Challenges and Opportunities for Wound Field Synchronous Generators in Future More Electric Aircraft

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***Abstract* – Electrical machines and drives keep moving away from traditional technologies such as brushed machines and wound field machines towards lighter, 'easier to maintain' machines. A very interesting aspect is that certain transport applications, especially the aerospace industry, still favour the classical wound field machine for its main generating system such as the Boeing 787.**

This paper focuses on investigating this particular trend by presenting a detailed overview of historical power generation systems on aircraft. This paper compares the current state of the art of wound field machines with other generator families. The results of this analysis are then projected into the needs of the electrical power generation and distribution system on aircraft. While power density is a major objective for any aerospace application, however the extra benefits associated with wound field systems are still essential in modern aircraft.

The paper then focuses on the main challenges for improving power density of wound field machines. Recommendations, opportunities and improvements related to wound field machines are discussed. In conclusion, if robust designs for higher speed wound field generators were consolidated, it would be very probable that these classical machines might still be implemented on future MEA platforms.

***Index Terms*—Salient-Pole Synchronous Generators, Wound field machines, Permanent Magnet Generators, Switched reluctance machines, More Electric Aircraft.**

I. INTRODUCTION

As the aircraft industry keeps moving towards greener and more electric solutions [1] [2], electrical power generation on aircraft will continue to play an ever-increasing role. The push towards 'bigger and better' power generation systems onboard today becomes more and more important. However, the truth is that on board power systems have been continuously evolving since the start of manned flight.

Before the 1950s, electric loads on aircraft were limited to very basic functions such as flight controls, lighting and heating. To accomplish these tasks, small DC generators were typically enough [3]. After the 1950s, more electric loads, such as de-icing, environmental control and flight control, etc. started to be introduced, resulting in heavier power requirements.

Fig. 1 summarizes the evolution of the most important power systems which have been implemented on aircraft since the 1950. As can be observed in Fig. 1, various power system configurations have been proposed and investigated to accommodate the progressively increasing electric loads. Early configurations included high voltage DC systems, such as the 112V DC bus adopted by the Vickers Valliant V Bomber [4]. Later on, DC distribution systems started to be replaced by AC systems coupled with constant speed drives (CSDs), thus resulting in constant speed-constant frequency (CSCF i.e. 400Hz) distribution systems. Such CSDs were available in 2 variants, namely axial gear differentials (AGDs) in the early 1960s [5] or integrated drive generators (IDG) [5]. Typical examples include the DC-9 in 1963 [5] and the Boeing 777 which is still in operation today [6].

The CSCF system is the common choice for more than 60 years. However, the limitation of such a system related to the required fixed 'input' speed implying the need for heavy mechanical gearboxes [7], nudged the aircraft industry to start looking towards more feasible and modern alternatives. Thus, the era of the variable speed, power distribution system was launched and today, such variable speed-variable frequency (VSVF) system can be found on various modern aircraft such as the Boeing 787 and the Airbus A380.

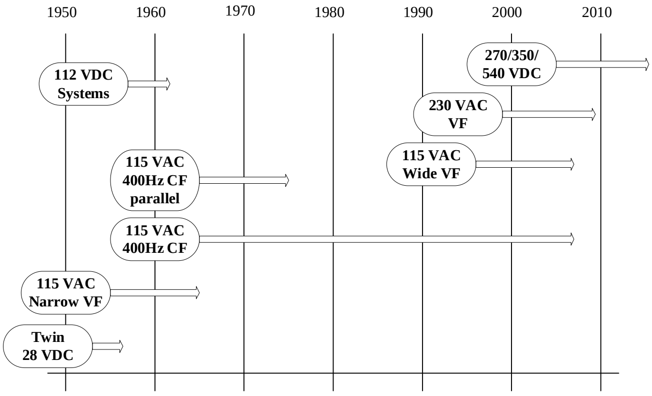

Fig. 1. Evolution of electrical power systems. [3]

In all the above, a component that is critical for any power generation and distribution system is the electrical machine

