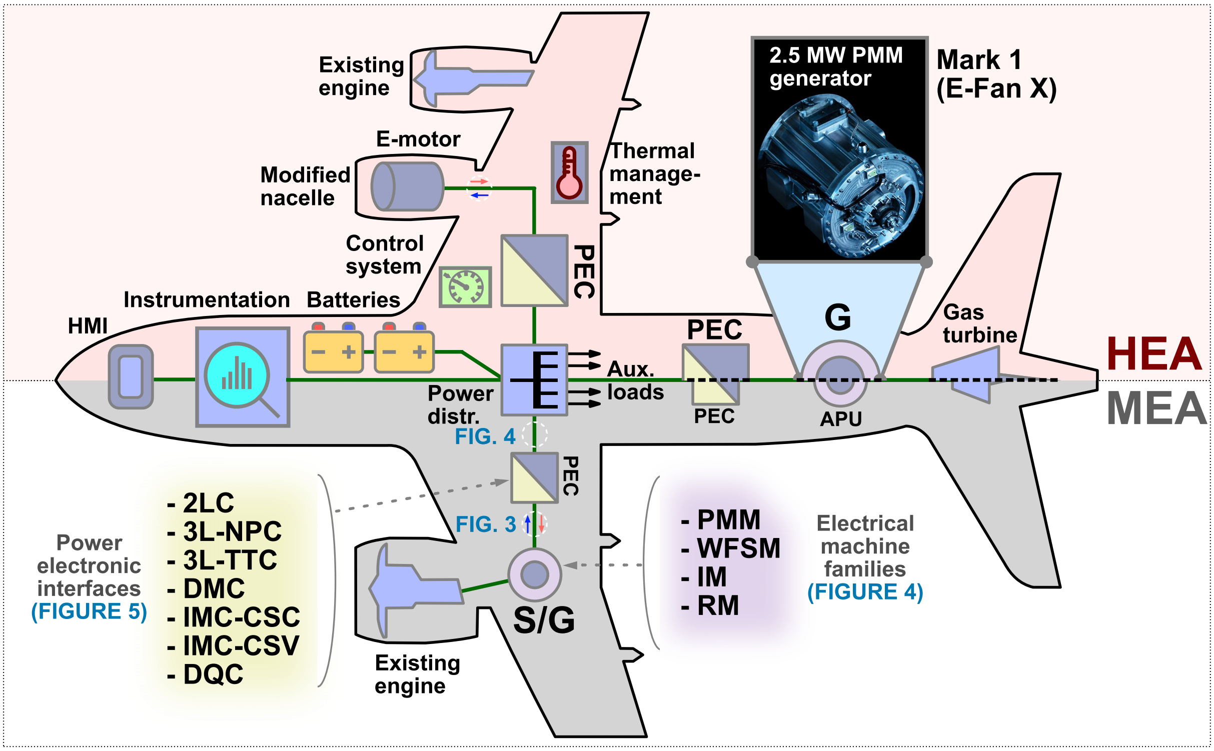


FIGURE 1. Illustrative example indicating the main elements of MEA and HEA architectures. The upper part shows an overview of the power distribution system for a series-hybrid HEA architecture, while the lower parts depict the main infrastructure of established MEA architectures. A PMM-based 2.5 MW, 14.5 krpm machine with its associated PEC (Mark 1 ground-based E2SG prototype (part of the E-Fan X project) is depicted in the highlighted HEA upper part (Courtesy of Rolls-Royce Electrical Norway) [1]. Control system and thermal management apply for both MEA and HEA. Different alternative electrical machine families and power electronic interfaces are mentioned in the figure, which outlines some of the literature review conducted in the paper.

I. INTRODUCTION

According to the 'Flightpath 2050' policy report on aviation research, the EU Commission aims to reduce emissions of CO2 by 75%, NOx by 90% and noise by 65% before 2050 [2]. Since the late 1990s, the ongoing development towards electrified aviation systems has received significant attention from the research community [3]. The move towards more electric aircraft (MEA) [3] and all-electric aircraft (AEA) [4] has been triggered by the ambition of curtailing the fuel consumption by minimizing the overall weight and improving the power management on board while increasing the trustworthiness and security [5]–[10].

The various more-electric functionalities, such as integrated starter-generator (S/G) solutions, are considered as the key technologies in the MEA paradigm. The gas turbines are configured for electric starting (''engine cranking'') using electrical machines (EMs), which then harvests mechanical power from the engine in generator mode [11]. Hence, hydraulic- and pneumatic systems can be eliminated [12].

The hybridization of aircraft propulsion systems is another recent trend continuing from the MEA initiative. The hybrid-electric aircraft (HEA) can increase the propulsive efficiency, reduce emissions during critical parts of the flight and mitigate the global increase in carbon emissions [4]. Fig. 1 contextualizes this paper by providing an illustrative example of a HEA and a MEA architecture to indicate their similarities and differences. In MEA systems, the propulsion is fully driven by jet engines [13]. However, also discussing components and systems for HEA concepts (e.g., referring to the E-Fan X electric generator [1]), may help to highlight where the cutting-edge advancements in the electrification of aviation are moving towards. Moreover, regional all-electric aircraft (AEA) will demand electrical machines (i.e., motors) in the range between 2 MW and 5 MW [14], which is in the same power range as the E-Fan X project. Such machines will have to comply with similar ultra conservative certification roadmaps as established for MEA applications [15]. The chosen case study (Mark 1 generator) is intended to deliver the required propulsion power consumed by one corresponding E-motor, as well as contributing to the on-board power system. Therefore, the power level goes beyond what is typically required by MEA configurations. This, in turn, helps to push the technological limitations in MEA architectures. As a point of reference, the total electric power capacities of the Boeing 787 (MEA) and the Airbus 380 (slightly MEA) designs are 1 MW and 0.6 MW, respectively [14].

The selected high-power generator, its power electronic conversion (PEC) technology and the power system architecture is at the core of the MEA/HEA technology. Overall, they can constitute a more-electric starter-generator (S/G) functionality, which has been widely applied in MEA/HEA systems [16]. Different alternative electrical machine families and PECs are listed in Fig. 1. The assessment of the different high-power topologies is just one of the open questions. Moreover, a myriad of different MEA/HEA architectures have been proposed [17]–[19]. In addition to the overall system configurations, Fig. 2 illustrates the principle of the S/G based on the bi-directional generator system. The two main families of arrangements in the MEA technology is indicated, i.e., AC and DC grid topology integrated with the S/G. All generator topologies with an active PEC at the stator-side can be implemented with electric starting functionality of the main generator, which has the potential to reduce wear and tear of the engine, as well as the need for maintenance.

Many MEA/HEA projects have been pursued around the world. One of them is the E-Fan X project (2017-2020) that developed the first prototype for the world's largest hybrid-electric aircraft. A 70-seater demonstrator HEA concept was developed by Airbus and Rolls Royce. In August 2019, a 2.5 MW (3400 hp) permanent magnet machine (PMM) was first tested at the Rolls Royce electrical machines facility in Trondheim, Norway (PMM depicted in Fig. 1) [1]. The machine was intended for a high voltage (3 kV) DC aircraft power system for high altitudes. In this HEA demo, a considerable fraction of the propulsive power was intended to be electrified (25 percent), replacing an existing engine. In MEA systems, the electric power is secondary [20], meaning that all propulsion power is directly originating from fuel engines (without electrical conversion). While Boeing 787 still favour classical wound-field synchronous machine (WFSM) generator technology [21] for secondary electric power, the E-Fan X project employed the PMM as its main generator [1], contributing to primary electric power as well. This highlights the fact that there is still an ongoing debate on the most suitable machine topologies.

Historically, some parallels have been drawn between the hybridization or electrification of vehicles and the move toward MEA/HEA technologies [13], as they are based on similar core EM technologies. Discussions regarding the most suitable EM and S/G technology for aircraft started more than twenty years ago [22]. Similar trends towards electrification are now occurring for electric motors and actuators in aviation research as well [20], [23]–[27].

In this article, the on-board power distribution systems and the interacting power electronic solutions for different electrical machine families in MEA/HEA power generation systems are reviewed and compared against each other. The main elements of this review have been developed from [11], but have been significantly expanded to provide a more comprehensive basis for the presented discussions and comparisons. In the following, section II is briefly exploring the general trends and developments toward MEA systems, the essential requirements for the machines and the principles of S/G functionality. Then, Section III presents an outline of the possible options for the MEA distribution grid and for the related power electronic interfaces interacting with the main power generation facilities. Section IV reviews the properties of the wound-field synchronous machine (WFSM) as either a uni-directional generator or as an S/G, including the excitation equipment needed for different additional functionalities. Further, Section V explores the main competitors to the WFSM. Finally, Section VI presents some state-of-the-art comparisons and assessments, as well as future perspectives and opportunities before Section VII concludes the paper.