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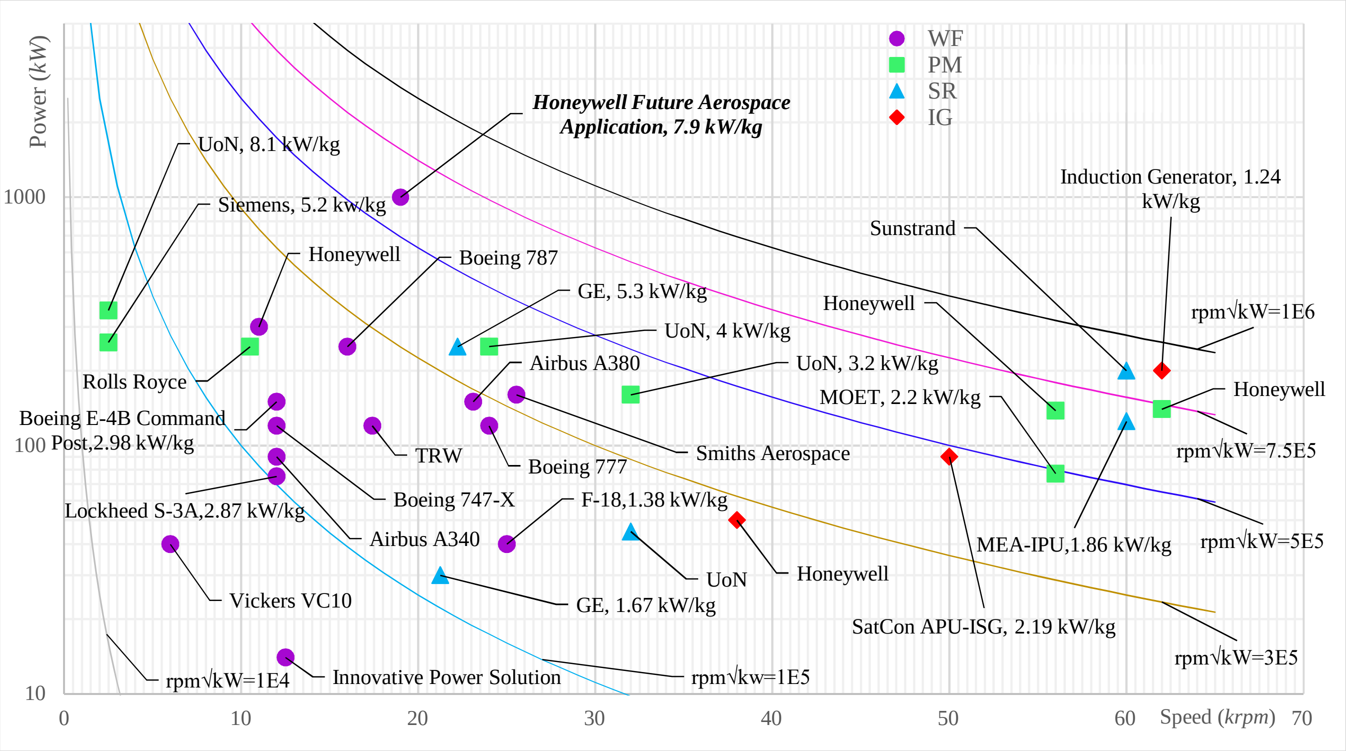

Fig. 2. Generators designed and tested or implemented for aircraft power generation systems.

responsible for generating the demanded power on board. Various types of electrical machines have been proposed and implemented throughout the years, but the most commonly and extensively used machine is and remains the wound field synchronous generator (WFSG) [8]. The WFSG is a consolidated, well-proven and reliable technology that has served as the main on board energy source for decades. Its key features include:

- Complete field controllability, a feature which is highly desirable for the aviation industry, as it gives an excellent fault mitigation capability.
- Very simple and practically-autonomous control schemes are required for operation.
- High flexibility in terms of general scheme and architecture configuration, leading to various operations being achieved, e.g. starter generator, three stage starter-generator, etc.

Even considering these advantages, the advances in power electronics (PE) and computational capabilities of the last decades enabled the toughest competition among WFSG, switched reluctance (SR) and permanent magnet (PM) machines.

Riding on the step-changing advances in new materials such as wide band-gap semiconductors [9], new packaging and manufacturing approaches and thermal management techniques, the field of PE is playing an ever-increasing role in the aviation industry [10] [11]. This in turn has allowed the PM machine to become a feasible and attractive contender for all areas of the industry.

With the assistance of PE, SR and PM generators become potential candidates for power generation on modern aircraft. The higher power density and efficiency offered by PM generators and the inherently robust nature of SR machines are very attractive features. These are therefore opening up debates about their supposed superiority over the WFSG for power generation.

On the other hand, while both technologies have been extensively proposed in literature [12] [13], however no known commercial aircraft has until now implemented PM or SR generators as the main electrical source, despite the perceived advantages offered by these technologies.

In light of all the above, this paper aims to investigate and report on the real situation with power generation machines seen today in the aerospace field. To do this, this paper first compiles a relatively detailed literature review of the various alternators and their associated systems found on aircraft. This is visually represented by one of the major outcomes of this paper, which is a comprehensive figure of all known generating aerospace machines. The paper then analyses more deeply a small number of the better performing machine systems, identified in the review process. The identified WFSG systems for aircraft applications are highlighted. All this is then projected into a discussion about the role of this machine in the aircraft industry and how this classical but ever-evolving machine is and will be still relevant to the modern aircraft industry in the near future.