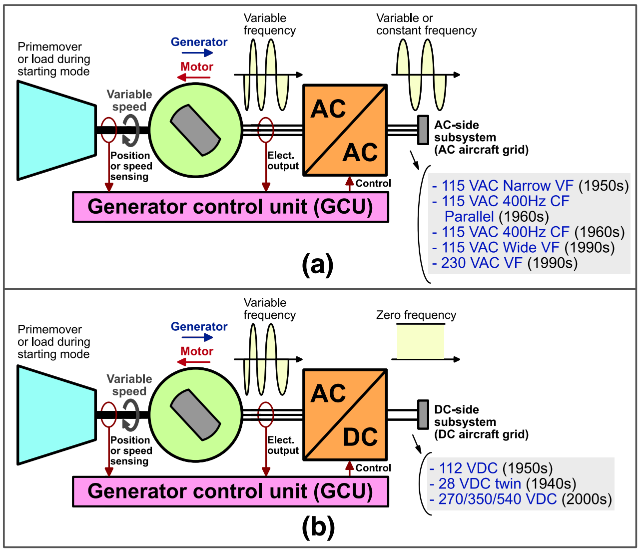


FIGURE 2. Two categories of MEA power distribution (based on the bi-directional generator system [22]), with some examples of distribution solutions in existing aircraft [39]. a) Variable speed constant frequency (VSCF) or "frequency-wild" AC distribution (which can also be implemented with DOL-connected WFSMs without stator-side PEC). b) DC distribution topology (which could also be implemented as a uni-directional DOL-connected WFSMs with passive stator-side rectifier, shown in Fig. 6).

II. POWER CONVERSION ARCHITECTURES FOR GENERATORS AND S/GS IN MEA APPLICATIONS

The incentives for the progress towards MEA concepts, the common configurations of the aircraft grids and the available power electronic conversion (PEC) topologies have been well documented in the literature [28]–[38]. In line with the recent trends, a brief overview of the requirements and the competing paradigms for MEA power systems and the operating basics for S/G-applications are presented in the next subsections.

A. *TRENDS IN THE BASIC MEA TECHNOLOGY*

The trends in the ongoing evolution of the aircraft power generation appear to be similar to ground-based machines and transportation systems when it comes to power density. However, extreme considerations related to weight reduction, thermal management, fault-tolerance and reliability are more emphasized. This subsection starts by introducing the design objectives and requirements.

1) BASIC MEA REQUIREMENTS AND RELIABILITY CONCERNS

The ongoing electrification revolution of MEAs is a direct consequence of the continuous innovations in high-performance PECs and electrical machines [40]. According to aerospace practices, an enhanced power density with low weight and high power capacity are among the key objectives. In achieving power dense electrical machine solutions, two possible approaches are increased magnetic fields and higher armature current loading. As a consequence of higher loss density, the management of heat flows becomes significantly more important [25], i.e., the early-stage machine design has to be more focused on the hot spots. Moreover, fail-safe abilities and insulation degradation [23] are key concerns. The critical field strength is drastically reduced due to lower pressures at higher altitudes. Thus, challenges with partial discharges can increase for motor windings as well as cable insulation in aircraft applications [41], [42]. Inside the aircraft body with the environmental control system (ECS) intact, the critical electric field is 25 kV per *cm* [43], which informs the insulation design of individual power components. Efforts toward partial discharge-free (PD-free) design of electrical machines have been reported to promote MEA reliability [44]. However, there is a trade-off since PD-free operation comes at the cost of reduced torque capability. It is the lowering of the absolute voltage magnitude across the machine insulation that causes the reduction of partial discharges (PD), and thus, affecting reliability. Another contributor to increased trustworthiness is the development in high-performance control of torque and speed, such as encoder-less algorithms that replace position encoders [45], [46]. Enhanced reliability is especially needed to enable ultra-high-speed operation.

2) POWER DENSITY

The need for ultra-high speeds in high power density machines can be easily perceived from the classical relation between the electrical power (P), the torque (T) and the machine speed (n)

$$P = T\omega_{mech} = T \cdot 2\pi \cdot \frac{n}{60}. \tag{1}$$

The machine speed is the most relevant target for power density improvements since a constant torque density is usually the first-hand limiting design factor. However, the power density does not always increase by simply increasing the speed. Higher frequencies lead to a significant increase in iron and AC copper losses, as well as higher requirements for PEC performance, which impacts weight and size [47], [48].

Under this perspective, the exploration of other machine designs may be fruitful. A slotless stator topology with a reduced core and a coreless rotor may be an interesting solution in MEA systems, as iron use is minimized and the slotting effect is eliminated [26]. Consequently, a weight-effective solution can be achieved for very high-speed applications. In [49], a promising 1 MW slotless machine was designed with an expected power density as high as 13 kW/kg, and 96% expected efficiency. Advancements in the same direction have already reached the first testing phase [50], and more testing results are expected to validate the remarkable potential highlighted in the design stage.

It is not only the stator slots that could be eliminated. Another issue is the fact that up to 50% of the electrical machine mass could be made of components that have no active role in the electromagnetic conversion process. Therefore, the reduction of non-active elements is an important objective, and increased power density can be achieved by optimizing structural components. It is worth noting that for any machine topology, higher speeds imply stricter containment requirements, i.e., to prevent components from disintegrate due to the centrifugal forces.

The power density (p) formulation can be either volumetric

$$p_{[W/m^3]} = \frac{P}{V_a}, \tag{2}$$

or gravimetric

$$p_{[W/kg]} = \frac{P}{m_a}. \tag{3}$$

They depend on either the active volume (V_a) or the active mass (m_a) that are accounted for in the power density specification, and whether the cooling system and the PEC topology are included or not. It is worth highlighting that the power density improvement in terms of weight (m_a) minimization is always the main objective for MEA systems.

3) COMPLEXITY ISSUES AND GOODNESS OF DESIGN

There are also other important design considerations in addition to weight reduction. To account for the complexity of the different design issues, including power capability, operational robustness, mechanical stress and critical speed, several performance indicators have been proposed. One of them is the goodness of design (GOD) factor proposed in [51], where

$$GOD = n[rpm] \cdot \sqrt{P[kW]}. \tag{4}$$

The different designs can be calculated in terms of GOD (using rated P and n) and then be categorized onto different GOD levels of performance (complexity of design), e.g., $1E5$, $3E5$, $5E5$, $5.7E5$ and $1E6$ [21].

4) EVOLUTION OF INSTALLED ELECTRICAL POWER CAPACITY

The power density issue (mentioned in Section II-A2) becomes more influential as a result of the ongoing aircraft electrification. The total electrical power capability in aviation has evolved excessively during the last twenty years [28]. The maximum power of the WFSM machine family has been as high as 250 kVA. It has been utilized as four equally rated WFSMs in the Boeing 787 Dreamliner platform [56], which has a total of 1450 kVA electrical power (including additional power generation facilities). Two so-called 'variable-frequency starter generators' (VFSGs) on two of the primary engines were included [57].

5) PARADIGMS OF POWER SYSTEM ARCHITECTURES

As a result of the increased aviation electrification, recent transformations have occurred in the on-board power architecture. Conventionally, the constant-speed constant-frequency (CSCF) system configured in a direct-on-line (DOL) arrangement has been extensively employed for more than 60 years [21], and it has been used in commercial solutions like Airbus A340 and Boeing B777 [58]. However, the constant speed drive (CSD) is a complicated, large and heavy system (i.e., input speed with heavy mechanical gearboxes), and performs with poor generation efficiency and inferior trustworthiness [3], [39]. In competition to the CSCF paradigm, 'variable-speed constant-frequency' (VSCF) systems [59] via DC-links or cyclo-converters have been used in military aerial systems like AV-8B, TR-1, F-117 [60] and F-18 [61]. The technical standard in regular VSCF systems is 400 Hz and 115/200 V [28].

The 'variable-speed variable-frequency' (VSVF) system has recently been attracting interest (i.e., "frequency-wild AC system"), and the first commercially available large-scale implementation of this category is employing four 120/150 kVA VF generators in the Airbus A380 platform. Moreover, VSVF technology is also found in Boeing B787 [21]. Recently, a 'variable-voltage' bus strategy has been proposed to enhance the power management [62]. Moreover, the DC-bus topology has been proposed with 540 V and 270 V for alternative aviation technologies [28], [63]. The E Fan-X project developed a demonstrator intended for 3 kV DC distribution for high altitudes [1].

In future MEA aircraft, the VSVF system or the DC distribution system will likely be the competing solutions. Therefore, this requires a bi-directional S/G configuration to embed an active PEC solution at its stator side to interact with the aircraft power system. However, the WFSMs can be direct-on-line (DOL) connected in VSVF configuration as well. In addition, the WFSG can be configured at the stator-side with a passive diode bridge rectifier without starting functionality (more details in Section IV).

The use of more active PEC results in a significant increase in the overall weight, which have been documented in both the AEGART S/G system [55] and the E FAN-X S/G [1]. Other concerns involve the impact PECs will have on the reliability of the S/Gs [64], [65]. More considerations on the distribution system with respect to the employed PEC topology for the S/G is presented in Section III.