II. Current Status of WFSGs Compared with PM, SR and Induction Generators as Individual Components

Despite the advantages, mentioned in section I, offered by the WFSG, SR and PM generators are also very appealing to the aviation industry and research institutes [14] [15] due to their robust high-speed characteristics, high power densities and system efficiencies [16] [17]. This section investigates the status of aircraft primary power generation methods implemented on aircraft by studying various topologies implemented or designed as engine driven main bus generators. The results are compiled on a dynamic speed map. The parameter termed as dynamic speed can be defined as a value that is able to define the “goodness”, in terms of power capability and operational robustness of rotating bodies. It was first proposed in [18] and its unity of measure “rpm √ kW” is its defining parameter, used to evaluate the severity of dynamic issues such as critical speed, peripheral speed and stress [18].

A. State of the art – WFSGs

Considering that light-weighting is always a critical key factor in the aviation industry, then an appropriate parameter for power density improvements is the machine speed. Fig. 2 [3, 5, 19-37] collects the dynamic speed information of four types of generator topologies, aimed for aircraft main power generation, from which the power density (*kW/kg*) can be easily derived.

By comparing machines at a similar dynamic speed (e.g. $rpm\sqrt{kW}$ =100,000) in Fig. 2, the PM machine developed by University of Nottingham (UoN) achieves the highest power density (8.1*kW/kg*) among all the candidates.

From Fig. 2, one can easily observe how classical WFSGs are typically found in the lower speed ranges of approximately 10 to 25 krpm. However, it can also be easily observed how the top part of Fig. 2 is dominated by PM machine designs [28] [38]. In addition, on the right-hand side of Fig. 2 (i.e. the higher speed ranges) is the realm of the one-body rotor machines such as SR machines and IMs [25] [29]. In the 250*kW* range, two-channel SR generators developed by GE demonstrate a competitive power density, even against a modern advanced Siemens machine [37].

The main outcome of Fig. 2 is that it allows to visually perceive that for high power densities, electrical machine manufactures are actually opting to investigate newer configurations such as PM machines. High performance and highly optimized SR machines are also an interesting concept. In Fig. 2, PM machines, SR generators and induction generator (IG) families can be observed to cover a significant amount of the high speed region, where the design and manufacturing of any machine is particularly challenging. In contrast, WFSGs are typically found for lower speed regions. The inherent difficulty of implementing WFSGs for higher speeds and by progression their lower power densities than PM or SR generators can thus be perceived.

It is the potential for higher power densities (through higher speeds) that makes PM machines and potentially SR machines so attractive for the aviation industry. A comprehensive study in [39] has shown that power density does not always increase with an increase of machine speeds. High speeds usually result in high frequency iron losses and ac copper losses which have a negative impact on further reduction of machine weight and size. It must be clearly stated that till now, it is still ‘just’ a research and development interest. The only known aircraft that implements SR generators is the F-22 [3] in 2001. No commercial aircraft has so far been equipped with any of the more ‘fancy’ machines. Even the most more-electric of them all, i.e. the Boeing 787 in 2009, has WFSGs as main engine driven starter generators. This clearly indicates that while weight is so important in the aerospace agenda, however there are other important factors, such as the direct control of the field option, the small component count. etc., which still prompt aircraft manufactures to choose the WFSG for power generation in aircraft.

B. Power density for past WFSGs and the state of the art WFSGs today

In the world of electrical machines, speed is proportional to power, so with some generalization and by considering a few assumptions, then one can safely argue that higher speeds practically means higher power for a given torque and therefore higher power densities. The highest speed WFSG that could be found in the available literature was in [40], which reports a generator tested up to 28*krpm* without failure in 1981. This machine was reported to achieve a power density at this speed of 2.47*kW/kg*.

While this is the best figure found in literature, advancements in design tools, new materials and new manufacturing techniques can result in much better performance and higher speed WFSGs. Even so, no evidence exists so far that any implemented WFSG has achieved a dramatic increase in power density that makes it able to compete against a PM machine.

It is however very important to mention one of the most exciting WFSG ever unveiled. In 2013, Honeywell demonstrated its dual three phase aerospace WFSG prototype that is claimed to be basically ‘playing in the same league’ as the most advanced PM and SR generators with an overall power density of 7.9 *kW/kg* [36]. Could this be the real major breakthrough for WFSGs?

C. Conclusive remark

The unveiling of Honeywell’s revolutionary WFSG closed the gap in terms of high power density between PM generators and WFSGs, stepping up competition among WFSG, PM and SR platforms, especially for future MEA applications. Apart from the power density, WFSGs still possess numerous advantages compared with PM and SR generators, such as easy control of the field, no need for active PEs, etc. Compared with PM and SR generators, the advantages for WFSGs mentioned above contribute to less components count, no permanent excitation field, thus more reliable systems favored by the aviation industry. Therefore, these will be considered in light of the system level design for WFSGs.

III. FUTURE POWER DISTRIBUTION SYSTEMS ON AIRCRAFT AND FUTURE IMPLEMENTED POWER GENERATION METHODS

Although the weight minimisation is always the main objective for the aviation industry, other factors such as safety, reliability, availability, etc. are also essential. Thus, apart from the generator itself, the selection of the power generation method on board is also driven by the system architecture and its associated efficiency and reliability. This section will discuss different power generation architectures on board and associated aspects, such as efficiency and reliability challenges [41]. The likely future power generation methods will also be mentioned in this section.

A. Constant speed power generation

Constant speed power generation systems include a CSD between a turbine or a turboprop engine [8] and a generator for conventional aircraft as shown in Fig. 3. Modern aircraft adopt AC systems operating at 115V and 400 Hz.

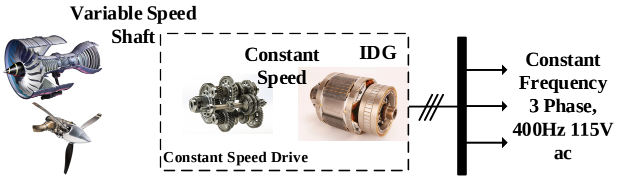

Fig. 3. Constant speed constant frequency system.

The primary AC power systems on board are three phase configurations with a neutral terminal available [42]. The 4-wire layout allows single-phase line-to-neutral, single-phase line-to-line or three-phase loads to be connected to the power distribution system. This flexibility creates its own downside of having unbalanced load even though aircraft loads are designed to be balanced. The unbalanced loaded conditions result from duty cycles and schedule of different loads.

B. *Variable speed power generation*

Variable speed power generation systems are implemented on Boeing 787 and Airbus A380. These eliminate the need of a CSD due to mechanical wear out [40] coupled between a turbine and a generator, as shown in Fig. 4.

Variable speed power generation can be achieved adopting one of the four options reported in Fig. 4. The first variable speed constant frequency (VSCF) option comprises cycloconverters directly coupled to the outputs terminals of the generator [43]. The F-18 is an example adopting this system [44] which requires that all the electric power is processed by a PE converter (PEC) connected to the main bus bar. Another VSCF option is the DC link method [45] implemented on the Boeing 777 as backup generator [6], which has a diode bridge rectifier, DC link capacitors and an inverter. Both these methods produce constant voltage and constant frequency output. The third VSVF system includes bus bars directly connected to the terminals of the generator, which is widely adopted by the latest power distribution architectures implemented onto Airbus A380 and Boeing 787 [8]. The last method is a high voltage DC distribution system, which is a concept raised more than 60 years ago [46] but studied and investigated only recently [47] [48]. However, apart from F-22 and F35, no known civilian aircraft implements such type of system [3] [49].

C. *Advantages of variable speed systems*

The Boeing 787 is considered today as the most advanced commercial MEA that exists from a technological point of view implementing VSVF systems. It replaces the consumption of pneumatic power with electric power (no-bleed systems) [50]. This increases the on board load up to $1MW$ and requires a generator with higher capacity (i.e. 250 kVA) [21] compared with generators (i.e. 150 kVA) [51] installed on A380.

The system architecture for Boeing 787 has offered significant amount of improvements such as a 50% reduction of mechanical system complexities compared to the Boeing 767 (constant speed power systems) [52], since no bleed systems are implemented. At the same time, the mean time between failures (MTBF) value, defined as in (1), has a 300% increment for the Boeing 787 compared to the Boeing 767. This changes the aircraft availability, which makes the Boeing 787 highly preferable for revenue services.

$$MTBF = \frac{\sum(start\ \ of\ \ downtime - start\ \ of\ \ uptime)}{Number\ \ of\ \ failures} \quad (1)$$

The advantages gained by implementing MEA (variable speed power systems) and proven by the Boeing 787 indicate that future aircraft adopting MEA concepts are the way forward [53]. Typical examples of this future trend of MEA [54] are the Boeing 737 next generation auxiliary power unit (APU) [52] and the Airbus A350 which adopts VSVF systems as their power generation methods. Although four different types of power generation and distribution systems do exist, VSVF and DC systems are considered the most promising options for future MEA.

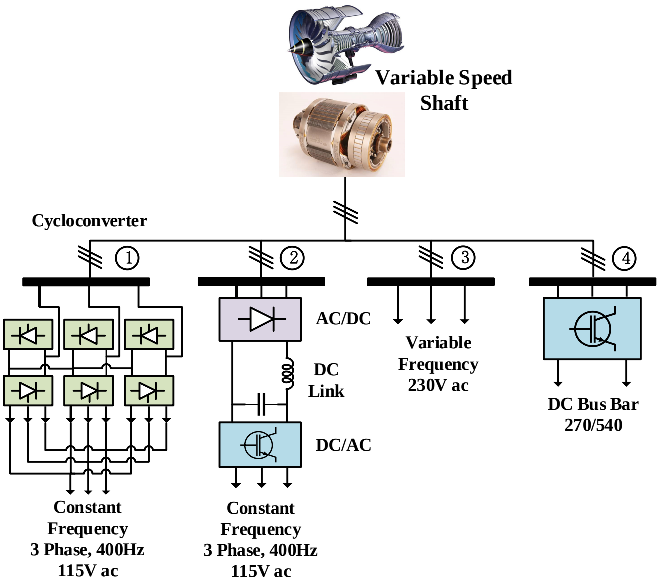

Fig. 4. Variable speed power generation.