B. BASIC PRINCIPLES OF STARTER-GENERATORS

With respect to the mentioned power system architectures, the starter-generator (S/G) functionality can be adapted for a wide range of power electronic interfaces and engine arrangements. Different definitions apply in industry practices and in academia, which is highlighted in Fig. 3. Fig. 3a) illustrates an alternative S/G terminology. Sometimes an electrical start of a generator is made by a separate engine-integrated electric motor that is only a fraction of the turbine power [53], [66].

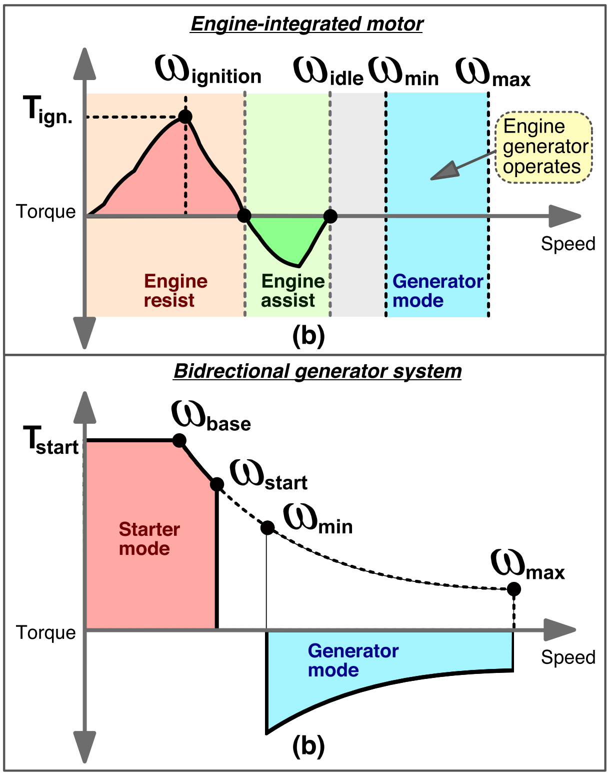


FIGURE 3. General torque-speed characteristics of starter-generators (S/Gs). a) Engine-integrated motor, i.e., integrated starter-generator (ISG) [5], [6], [52]–[54]. b) Bi-directional generator system [11], [22], [55].

In Fig. 3b), the characteristics of the bi-directional S/G generator system is depicted. It is the second definition of S/Gs that are applied in this paper, i.e., that the main generator can start the engine itself. In every case of such functionality, an S/G is configured for bi-directional power flow and operates in two modes, as depicted in Fig. 3b).

1) MODES OF OPERATION

- Starting mode: S/G operates as a motor where the primary engine is behaving as a mechanical load. The engine is accelerated to the self-sustaining speed (ω_{start}).
- Generating mode: The variable speed (VS) engine sustains itself, and the interfacing PEC supplies the onboard loads through DC supply, constant frequency (CF) or variable frequency (VF).

The power is managed by the PEC interface when operating in both modes.

2) ELECTRICAL MACHINE FAMILIES FOR S/GS

A multitude of machine technologies have been suggested for high-power machines or S/G applications [32], [67], including

1) wound-field synchronous machines (WFSMs) [21], [68],
2) permanent magnet machines (PMMs) [69], [70],
3) induction machines (IMs) [71]–[73], and
4) reluctance machines (RMs) [74]–[77].

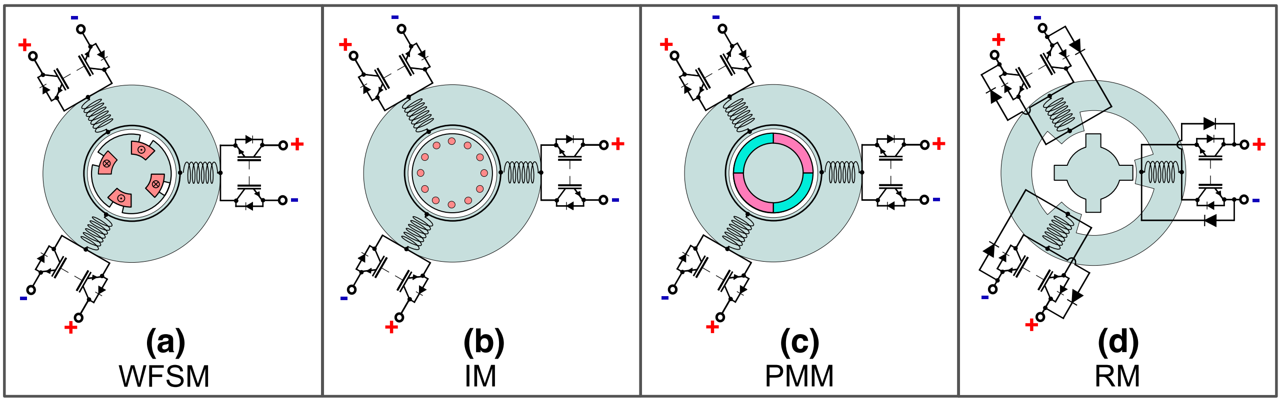


FIGURE 4. Considered high-power electrical machine families and S/Gs in MEA architectures [5] with an AC/DC topology (see Fig 2b). a) Wound-field synchronous machines. b) Squirrel-cage induction machines. c) Permanent magnet machines. d) Reluctace machines.

TABLE 1. Outline of the PEC interfaces for starter-generator applications.

PEC type	Benefits	Drawbacks	Ref.
Two-level converter (2LC)	• Most standard converter topology; • Minimum number of components;	• High voltage THD, high dV/dt and insulation stress; • Large DC-side capacitor.	[40] [78], [79]
Three-level neutral point clamped converter (3L-NPC)	• Reduced voltage THD, dV/dt and insulation stress; • Reduced harmonic losses with higher efficiency.	• Non-uniform losses and high number of components; • Increased capacitor volume.	[79] [80]–[83]
Three-level T-Type converter (3L-TTC)	• Reduced harmonic content and insulation exposure; • Lower harmonic losses and increased efficiency.	• Non-uniform losses and high number of components; • Devices with different voltage ratings.	[79], [80] [84], [85]
Direct matrix converter (DMC)	• Capacitor-free topology.	• Complicated control.	[86]
Indirect matrix converter (IMC)	• DC-link avoided, reducing size and weight; • Small AC-AC interface filters required.	• High number of components required; • Higher output current demand (low transfer ratio).	[87] [88]
Dual-quadrant converter (DQC)	• Independent control of different phases.	• Tailored solution for SRMs.	[74]

Fig. 4 illustrates the basic structure of each electrical machine family and the classical PEC topology of each type. It assumes the AC/DC topology of Fig. 5a), i.e., 2LC for the WFSM, the IM and the PMM. In addition, the interface of Fig. 5c), DQC, is assumed for the RM. More considerations regarding the electrical machine families are the focus for Sections IV and V. Since IMs, PMMs and RMs demands active PEC at the stator-side, all of them will automatically include S/G functionality, and will be treated as S/Gs hereafter.

III. POWER ELECTRONIC INTERFACES FOR S/GS

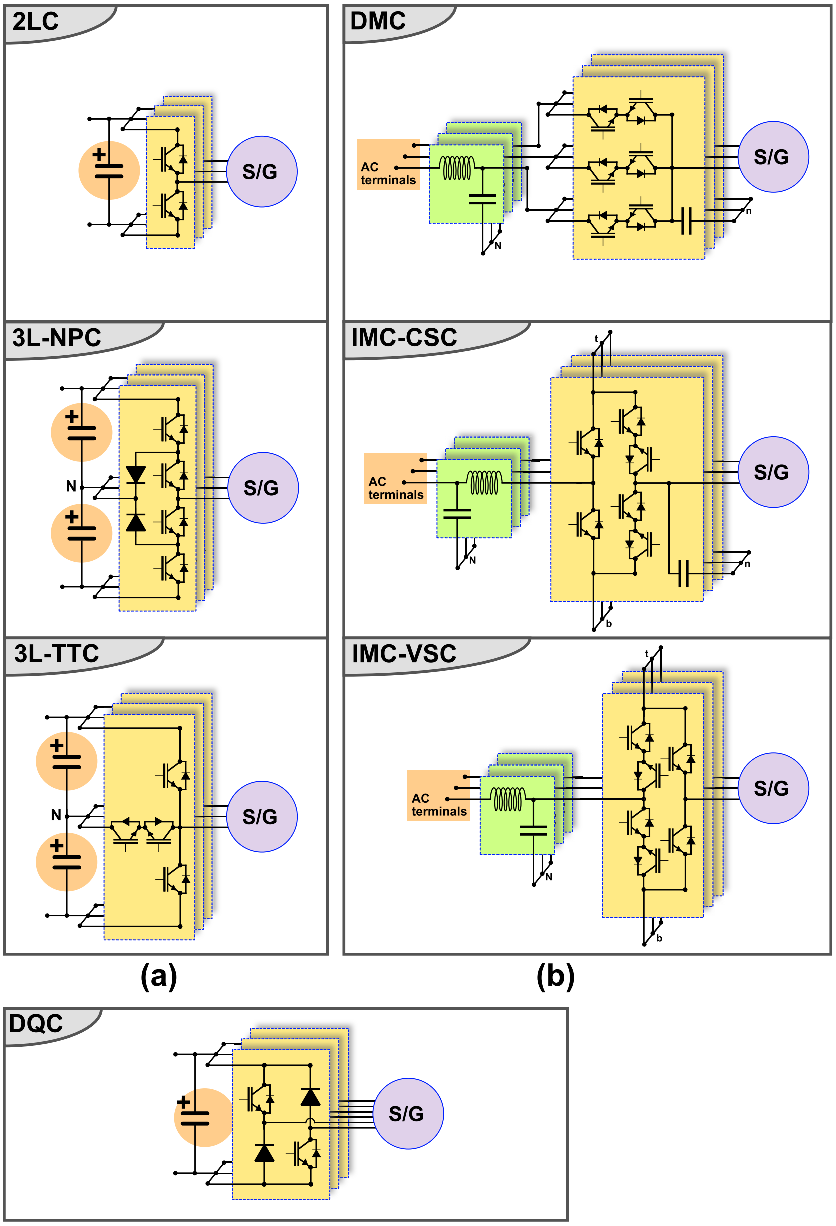
Power electronics is already a well-integrated technology in different parts of the aircraft, and the utilization of power electronic conversion is continuously increasing in the MEA context. Thus, power electronics is one of the most important enabling technologies for the MEA umbrella [89]. The focus of this paper is on the S/G applications, and the basic options for the on-board power distribution with the associated requirements for the PEC interface are presented in this section.