D. *Efficiency of the overall system*

The overall efficiency is one of the critical factors to evaluate the performance of an electrical system. Table 1 compares various generator technologies under different power system architecture. Typically WFSGs demonstrate the lowest efficiency among all type of generators. In general, it is clear that PM generators have the highest efficiency compared with WFSG and SR generators. The efficiency of SR generators is better than WFSGs but lower than PM generators in general. However, it is very important to note that the lately introduced Honeywell mega-watt class WFSG [36] features an almost comparable system efficiency of around 97%.

Table 1: efficiency comparison for various generators found in the literature

Source	Topologies	Power system	Rating (KVA)	Effi.	Ref.
F-18	WFSG	VSCF	40	78%-80%	[44]
V22	WFSG	CSCF& VSVF	40 50	74% 80%	[55]
Honeywell	WFSG	600VDC	1000	97%	[36]
GE	SR	270VDC	250	90.8% - 93.1%	[22]
UoN	PM	270VDC	45	95%	[28]

E. *Reliability concerns*

Future MEA aircraft will most likely adopt VSVF or DC power distribution systems as the primary buses. This requires all three types of generators considered in this paper to install a fully or overrated PECs to condition the output power. The fully rated power conditioning device not only contributes to the overall weight of the power generation system, but also raises issues related to reliability, such as component count, which is a major concern for aviation industry [56].

1) *PECs implemented on the main bus power distribution*

PECs are subject to 4 failure factors: thermal shock, over voltage, mechanical forces and environmental effects [57]. Till now the failure mechanisms due to those 4 factors are still not comprehensively understood. Thus, this situation results in unpredictable lifetime of PECs implemented on the primary bus bars. Power loss on the main bus bars would be an unacceptable and catastrophic failure for aircraft.

In [58], an authoritative survey on reliability issues for PE systems designed for applications such as variable speed drives, electric vehicles, renewable energy systems and MEA is presented. This was conducted by consultation of various leading researchers in the field of reliability for PE systems. The key aim of this survey was to investigate the industrial challenges on reliability issues for future application specific PE systems.

The 87% of the consulted industry experts believe that the current focus and quantity of research on reliability of PECs are insufficient. Semiconductor modules and capacitors are aspects of PECs subject to most failures [58] [59]. Nearly the 66% of the specialists agree that reliability of power modules and capacitors is imperative [58]. Due to the emerging demands for high reliable PECs from industry, an increasing research effort is being conducted with the aim to further the understanding of physical failure mechanisms, online monitoring and lifetime prediction techniques [60]. However, more than half of the industry participants considered that current research efforts are not enough for aircraft industry [58].

2) *Reliability issues for diode bridges*

WFSGs are already implemented for VSVF power distribution systems (the Boeing 787). As for DC power distribution systems, WFSGs can be equipped with a diode rectifier or PECs to provide constant DC voltage on the primary bus. It is reported that diodes only has 25% of the failure rate compared to active switches [57]. Therefore, three phase diode bridges are more likely to be implemented on the main bus for aircraft power systems compared with active rectifiers.

3) *Fault conditions for PM generators*

According to MIL-STD-704F, the loss of one of the phases should not cause hazards or damage to utilization equipment. In addition, a main challenge with PM machines directly connected to prime movers is the risk associated with turn to turn short circuit fault. This has the risk of an uncontrollable fault sequence, which might result in damage to the PEC itself and to the DC link capacitor [34]. To address this issue, fault-tolerant PM machines developed by Honeywell [61] and very advanced fault detection and health monitoring techniques [62] are also investigated with promising outcomes being achieved. However, these techniques do not actually clear the fault condition but are only able to control the fault when this is within a limited range. Therefore, turn to turn short circuit fault is a risk for PM generators not passing the aviation electrical power system standard. High speed PM generators are often equipped with sleeves made of carbon fiber or Inconel [63] which is subject to failure if not well designed.

4) *Conclusive remarks*

At system level, PECs that make PM and SR generators competitive candidates in MEA power generator systems are also the bottleneck for PM and SR generators to be implemented soon on commercial flights at current stage. This is due to the fact that justifying the reliability of PECs might take a relative long time. In contrast, WFSGs are much more flexible in terms of adapting VSVF or DC power systems without the assistance of PECs. Meanwhile, the efficiency for Honeywell's WFSG is dramatically increased.

The primary buses on commercial aircraft must have the highest reliability compared with other level of distribution buses. Therefore, it is impractical to implement PECs on the primary buses of commercial aircraft without a comprehensive understanding of the reliability and lifetime of PECs. Therefore, the implementation of PM and SR generators on DC primary distribution buses would have to wait until the reliability of PECs are justified. As for VSVF distribution systems, neither one of PM or SR generators are able to provide constant voltage variable frequency output without PECs.