As mentioned in Section II, the PEC configuration of an S/G must be bi-directional, operating as a rectifier in generator mode and as an inverter in starter mode. Thus, the main differences in the configuration of the PEC interface depend on the power distribution system. However, the functional requirements for the machine-side of the PEC interface are independent of whether the S/G is interfaced to a DC- or an AC-distribution system. A summary of the most relevant bi-directional PEC topologies applicable for S/Gs (covered in the latest research) is presented in Table 1, which highlights the merits and demerits of each topology, depicted in Fig. 5. In the following, the interfaces will be described more closely in terms of the type of distribution system in the aircraft.

A. AC DISTRIBUTION SYSTEMS

The general configuration of an S/G interfaced to an AC distribution system by a PEC interface is depicted in Fig. 2a). Indeed, AC distribution systems have traditionally been utilized for aerial power grids, and both solutions with constant frequency and flexible frequency (i.e. frequency-wild systems) have been widely applied. For systems with AC-distribution, a full-scale AC-to-AC power conversion stage is necessary for providing the controllability required by an S/G. A PEC interface can be provided by either two-stage AC/DC and DC/AC topologies or by a single-stage direct AC/AC conversion.

It should be mentioned that passive diode rectifiers have traditionally dominated as AC-to-DC converters in aircraft power systems due to their high reliability. Indeed, passive rectification is still a relevant solution for WFSMs interfaced to DC distribution systems or as an interface between frequency-wild and fixed frequency distribution systems. However, power quality and tight EMI requirements is also a major concern for the future large power demand required in the MEA systems [90]. Thus, active converters are increasingly studied for MEA applications. Furthermore, passive



(a) (b)

(c)

FIGURE 5. PEC interfaces suitable for S/Gs. a) AC/DC interfaces, including the two-level converter (2LC), the three-level neutral point-clamped converter (3L-NPC) and the three-level T-type converter (3L-TTC). b) AC/AC interfaces, including the direct matrix converter (DMC), the indirect matrix converter with current-sourced converter at S/G side (IMC-CSC) and the indirect matrix converter with voltage-sourced converter at S/G side (IMC-VSC). c) The full-asymmetric dual-quadrant converter (DQC), exclusive for reluctance machines (RMs).

rectifiers are not applicable to S/G systems, and are, therefore, not further discussed in the following.

1) TWO-STAGE TOPOLOGIES

The classical machine-side PEC topologies studied for S/Gs are depicted in Fig. 5 (a). Indeed, two-stage topologies based on voltage source converters (VSCs) with an intermediate DC-link capacitor is the most common design. The two-level converter (2LC) utilizes the least amount of active switches, yielding simplicity and trustworthiness. The three-level neutral-point-clamped converter (3L-NPC) or the three-level T-type converter (3L-TT) are commonly employed to accomplish increased efficiency, higher fundamental frequency and minimal EMI emissions, without increasing the switching frequency of the semiconductor devices [79], [84], [91]. The reluctance machine drive is configured with phases that are controlled separately by dual quadrant converters (DQCs), as depicted in Fig. 4 d) and Fig. 5c).

The configurations in Fig. 4, Fig. 5a) and Fig. 5c) are all configured with a DC capacitor. As a result, they are directly applicable for DC distribution systems, as assumed in Fig. 2 b). However, high voltage DC distribution (270/540 V or higher voltage levels) based on VSCs with DC-side capacitors also introduces concerns on the protection and the fault handling, which relies on emerging semiconductor-based breakers [63]. Thus, current-source PEC interfaces can also be considered, as suggested in [14], although they are not currently common for MEA applications. Furthermore, the remaining challenges with high power DC distribution systems imply that AC-distribution systems are still relevant. Thus, direct AC/AC conversion systems are also being considered to avoid the two-stage conversion process with the intermediate DC-link.

2) DIRECT AC/AC CONVERSION WITH CAPACITOR-FREE TOPOLOGIES

DC-link capacitors are one of the most frequency sources of failures in PECs [14], [64], and they contribute to overall weight and volume. In mitigating the need for a large DC capacitor in a two-stage conversion, matrix converters can directly convert from variable frequency AC to fixed frequency AC without a DC-link [30]. As an example, an indirect matrix converter (IMC) is studied in [87]. Matrix converters, without a DC capacitor interface, have for many years been a suitable choice of the converter when compact solutions with high power density are required. Traditionally, a significant motivation for capacitor-free solutions has also been to increase reliability by avoiding electrolytic capacitors. Topologically we can find several matrix converter alternatives within the classes of direct and indirect matrix converters (DMC and IMC), as shown in Fig. 5b). They differ in the modulation principle and the number of switches. However, the lack of a buffer capacitor makes this type of conversion more vulnerable to faults and imposes strict requirements for the controllers. In general, control of these type of converter features higher complexity than for AC/DC converters. Moreover, direct matrix converters can experience challenges with over-current limitation in starting mode. In avoiding this problem, the indirect matrix converter has been proposed for S/G applications [87].

B. DC DISTRIBUTION SYSTEMS

The typical configuration of an S/G unit interfaced with a DC distribution system was depicted in Fig. 2b). As outlined above, constant frequency AC-distribution employing the highlighted interfaces in Fig. 5a) is most commonly based on two-stage AC-DC-AC PEC configurations, which adds extra hardware and losses to the MEA technology. These considerations make a case for the high voltage DC-bus (HVDC) configuration [31]. Thus, DC distribution in aircraft systems is becoming more attractive as the power levels are increasing while both generation and load are predominantly based on power electronics interfaces. Indeed, DC distribution can in many cases save two conversion stages (i.e. DC-to-AC and AC-to-DC) between the power source and the load. Furthermore, increased voltage levels are also being considered for reducing losses and weight of the cables of the distribution system when the required power levels are increasing. Thus, the power distribution system for the E Fan-X HEA project is assumed to be at 3 kV DC [1].

As already explained, Fig. 5a) shows the typical AC/DC converter configuration with DC-side capacitance. Thus, these topologies are directly applicable for AC-to-DC conversion in DC distribution systems.

C. PROSPECTS AND CHALLENGES OF ONGOING PEC DEVELOPMENTS FOR S/G APPLICATIONS

Although not extensively treated in the following, it is worthwhile mentioning that many of the ongoing developments of PEC technology are supporting the potential for electrification of aircraft systems. Especially, the developments towards the commercial application of wide bandgap (WBG) semiconductors are expected to have significant implications on the development of MEA applications. Applications of PEC solutions based on WBG are already widely considered for the established voltage levels of aircraft distribution systems [85], [92]–[94]. Indeed, the use of WBG devices is generally advantageous for reducing losses and for increasing switching frequency, which again can influence the power density. The characteristics of WBG devices are also expected to support higher reliability of PEC units for MEA applications [95]. Furthermore, especially silicon carbide (SiC) devices have the potential to enable the high-temperature operation of PEC interfaces.

For the established MEA applications, the potential improvement of power density might be most significant for DC/DC converters and/or DC/AC inverters operating as an interface between a DC-stage and a fixed frequency AC distribution system. Indeed, the achievable power density of these applications can benefit from the reduced size and weight of magnetic components enabled by increased switching frequency, and/or from reduced cooling requirements due to lower losses. However, for high power S/G application, the use of SiC devices also has significant potential to support the development of distribution systems at higher voltage levels. Thus, MW scale medium voltage systems based on SiC or hybrid Si-SiC PEC solutions are already being considered for future hybrid aircraft systems [96], [97], and this is also reflected by S/G specifications for the E-Fan X project [1]. Furthermore, the capability for high switching frequency operation can be necessary for effective utilization of coreless machines with low inductance and for ultra-high-speed operation with fundamental frequencies reaching the kHz-range [98].

The use of WBG devices can also introduce additional challenges for the insulation system design in MEA and HEA applications. Generally, reducing the switching losses by taking advantage of the potential for faster switching of WBG devices, will increase the challenges with EMI and the potential for partial discharge activity in insulation

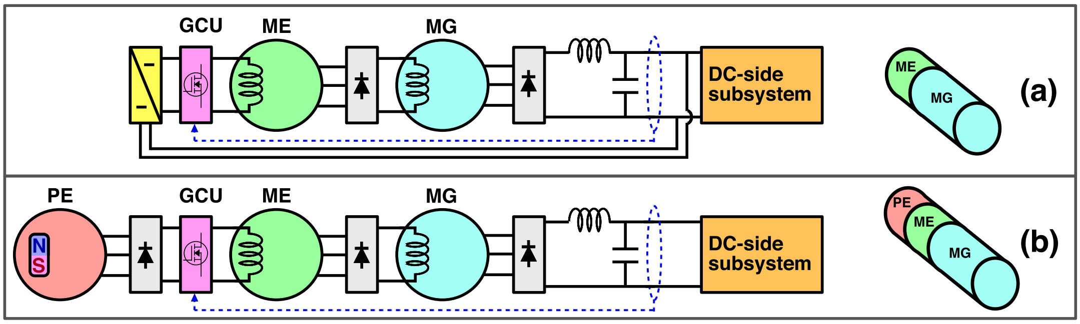


FIGURE 6. Examples of WFSM configurations without active PEC on the stator side feeding a DC-side subsystem [108]. The architectures do not have birectional electric start functionality. GCU = 'generator control unit', ME = 'main exciter' and MG = 'main generator'. a) Two-stage excitation system. b) Three-stage excitation systems with pilot exciter (PE).

materials [41], [42], [99]. Thus, the utilization of SiC devices in established converter topologies for S/G applications and other electromagnetic actuators, might lead to the need for dedicated dV/dt-filters [100], [101]. Furthermore, the stresses on the insulation materials will increase with the voltage level and the dV/dt during switching. Thus, utilization of multilevel converters can be a suitable approach for reducing the stress on insulation materials [102]. As a consequence, multilevel PEC topologies are expected to become more important when utilizing WBG technology to reduce switching losses while increasing the voltage levels. However, there also exists examples of machine designs that can tolerate high dV/dt without suffering increased problems with partial discharges [103]. Therefore, in line with the recent trends, multi-physical design tools are needed for PECs for future industry advancements [104]–[106], where the machine design objectives are included [107].

IV. WOUND-FIELD SYNCHRONOUS MACHINE AS STARTER/GENERATOR

Brushless WFSMs are extensively used as the generator technology in conventional aviation [21]. Moreover, it is the classical solution for high-power inverter-fed electric drive systems [109]. Nowadays, WFSM is a robust solution with a high level of trustworthiness and simple maintenance. Therefore, it is still a very competitive solution for MEAs with either constant frequency, flexible frequency or DC distribution systems. The main advantages are high power generation capacity over a broad speed range and fail-safe fault handling. In general, the rotor of the WFSM has high thermal inertia, which makes the machine less sensitive to short-term overloading [110], [111]. On the contrary, PMs are more vulnerable to thermal transients. However, the WFSM is not competitive for smaller aerospace systems, considering the overall costs.

A. GENERAL PERFORMANCE PROPERTIES OF WFSMs

For larger machines, WFSMs avoid the relatively high costs of PMs but at the expense of increased size and weight (if no superconductor designs are employed). Consequently, WFSMs can compete with the PMMs in the segment for large generator systems. However, WFSMs need a DC supply for the wound rotor winding. An additional winding to be controlled adds complexity and total weight to the system. Moreover, brushes and slips rings should be eliminated in ultra-secure MEAs. In line with these considerations, a rotating transformer or a brushless excitation system is required. A classical brushless rotating exciter solution with two electrical machines is depicted in Fig. 6a). Moreover, the three-stage system with three electrical machines on the same shaft [112] is illustrated in Fig. 6b). Both are illustrated for a DC distribution system. The three-stage system consists of a main generator (MG), a main exciter (ME) and a pilot pre-exciter (PE). The small-size PE is conventionally a permanent magnet generator (PMG) that extends the shaft. However, it can be eliminated by alternative external supplies [113] or fed from the DC bus, as seen in Fig 6a). A conventional field-wound brushless exciter (configured as an inside-out WFSM) can only excite the main machine in generator mode since a non-zero mechanical speed is required to deliver excitation power to the rotary domain. To be able to operate from standstill, different topologies of asynchronous brushless exciters are used, as further explained in Section IV-B.

1) SPEED LIMITS OF WFSMs

Classical WFSM are usually found in the lower speed range of commercial aircraft solutions, i.e., 10 to 25 krpm [21]. The challenges in reaching higher machine speeds are the main limitation for increasing the power density of WFSMs. In fact, brushless excitation and rotating diode rectifiers add space on the rotary shaft, and their mechanical limitations restrict the maximum speed of the WFSM (see Fig 7). An advanced design solution for the whole brushless WFSM is needed to mitigate mechanical malfunctions. In practice, the radial dimensions must be minimized to restrict the centripetal forces, and the rotating diode rectifier is placed inside the ME rotor to save axial space. A maximum realistic speed limit is perceived to be around 20 krpm [55], but there are efforts to push this limit for larger machines. In fact, the integrated drive generator (IDG) of the Boeing 777 aircraft (first flight 1994) operates at 24 krpm [114]. Moreover, it can be found that a fully functioning WFSM from 1981 was tested with 28 krpm at a power density of 2.47 kW/kg [115]. Even though the speed is impressive, there are many opportunities to improve the WFSM for higher power densities at higher speeds. In this way, it can compete with alternative solutions (e.g., the PMM). In fact, Honeywell demonstrated a WFSM prototype in 2013 that could achieve a power density as high as 7.9 kW/kg at 19 krpm [116]. Such demonstrations prove that the WFSM could join the competition with the more modern electrical machine topologies for MEA S/Gs.

2) BENEFITS OF THE ROTOR FIELD CURRENT CONTROLLABILITY

The WFSM yields diverse opportunities in terms of optimization. It has three control states, i.e., the d-axis armature current (I_d), the q-axis armature current (I_q) and the rotor excitation current (I_f). The excitation current is a variable that can be minimized with dedicated design optimizations. Moreover, the excitation current can be controlled to achieve the needed flux de-regulation capacity. In addition, a redundant de-excitation circuit improves the security for the S/G [117]. This because it has the opportunity to eliminate the fault current shortly after a short-circuit or a high voltage occur. The de-excitation circuitry functions independent of the PEC at the armature-side, thus achieving a fail-safe solution. During high-speed flux de-regulation mode, the power factor and the efficiency are still high. The synchronous rectifier mode can be applied under generator operation to limit EMI and enhance efficiency (converter losses). The possibility to run the stator with passive power electronics (diode bridge rectifier) to feed a DC bus is a significant benefit for WFSMs. Such a passive interface would typically have a failure rate of about 25% of the failures of active PECs [118]. In addition, the low transient reactances makes the commutation voltage drop during diode bridge rectifier operation to be small [119]. Such considerations favour combinations of active PEC for engine starting (or an engine-integrated motor starter) with passive rectifier operation in generator mode. WFSM is the only solution that can provide constant-voltage variable-frequency (CVVF) without being fed by active PECs at the stator side.

Fig. 6 depicts two classical configurations where the WFSM works as a DC generator, i.e., the two-stage and the three-stage configuration. There are also other types of more advanced two-stage systems available, based on rotating PECs [120]–[122]. In this approach, the WFSM only needs a generator control unit (GCU) to control the field current of the main generator (MG) via the main exciter (ME). An uncontrollable diode bridge is applied at the stator side [123], [124], which promotes reliability and fault-tolerance [125]. Rotor position sensors are not needed in this configuration. This classical solution yields a very robust, simple and practical control scheme, but at the cost of slow dynamic response. For faster dynamics, rotating power electronics (RPE) is needed on the shaft of the MG, where a lot of different solutions exists [126]–[128]. There is also a myriad of available exciter-less solutions that eliminates the need for an external source to the ME [117].