In conclusion, PECs prevent PM and SR generators to be implemented as main bus generators on MEA at the moment. Meanwhile, WFSGs can be integrated into VSVF and DC systems by adopting nothing or diode rectifiers which is much more reliable than PECs. Therefore, WFSGs will have a higher chance to be implemented for future MEA before the reliability issue for PECs are justified compared with PM and SR generators [64] at system level considering aspects such as efficiency and reliability.

IV. CHALLENGES FOR WFSGS ACHIEVING STATE OF THE ART PERFORMANCE

The power density of the highest performance WFSG ever-recorded, namely the one demonstrated by Honeywell [36], is very competitive against that of PM and SR generators as individual components. While very little information is available on how Honeywell's state of the art generator is achieved, it is very clear that, to obtain that level of power density, then all the aspects of the WFSG must be pushed beyond the standard boundaries. This requires a full understanding of each individual component in a WFSG from electromagnetic, thermal and mechanical aspects. This section therefore re-calls the basic structure and make-up of a WFSG including how all its components and sub-assemblies fit together. Finally, challenges arising from electromagnetic, thermal and mechanical aspects are identified.

A. *Background for WFSGs*

Fig. 5 depicts a schematic of the most common configuration of a WFSG (i.e. 3 machines on the same shaft) system for aviation industry. Its system comprises a WFSG, a main exciter, a permanent magnet generator (PMG) and an automatic voltage regulator (AVR) [65] [66]. The AVR controls the WFSG output voltage by feeding the exciter field winding. The exciter armature winding, in turn, is connected to a rotating diode rectifier whose output DC terminals are directly linked to the main alternator field winding. The PMG ensures a reliable power supply for the AVR.

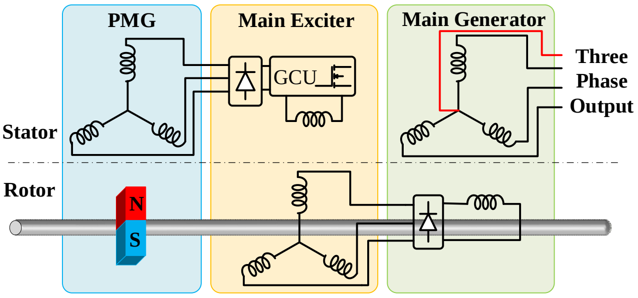

Fig. 5. Schematics of a 3-stage system comprising the PMG, the exciter, the diode rectifier and the WFSG.

Fig. 6 presents a typical rotor structure of a WFSG. Major challenges for WFSGs designed for aviation industry involve thermal [67] [68] and mechanical aspects. In addition, in the context of aerospace applications, where the power-to-weight ratio is a critical factor, the traditional machine limits need to be improved and this is usually done by addressing materials [69], cooling capabilities [70] [71] and structural mechanical design and analysis [72].

Fig. 6. Rotor structure of a typical WFSG.

B. Thermal challenges for WFSGs implemented for variable speed systems

Effective cooling methods can improve the weight reduction for WFSGs [73]. WFSGs have two major heat sources on the rotor onto which effective cooling systems are difficult to implement: the rotor field winding and the damper cage.

The field winding on the rotor is used to provide the excitation field for the main alternator. The loss from this winding is of course dissipated as heat. Considering the difficulty of heat extraction from a rotating body, this can become a limit on the actual size of the rotor.

The electrical frequency for WFSGs implemented for variable speed systems is typically 360 - 800*Hz*. This results in higher order harmonics in the air gap, thus, induced high frequency currents in the damper cage are observable. In the example of Fig. 6, the damper cage is embedded into the inter-pole gaps and into the rotor slots. In addition, the high electric frequency of the magnetic field also results in high losses and temperature increase in the magnetic core and stator windings [74].

In general, forced air and oil cooling are commonly seen on aircraft cooling systems. Oil cooled generators are preferable in CSCF system since oil circuits are already available within the mechanical gearbox or IDGs. However, with variable frequency generators, no existing oil cooling units are available. This leads to the need of extra cooling circuits, pumps and gauges directly mounted onto the WFSG, which contributes to weight and complexity increase of the overall system. In [40], it is reported that the cooling oil might not even be available to a generator at certain flight mission cycle if shared lubrication oil is implemented as a system cooling agent. Therefore, an important potential challenge for the design of variable frequency systems is the trade-off needed to maximize power density and minimize system complexity and weight, both for generators and periphery accessories.

C. Mechanical challenges for WFSGs implemented for variable speed systems

In Fig. 2, the typical operating speed range for WFSGs is from 10*krpm* to 25*krpm*. High speeds with large power demands imply high peripheral speeds at the rotor surfaces, which can easily cause mechanical fatigue or damage.

Apart from speed and volume, an inherent mechanical challenge is that WFSGs have a field winding wound on the salient poles as shown in Fig. 6. Besides their electromagnetic functions, pole tips are typically used as mechanical structures to withstand centrifuge forces caused by field windings. Therefore, very high mechanical stress levels can be registered at the rotor bore and pole tips [75].