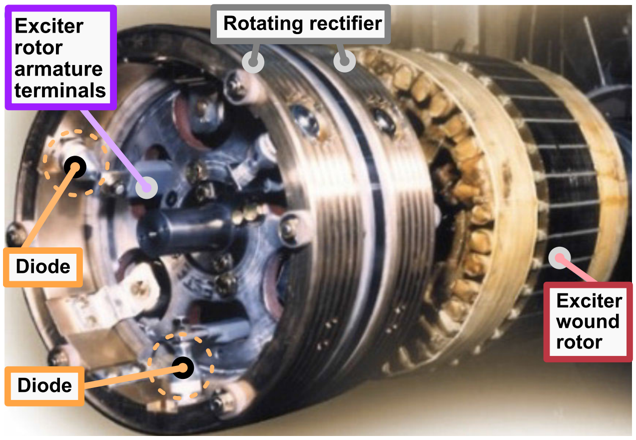


FIGURE 7. Rotor of main exciter (ME) and externally-mounted rectifier for a high-speed synchronous WFSM [133].

3) CHALLENGES AND SOLUTIONS TO THE ROTOR FIELD CURRENT CONTROLLABILITY IN ELECTRIC STARTING-MODE

The ME armature and the MG armature should be coordinated during starting mode of the WFSM [129]. Excitation boosting during starting is a great benefit of the WFSM to improve the starting process. However, this functionality demands carefully designed exciters with dedicated control methods. Without the use of measured rotor quantities, the MG excitation current is unknown. Among the challenges is the increasing complexity added due to the starting mode, i.e., the control strategy is significantly different from the generator mode. The strategy must mitigate the non-linearities in order to magnetize the WFSM with good controllability at zero speed. The electromagnetic coupling between the ME and the MG is especially strong during the starting process. In addition, the rotating diode bridge between them introduces non-linear behaviour. Therefore, a decoupled control strategy with coordination has been recently developed [130].

The main excitation schemes are based on asynchronous exciter (AE) machines, however, rotating transformers and efficient capacitive transmissions have been proposed to make the WFSM less speed-dependent [131]. Such concepts have a unique potential to improve the overall weight of WFSMs as a result of the on-going breakthroughs in material science [132].

B. BRUSHLESS ASYNCHRONOUS EXCITER STARTING-MODE SOLUTIONS FOR WFSMs

In the following subsections, the three possible brushless asynchronous excitation (AE) methodologies for WFSMs in electric starting mode are described. The main points are then highlighted in Table 2.

1) ONE-PHASE BRUSHLESS AE

The one-phase AE is similar to a classical synchronous exciter, as depicted in Fig. 8. However, the field winding in

TABLE 2. Outline of the excitation solutions for WFSM starter-generator functionalities.

Exciter type	Benefits	Drawbacks	Reference
One-phase AEs	• The ME can be a standard synchronous machine; • Ease of control in generator mode;	• Limited and pulsating excitation in starting mode; • Poor starting torque capability;	[134]–[137]
Two-phase AEs	• Contributes with high starting torque; • Simple control criterion in generator mode;	• Uncommon topology for standard exciters; • Need to oversize a single converter leg	[138]–[143]
Three-phase AEs	• Contributes with higher starting torque; • Wound-rotor IMs are a standard product;	• 12 IGBTs converter topology for DC excitation ; • Complicated control method in generator mode;	[68] [144]–[147]

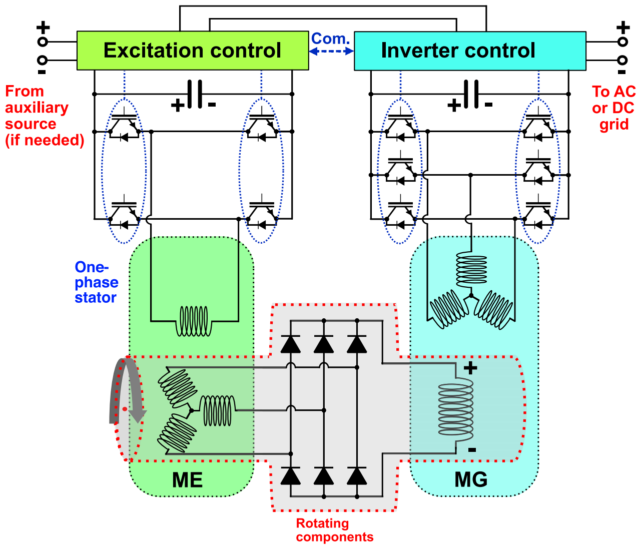


FIGURE 8. The asynchronous excitation system reported in [135], [136], with a single-phase configuration, where ME is the main exciter and MG is the main generator.

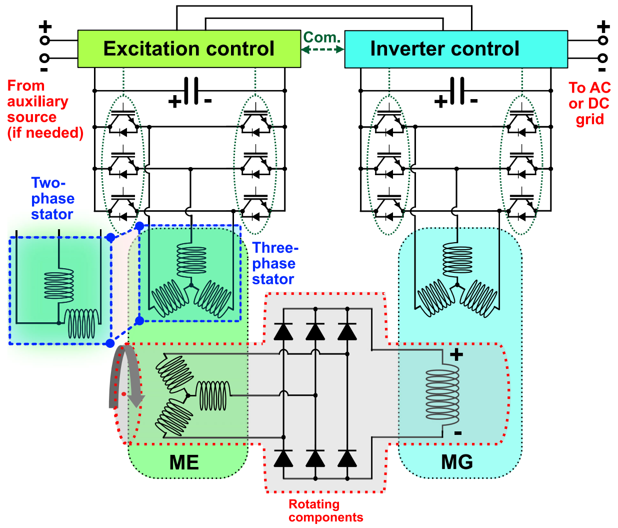


FIGURE 9. The asynchronous excitation systems configured as a two-phase arrangement [139], [140] and as a three-phase arrangement [68] (combined schematic), where ME is the main exciter and MG is the main generator.

the stator can be supplied with both DC and AC voltages. In fact, an AC current is required to magnetize the WFSM from zero speed [134]. However, it is largely restricted by ripples in the excitation power. Moreover, the high field inductance limits the AC current, which deteriorates the performance during the starting process. Such considerations make the one-phase AE is insufficient for off-the-shelf solutions in high-power MEAs [113]. As the WFSM approaches a sustainable speed, the AE is fed with DC current instead of pulsating AC current. The DC excitation is simple to control; however, it can only be used in the generator condition.

2) TWO-PHASE BRUSHLESS AE

To solve the issues with the one-phase AE, the AE can be arranged with two orthogonal stator windings (displaced 90 degrees electrically). It can enhance the excitation efficiency during electric starting condition (see Fig. 9). A high current rating is needed for a third return conductor, as depicted in the figure. It has other benefits, such as higher power density and lower kVA/kW input-to-output ratio of the exciter machine. The arrangement can directly generate a rotating magnetic flux from the stator-side of the AE without pulsations, and it behaves electromagnetically as an asynchronous generator. The control of the starting process can be straightforward if the rotating excitation field is sustained. This is feasible by controlling the two-phase currents of the AE stator, in order to sustain a relative speed difference between the rotor and the rotary magnetic flux of the ME [139].

Under the generator mode, DC currents will feed the stator armature of the AE. Equal excitation current in both windings ensures uniform thermal stress in the AE. In principle, the generator mode control strategy becomes equal to the one-phase arrangement explained in the previous subsection.

3) THREE-PHASE BRUSHLESS AE

Fig. 9 also depicts the three-phase AE that can enhance the excitation of the WFSM during the starting process [113], just as the two-phase AE solution. In this arrangement, the stator has three distributed armature windings, that can be supplied with AC voltages during the starting process [148]. This solution operates similar to the three-phase rotating transformer in the starting mode. It is a matter of the fact that a rotary flux is possible using both a two-phase and a three-phase AE. In achieving simple control of the three-phase AE in generator mode, a dual inverter is proposed to reconnect the three-phase windings for DC excitation [149]. However, the arrangement becomes more complex than the two-phase

AE solution. This is because all phases must be opened between the inverter legs. As a result, it requires 12 IGBTs, which inevitably complicates the overall PEC interface (twice the number of switches for a 2L VSC topology). The final assessment between the AEs is highlighted in Table 2.

V. ALTERNATIVE ELECTRICAL MACHINE FAMILIES OF STARTER/GENERATOR CONCEPTS

This section explores the alternative machine families to WFSMs as high-power topologies and S/Gs in future MEAs. A significant amount of the commercial high-speed electrical machine solutions are made by IMs, PMMs or RMs. Those will be covered in the following.

A. THE INDUCTION S/G

Induction machines are well-known for covering a privileged position, among the different electrical machines, when it comes to failure robustness and safety [150]. In general, they can be classified as a good compromise between reliability and performance. Considering the passive rotor configuration, they boast the ability to support high-temperature operation (up to 250°) [5]. Moreover, by adopting a multiphase architecture, they can remarkably boost the reliability and, more particularly, include the possibility to operate under single-phase fault circumstances [151]. With the aim of enhancing the internal power flow, a double set of stator windings was proposed in [152].

It is worth mentioning that significant rotor losses can contribute to low efficiency. Moreover, wound-rotor architectures have limited fault tolerance. The low torque density, along with the reduced reliability, in starting mode were highlighted in [151]. Moreover, the full-power converter on the stator side may have to be oversized if higher starting torque is required. Furthermore, the stator is also required to provide the magnetizing current. As a consequence, in case of wider clearance required for the air gap (e.g. due to vibration), an added burden on the power converter side is inevitable.

The adoption of doubly-fed induction machines (DFIMs) were investigated for an aero-generator application in [71]. The goal was to replace the hydraulic constant speed drive (CSD), to meet the variable speed operation of the engine. The inverter controlling the rotor winding is designed with a fraction of the full system rating; thus, reducing the power converter cost and achieving variable speed operation with no additional mechanical components. The latter point is what has made DFIMs an interesting option in several applications. However, it is worth noting that the power to the rotor is supplied by means of slip-rings and brushes, which reduce reliability, especially considering harsh operating environments. On the other hand, the brushless configurations for DFIMs require rotating power electronics (RPEs), which yields a complicated overall system [153].

B. THE PERMANENT MAGNET S/G

The drop in the price of PM material, combined with a significant improvement in performance, initiated several new developments in the family of permanent magnet machines (PMMS). The main benefit lies in the absence of any active component in the rotor, which leads to inherent high power density and efficiency. The peak torque, which would be available even at zero speed operation, may be limited by power electronics devices ratings, thermal limits and demagnetization concerns.

The design of PMMs can be aimed at increasing the admissible operating range by allowing flux-weakening operation. In such a case, a high-efficiency operation can be observed with high d-axis current beyond the rated operating point. The adoption of concentrated windings does help in this regard, enhancing the flux-weakening capability and providing a more fault-tolerant design a the same time [154].

With the aim of widening the operating range of PMMs, the need for a focused and optimized design procedure is essential [155]. Nevertheless, a proper design process is required to account for reliability as well. The risk of demagnetization is to be suitably assessed both for transient overload operation and high-temperature operation. Permanent magnets happen to be vulnerable to corrosion, and this might become a crucial aspect when it comes to meet aerospace requirements. This being said, the use of Samarium-Cobalt (Sm_2Co_{17}) as PM can be advantageous considering the ability to operate up to 300°C [156] (maybe up to 350°C [157]), although 300°C appears to a reasonable worst-case temperature for the PMM S/G [55]. Operation at such critical temperatures would inevitably impact the machine lifetime and its ageing. In this regard, stator cooling could help to reduce the temperature-dependent copper losses; thus, increasing the insulation lifetime [158].

Compared to other machines described beforehand, PMMs have a permanent excitation. This means that uncontrolled speed overshoots or PEC failure during flux-weakening operation may lead to the potentially disruptive induced voltage on the power converter itself. In fact, all voltage regulation of PMMs and foolproof functionalities has to be embedded in the PEC interface. There are standards specifying that equipment survive an open phase-loss [159]. Another potential risk is the turn-to-turn short-circuit fault. As a consequence, fault-tolerant machines are being developed, and detection schemes are being investigated [160], [161]. Another concern related to high-speed operation is the centrifugal force acting on the magnets [157]. This problem is particularly relevant for in-runner machines, where a retaining sleeve is to be conveniently designed to avoid magnets detachments. For outrunner PMMs the problem may not occur if the backing iron is thick enough to withstand the forces.

C. THE RELUCTANCE S/G

Despite the fact that reluctance machines (RMs), has not seen its arrival in commercial aircraft, they appear to be a rather known type of S/G in military aircraft like the Lockheed Martin F-22 from the early 2000s [39], and they have been applied for aircraft development from the early 1990s [162].

The justification can reasonably be ascribed to the lesser power demand required by military aircraft. The ease of construction, along with the robust topology given by the basic single-element rotor topology and concentrated stator windings, appear to be the main strengths of this type of machines [163]. The absence of any field source applied to the common single laminated rotor part contributes to the high-reliability grade of this topology. Considering the challenging thermal design required by future aircraft applications; the limited rotor cooling requirements for RMs could push the temperature limit in the 400°C range [164] thus, showing inherent adaptability to very harsh operating conditions. However, as a drawback, the windage losses tend to be magnified by the salient shape of the rotor; hence, limiting high-speed operation [164]. As a solution to the latter problem, the gaps could be filled with non-magnetic material at the expenses of complicating the construction process. Although the added material increases the weight, the higher inertia helps to smooth torque pulsations. On the PEC side, one could argue that despite the overall tailored topology and dedicated control algorithms, the possibility of adopting off-the-shelf components, i.e., utilizing two bridges consisting of three legs or three H-bridges could reduce the manufacturing costs.

In view of the inevitable growth of MEA solutions, the SRM covers an attractive position when it comes to choosing the optimal S/G; especially if the inherently wide operating range is highlighted. However, among the main and well-known drawbacks of high power SRMs, the lower efficiency, compared to the opposing machines listed beforehand, has an important impact when classifying the potential solutions. The efficiency can be as low as 80-82% [77], [156], and the power density cannot be as high as PM machines [165], albeit it could find a fair comparison against IMs [166]. Conventional machine designs along with standard switching devices, yield low starting torque capability, which represents a non-negligible aspect when it comes to considering SRMs for S/Gs. As shown in Figs. 4d) and Fig. 5c) the PEC interface consists of a dual-quadrant full-asymmetric bridge for each phase, allowing independent control of each and every phase. It is worth mentioning that in generator mode the voltage ripple is significant, and torque pulsations appear to be an intrinsic drawback. Nevertheless, differently from what would happen for PM machines, SRMs are inherently safe against failure on the PEC side during high-speed operation, since the induced voltage will be zero.

VI. PRESENT STATUS, ADVANCEMENTS AND TRENDS

Different aspects have been explored throughout the paper regarding the most relevant electrical machine families and power electronic conversion interfaces for aircraft power generation. As of today, the largest built and tested electric aircraft generator is the 2.5 MW Mark 1 PMM that is preliminary just built for validation and simulation purposes [1]. It is not yet optimized in terms of weight, neither for the PEC nor the machine itself. This was the objective for the next version, i.e., Mark 2. Finally, the third version (Mark 3) was intended for installation in the flying system. However, the remaining parts of the E-Fan X project has been cancelled. Still, it is possible to draw some conclusions regarding the performance of the design from the Mark 1 (i.e., technology readiness level 5) [1].

1) THE EFFICIENCY PERSPECTIVE

The efficiency is a critical performance indicator for electrical machines. From a detailed analysis, an efficiency map for different loads and speeds can be obtained, which depicts a performance footprint of the machine. Fig. 10a) depicts the efficiency contours for the Mark 1 2.5 MW PMM generator [1]. The speed-dependent no-load losses of the machine, plotted separately in Fig. 10b), are less than 0.5%. The expected total losses in this type of machine are typically about 1-2%.

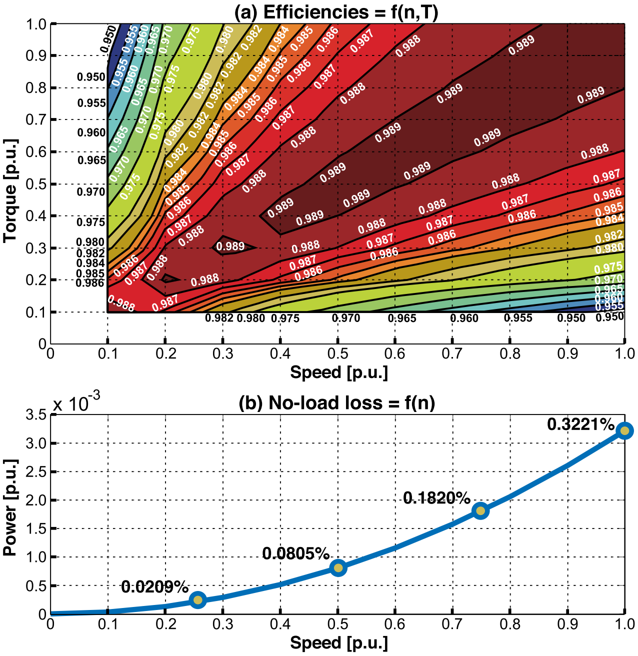


FIGURE 10. Characterization of the world's most powerful aerospace generator, Mark 1, for the E-Fan X project (hybrid-electric commercial aircraft). The ground-based prototype 2.5 MW, 14.5 krpm PMM S/G is depicted in Fig. 1 (Courtesy of Rolls Royce Electrical Norway) [1]. (a): Isoefficiencies of the load matrix with torque base: 1.64 kNm. (b): No-load losses with power base: 2.50 MW.

TABLE 3. Efficiency comparison of large aircraft generators with a DC power architecture.

Source	Type	Voltage	Rating	Eff.	Ref.
RR	PMM	3.00 kV DC	2.50 MW	98.9 %	[1]
Honeywell	WFSM	0.60 kV DC	1.00 MW	97.0 %	[116]
GE	RM	0.27 kV DC	0.25 MW	93.1 %	[162]

In Table 3, the Mark 1 prototype is compared to competing machine types. It can be seen that the voltage level is correlating with the power rating of the machines. It is as expected that the PMM generator has the highest efficiency, but the WFSM has quite high efficiency as well. It shows that the competition is a close race. The efficiency saves fuel and cut emissions. NASA's generator efficiency requirements for future aircraft have been specified to be 99.3% [167]. However, there are other issues that must be addressed as well, such as weight, safety and reliability concerns.