Another challenging aspect of WFSGs relates to the damper cage which is located on the surface of rotor poles, as depicted in Fig. 6. Hollow structures on the surface of rotor poles designed to accommodate the damper cage potentially weaken the structure of rotor pole at high-speed operation. The thermal expansion of the damping bars may worsen the case to a certain degree.

In addition, due to the mechanical vibrations and centrifuge forces, field windings need to be retained by extra mechanical structures such as retaining rings for end windings [5] [76] as indicated in Fig. 6. Equation (2) can be used to roughly estimate the highest stress (τ_{mech}) found on a rotor core. C' is the Poisson's ratio related parameter; ρ is the mass density of the core materials; r is the radius of the machine; Ω is the angular speed.

$$\tau_{mech} = C'\rho r^2 \Omega^2 \tag{2}$$

D. Other challenges associated with variable speed systems for WFSGs

Another important challenge of variable frequency generators is whether starting capability of turbine is required, such as for the Boeing 787, where electric starting capabilities for WFSGs are necessary for successful implementation of the Boeing 787's 'no-bleed' system. This requires the field windings to be fed by a standstill main exciter. The key challenge for this auxiliary machine during system start-up is to supply the field winding with adequate DC currents [77] without oversizing. Therefore, the key objective function here is the maximization of *kVA* input to *kW* output ratio.

E. Summarizing remarks

In sections II.B and II.C, the challenges associated with WFSGs at machine and at system-level have been highlighted. The key challenges of such a system can be summarized as follows:

1. Mechanical aspects:
    a) Stress concentration at the corner of rotor bore and of rotor pole shoe.
    b) Stress concentration on the rotor iron bridges between damper bars and main air gap.
    c) Structures required preventing end winding from falling apart.
    d) Structural failures associated with rotating diodes.
    e) Rotor dynamic issues and vibrations.
2. Thermal aspects:
    a) Effective stator and, most critically, rotor coil cooling methods.
    b) Iron losses both in stator and rotor cores.
    c) AC losses resulting from stator coils.
    d) Selection of cooling type.
3. Power quality aspects:
    a) Stringent requirements for AC power systems [78] [79].
    b) Ripple [80] requirements for DC power system.
4. Extra functionalities:
    a) Exciter design and criticalities at start-up.
    b) *kVA* input to *kW* output ratio during starting.

The main important point to consider here is that for real breakthrough in terms of WFSG performance, these challenges cannot be considered individually. A step change in terms of performance would require interlinked multi-disciplinary approaches. Novel modelling and design techniques that can help addressing these challenges are required.

V. OPPORTUNITIES FOR WFSGS TO ACHIEVE STATE OF THE ART PERFORMANCE

In the previous section, the challenges for designing WFSGs were identified. This section will discuss what has been 'tried' to achieve optimal performance by addressing the challenges raised above.

A. Thermal aspects – structures associated with WFSGs

In a VSVF system, WFSGs equipped with damper cages [74, 81, 82] are required due to following reasons [83] [84].

1) Suppressing hunting oscillation.
2) Damping oscillations resulting from short circuits or switching.
3) Preventing voltage distortions caused by unbalanced loads.
4) Balancing the terminal voltage due to unbalanced loads.

A recent study [84] reveals that damper cage design has influence on mutually affecting parameters, namely losses and power quality. For AC generation and distribution systems, conventional techniques at machine level for reducing the total harmonic distortion (THD) include the following three aspects [85] [86]:

1) Pole shaping.
2) Short pitching.
3) Skewing of stator cores.

The THD of any generic function *a(t)* is defined as in (3), where A_n is the rms value of the n-th harmonic and A_1 is that of the fundamental component. The THD levels can be maintained within the requirements by adopting the conventional techniques listed above, but usually at the cost of reducing the fundamental component [79]. To compensate for such side effects, the field current is boosted, however, rotor cooling can become ever more challenging.

$$THD = \frac{\sqrt{\sum_{n=2}^{\infty} A_n^2}}{A_1} \tag{3}$$

An advanced technique named damper cage modulation has recently shown a great potential in improving the output waveforms' quality, minimizing damper cage losses [84] and in enabling the removal of stator skew [81], without compromising the fundamental components of the output quantities, thus no boosting of the field current is necessary.

Apart from VSVF systems, all the systems shown in Fig. 4 need PE on board to condition the output power, which decouples the bus bar voltage from the generator outputs [44] [87]. Therefore, the unbalanced loads that are decoupled from the output terminals of WFSGs will potentially no longer be an issue and the need for damper cages will also be removed. Salient-pole WFSGs with no damper cages offer several advantages both mechanically and thermally.

In [88], the optimal losses distribution is as equally important as losses reduction from electromagnetic design perspective. With damper cages eliminated from WFSGs, one of the heat sources especially acting during any unbalanced operation is removed from the rotor. This leads to an improved thermal management of the machine.

Advanced harmonics or losses reduction methods also exists using active devices such as active power filter [89], active rectifier [90] for WFSGs. However, as mentioned earlier, the reliability for active devices are still major concerns for aviation industry. Therefore, those advanced techniques may not be implemented on aircraft soon.

Aerospace-oriented WFSGs often adopt oil-spray cooling as their effective cooling methods [91] [92]. However, to bring the power density of WFSGs to a different level, thorough studies of spray cooling methods are required.

B. Mechanical aspects - materials

One of the key factors limiting rotating machines to achieve high peripheral speeds is the relatively low yield strength (460MPa) featured by the common ferromagnetic materials typically employed for the rotor core. Increased power demand for MEA requires WFSGs to be designed with larger rotor radii. This leads to the implementation of high-grade materials such as cobalt iron.

Commonly known developments in cobalt iron (CoFe) materials achieve yield strengths in the range of 800MPa (Vacodur S Plus). Other recently developed materials like JNEX900, JNHF600 [69] and 2605SA1 [93] are all having relatively high yield strength. The lately introduced material 35HXT780T can achieve a maximum yield strength of 860MPa [94]. Far more advancements in materials' technologies are expected in the future.

High strength material may address the challenges in salient-pole WFSGs related to local stress concentration raised in the previous section.

Apart from the local stress concentration, end windings deformations due to centrifugal forces must also be considered. WFSGs implemented on board use retaining metallic rings to prevent rotor end windings from bending outwards touching the stator [76]. Carbon fibre or high strength sleeves can be used for retaining the field coils in WFSGs as shown in Fig. 6, as similarly done for the PMs in PM machines [95] [96].

C. Thermal aspects - materials

Variable speed power generation concepts increase the maximum operating frequency for WFSGs up to 800 Hz. Therefore, high-speed power dense generators suffer from high surface losses due to high frequency harmonics. CoFe materials present the advantage of achieving high magnetic loading but an associated downside is that they feature high hysteresis and eddy current losses. In contrast, special silicon steels have relative low magnetic loading but significant lower losses. Studies elaborate that the power density of a PM starter generator adopting CoFe (high core losses material) and high silicon content steels (low core losses materials) remains similar at relatively high-speed level [97] [98]. Therefore, low losses materials are potential candidates for high power density and cost effective WFSGs for high-speed applications.

High thermal conductive (230W/mK) ceramic materials are widely investigated by material scientists [99]. Ceramic materials also feature high dielectric strength allowing it to be considered as insulation materials in electric machines. Therefore, adopting ceramic materials can potentially reduce the thermal resistance from a heat source to ambient.

D. Extra functionalities

Emergent MEA concepts require WFSGs to start the turbine. This extra functionality introduces challenges in the design of the exciters of such generators. Various methods have been proposed for new topologies and can be summarized as follows: single phase, dual, three phase and two windings exciters [100-102]. Dual and three phase exciters have demonstrated significant improvements of *kVA* input to *kW* output ratios. This increases the exciter power density, but at the cost of increasing the control complexity. Apart from developing topologies achieving high *kVA* input to *kW* output ratio exciter, advanced control algorithm are developed by Honeywell to achieve the same goal [103].

Investigations on how to improve the generation system efficiency by acting on the exciters of WFSGs have been described in [66] [104]. Capacitive couplings and rotating transformers are considered as alternatives replacing traditional exciters due to less speed dependent and efficient power transfer features [105]. A capacitive coupled SG via journal bearings has demonstrated weight, volume and efficiency improvements of 80%, 54% and 31% respectively, compared with an existing exciter [106]. Therefore, capacitive power transfer has great potential to improve system weight and efficiency with the potential advancements in materials science in the future.

VI. CONCLUSION

This paper has tried to investigate why the aerospace industry still favours the classical WFSG as the main source of electrical power generation on board aircraft. Following a detailed but wide review of existing materials, this paper has shown how the direct controllability of the field for a WFSG, its robustness and the inherent reliability bottleneck of more advanced machine (PM, SR) drive families have all contributed to this trend.

Following this, the paper then focused on highlighting the main challenge of such WFSG systems, i.e. their inherent low, system-level power density. The traditionally low operating speeds associated with WFSGs need to be increased by significant orders, even when considering the mechanical challenges associated with such rotating field systems. The current state of the art WFSG that exceeds all other systems is the generator developed and demonstrated by Honeywell that can achieve 7.9*kW/kg* at a rotor speed of 19,000 rpm. This demonstrator has shown that by overcoming the mechanical challenges associated with higher speeds, then a WFSG can achieve comparable power density levels to those coming from more advanced technologies such as PM and SR drives. Combining this improvement in power density with the traditional benefits of wound field systems (controllability, reliability and robustness), then it can be clearly perceived that the WFSG still has a lot to offer even in such harsh and demanding environments such as that of the aerospace industry.

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