2) MACHINE SPEED AND POWER DENSITY REQUIREMENTS

When it comes to commercial aircraft, the trend is clear. The aircraft Boeing B787 from 2009, is the most electrified MEA solution and it uses WFSMs as the selected solution for its 250 kW starter-generator (power density of 2.5 kW/kg power). It is well known that the WFSM is an attractive topology for large aerospace generators. It appreciates high trustworthiness and intrinsic security with a fail-safe and adjustable excitation. The WFSM can operate with unity power factor for all speeds when the excitation system handles the flux management (excitation power is generally around 1-2% of nominal rating). However, challenges in achieving higher feasible maximum speeds limit the theoretical power density potential. In fact, the main rating of the AEGART S/G system is 32 krpm, which outperforms the WFSM in terms of maximum speed [55]. However, there is still significant research going on for WFSMs, especially on excitation systems and its related control implementations to include electric starting capability. Moreover, the Honeywell Future Aerospace demonstrator for WFSM has been shown to achieve a power density of 7.9 kW/kg at 19 krpm [116] with a total power of 1 MW. This is an auxiliary power unit (APU), not directly customized for propulsion. By solving major mechanical challenges related to high-speed operation, the WFSM will continue its existence in aircraft applications in the future as well. The WFSM technology will be less sensitive to major breakthroughs in the reliability of PEC interfaces.

At the present technology stage, the Mark 1 2.5 MW PMM has not been optimized for weight. The potential for the next Mark 2 prototype is promising. In fact, the PMM appears to be a competitive solution to improve power density. The mentioned AEGART prototype announced 16 kW/kg power density for its high-speed PMM technology combined with 4 kW/kg for the PEC interface [55]. In comparison, a recently reported RM technology achieves only about 1.27 kW/kg [77], i.e. a 92% lower power density. It is generally recognized that ultra-high-speed design would be needed to take full advantage of the RM power density potential. In general, RM performances is somewhat related to behaviours of IMs. Both topologies generate relatively higher kVA/kW ratios since their stator armatures have to induce the main magnetic field to catalyze in their operation.

3) SUPERCONDUCTING MATERIALS

In enhancing the aeroplane fuel efficiency further, it is perceived that the power density must climb towards 30 kW/kg for electrical machines. New technologies must be under consideration as well, in order to get this massive improvement. Since its discovery in 1987, superconducting materials have not made a commercial breakthrough in electrical machine applications [186]. Although superconducting machines have been successfully demonstrated [187], large-scale commercial success is missing. Superconducting machines embed materials that can handle massive amounts of currents with no resistance. As a result, high currents can flow in armature windings without dissipating heat. It enables smaller machines, i.e., up to a third of the volume and the mass. Even superconducting WFSMs (both stator and rotor) has been shown to have 24% less weight than a corresponding PMM [188]. Since superconducting solutions is still a wide-open research topic, it does not seem to be always clear whether the very high reported power densities do account for the cooling system or not. In this regard, a big challenge is introduced in the optimization of cryocoolers' specific mass (kg/kW mass over input power required) to meet the specific power requirement of the whole system, i.e., superconducting machine + cryocooler. [189]. The future success of superconducting solutions is left for future investigations.

4) NEEDED DEVELOPMENTS FOR MACHINES AND PECs

This paper highlights that significant advancements are currently occurring for PMMs in aerospace applications. However, the alternative competitors explored in this survey are still relevant due to the issues regarding failure tolerances, trustworthiness and inherent security. Current methods intend to optimize both electrical machines and PECs in a combined multi-physics environment [55], in a way to overcome the demerits of the specific machine topology under consideration. For the high-power machines, in general, and S/Gs in particular, future research would take advantage of a heavy focus on the following issues.

1) Ultra-high power density [190] with intensive cooling [67] integrated with PEC.
2) Potentialit for using coreless designs and/or superconducting materials.
3) Improved heat transfer properties using insulation materials with ultra-high thermal conductivity [191] to reduce hot spots.
4) High-temperature solutions (needed for PMMs) with improved heat management of end-windings [192].
5) High-voltage technology for high altitudes in aerospace applications (beyond 3 kV) [42], [193].
6) Efficient and lightweight PECs, based on WBG devices, for loss reduction and ultra-high switching frequency. An increased switching frequency can be required for high-frequency electrical machines [194] with high-speed operation, i.e., fundamental frequency (f) moving toward the kilohertz (kHz) territory, as well as solving challenges for iron-less (or coreless) machines with low inductance. The capability of WBG devices can also be utilized for improving power density by reducing the filtering requirements of PEC interfaces to AC or DC distribution systems. However, WBG-based designs must include careful trade-offs with respect to insulation stress.

TABLE 4. Outline of the electrical machine families for high-power machines and starter-generator topologies.

Machine type	Benefits	Drawbacks	Reference
Wound-field synchronous machines *(WFSMs)*	• Can generate with passive PEC on the stator-side ; • Optimal control through the three variables: I_d, I_q, I_f ; • Inherent de-excitation-related safety ; • Convenient voltage regulation ; • High power factor over a broad speed range ;	• Multi-variable control algorithm complexity; • The additional exciter machine lowers the speed limit; • Complex starting control methodology; • State-of-the-art limits high machine speeds; • Extra exciters compromises overall weight and space;	[68], [114] [135], [136] [139], [140] [168]
Induction machines *(IMs)*	• Wide speed range operation; • Inherently fault-tolerant topology; • Supports high rotor temperatures; • Natural field weakening ability;	• Low power factor at high speed operation; • Burden of magnetizing current on the converter; • Reliable starting mode at lower torque; • Rotor cooling management;	[16], [152] [169]–[171]
Permanent magnet machines *(PMMs)*	• High efficiency (even in flux-weakening mode) ; • Wider operating range for interior magnets topology; • High speed ability & power density; • High power factor over a relatively broad speed envelope; • Compact design with low mass;	• Hazardous voltage if flux-weakening fails; • Demands auxiliary protection system for security; • Risk of irreversible demagnetization; • Magnets retention system needed for high speeds; • Does not include a foolproof de-excitation system;	[55] [69], [70] [155] [172]–[175]
Reluctance machines *(RMs)*	• Suitable for high-speed operation; • Fault-tolerance in harsh environments; • Ease of manufacture with a one-material rotor; • Inherent overcurrent protection; • Expanded torque-speed range in motor mode;	• Inferior efficiency and considerable torque ripple; • High voltage pulsations in generator mode; • Tailored converter design required; • Requires precise rotor position monitoring; • Depends on accurate control algorithms;	[74], [77] [162] [176]–[185]

7) PEC failure investigations including thermal shock expansions, voltage peaks, mechanical stresses and environmental impacts [118]. Reliable PEC is especially important for PMMs and RMs, and further improvements are needed for high-power S/Gs. The impact of the PEC on the machine lifetime and trustworthiness must also be emphasized.
8) Safe, fault-tolerant and reliable machines, i.e., high precision manufacturing is needed with low tolerances in safety-critical applications.

VII. CONCLUSION

The prospect of this review article was to give an update on the trends in the research and advancement of high-power machine topologies and starter-generators (S/Gs) in more electric aircraft (MEA), also considering the cutting-edge developments in hybrid-electric aircraft (HEA). The intention was to provide a comprehensive overview of the different perspectives of the subsystems involved, which impacts the speed of take-off for the MEA paradigm and the electrification of aviation in general, with a main emphasis on the power generation systems. In summary, the key points of the different power electronic interfaces and machine families are highlighted in Tables 1 and 4, respectively.

In designing optimal overall solutions, sub-optimization alone is not going to be the only way to achieve better MEA designs because of the many conflicting ambitions in the different subsystems. For instance, less use of active PEC interfaces could, in the short term increase reliability while in the long term, reduce functionality. Moreover, mature technologies (e.g. WFSMs) performs with a high level of safety and reliability, but further advancements in power density is a challenging issue to be dealt with. Therefore, other potential solutions are assessed in parallel, such as the PMM topology. The initial results of the Mark 1 2.5 MW PMM generator generator are promising.

In dealing with the number of interrelated issues highlighted in this paper, a call for new design methods with a holistic approach is advised for future developments beyond the state-of-the-art. Tools for the optimal and overall design of multi-physical systems will accelerate the take-off of the MEA initiative by decreasing the time of conception and the number of prototypes before the final product can reach a certain technology qualification level. The required tools must couple thermal, electrical and magnetic performances in its simulation modules to acquire accurate behaviour. The various physical components and the system overall is then treated as a whole, to optimize for the best overall solution, obtaining a trade-off between the output performances and the reliability levels. The possible new pathways and the multitude of possibilities will emerge from this global approach in pace with the ongoing advancements in the different parts of the systems, including the grid, the machine-side inverters and the machine itself.

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