Feasibility of a New Ironless-stator Axial Flux Permanent Magnet Machine for Aircraft Electric Propulsion Application

Zhuoran Zhang, senior member, IEEE, Weiwei Geng, member, IEEE, Ye Liu, student member, IEEE, and Chen Wang, student member, IEEE (Invited)

Abstract— With the development of aviation electrification, higher demands for electrical machines are put forward in aircraft electric propulsion systems. The aircraft electric propulsion requirements and propulsion motor features are analyzed in this paper. Comparing with conventional PM machines, ironless stator axial flux permanent magnet (AFPM) machine topologies with Litz wire windings allow designs with higher compactness, lightness and efficiency, which are suitable for high-frequency and high-power density applications. Based on the motor requirements and constraints of aircraft electric propulsion systems, this paper investigates a high-power 1 MW multi-stack ironless stator AFPM machine, which is composed of four 250kW modular motors by stacking in axial. The design guidelines and special attentions are presented, in term of electromagnetic, thermal, and mechanical performance for the high-frequency coils and Halbach-array PM rotor. Finally, an ironless stator AFPM motor is manufactured, tested and evaluated with the consideration of cost and processing cycle. The results show that the output power is up to 53.8kW with 95% efficiency at 9000r/min at this stage. The proposed ironless stator AFPM machine with oil immersed forced cooling proves to be a favorable candidate for application in electric aircraft as propulsion motors.

Index Terms—Axial flux machine, electric aircraft, electric propulsion, ironless stator permanent magnet machine, oil cooling.

I. INTRODUCTION

The concept of aircraft electric propulsion gradually becomes the main melody of aviation industry development. With the fast development of air traffic, the environmental impact of air traffic has caught more and more attention, and aircraft electrical power systems have developed substantially [1]-[3]. NASA has proposed strict goals for fuel consumption, NOx emission and noise for the next three generations of aircraft in shaping its technology roadmaps, namely N+1, N+2 and N+3 [1]. Table I gives these detailed goals.

<table>
<thead>
<tr>
<th></th>
<th>N+1 (-2015)</th>
<th>N+2 (-2020)</th>
<th>N+3 (-2030)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Noise</td>
<td>~32dB</td>
<td>~42dB</td>
<td>~71dB</td>
</tr>
<tr>
<td>NOx emission</td>
<td>~60%</td>
<td>~75%</td>
<td>&lt;~80%</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>~33%</td>
<td>~50%</td>
<td>&lt;~70%</td>
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</table>

The development of aero engine technology is one of the main approaches to realize the subsonic airline performance goals. However, it is difficult to realize the goals of N+3 due to the low energy conversion efficiency of propulsion system and secondary power system. In this context, the ideas of more electric aircraft (MEA) and electric propulsion technology emerge.

In order to improve the reliability and maintenance of the secondary power, the capacity of electrical power is raised to replace the hydraulic, pneumatic and mechanical power, defined as MEA. The power system is simplified in MEA, which brings some distinct advantages, including reduction of aircraft weight, low operating costs, efficient energy management, high reliability and maintenance, and low environmental impact [4].

Developing the electric propulsion system, especially the distributed electric propulsion system, is considered as a feasible method to realize N+3. Many relevant research studies have been conducted. Furthermore, a number of aircraft electric propulsion systems require high-speed and high-power ratings with the constraints, including space, weight and efficiency [5]-[9]. High power density electrical machines are always included as key underlying components in electric propulsion systems.

Considering the higher demand for efficiency and torque density of electric machines in aircraft electric propulsion systems, permanent-magnet (PM) machines are the go-to solutions, including radial-flux PM machines and axial-flux PM (AFPM) machines. AFPM machine has attracted more and more research efforts in the past decades due to the high torque density, high efficiency and high compactness. AFPM machines are more suitable for drive applications for favorable electromagnetic characteristics, such as high torque and power density.

Ironless stator AFPM machines are considered as a prominent branch of AFPM machines, which have attracted
Electric Power

Aircraft Electric Propulsion Requirements and Propulsion Motor Approach

A. Aircraft Electric Propulsion Requirements

The concept of electric drive or propulsion system has been widely used in hybrid and electric vehicles, and many mature commercial products of electric drive or propulsion are emerging in the automotive industry. There are numerous electric drive or propulsion system architectures which have been proposed for electric propulsion powertrains. In this paper, from the perspective of power output composition, three hybrid power systems combining batteries and gas turbine engines for propulsion are shown in Fig. 1.

1) Fig. 1(a) gives a typical power architecture of electric propulsion system: mechanical parallel by gear box for hybrid power. In this architecture, the engine and the motor jointly drive the bypass fans or propellers through the transmission device. The propulsion motor is used to accommodate with the engine to operating at the state of the best fuel economy. As shown in Fig. 1(a), with the transmission device as the medium, the propulsion motor can work in generating and motoring modes. In fact, the propulsion motor just acts as an energy balance regulator, however, because the engine is directly coupled to the aircraft propeller drive shaft through the transmission device, hence, this power architecture is defined as a weak mixing of hybrid power. However, the main drive of the engine and existence of the transmission device limit the further improvement of efficiency and the flexibility of power system layout.

2) Fig. 1(b) shows the mechanical series power architecture with transmission shaft. The engine and propulsion motor are coaxially mounted and mechanically coupled through the drive shaft. The power proportion of the propulsion motor and engine directly determines the degree of hybridization of oil fuel and battery power.

3) Fig. 1(c) gives a more acceptable power architecture, which is defined as electrical parallel between generator systems and battery. The power input of bypass fans or propellers is only from the propulsion motor. It can eliminate the gear mechanism by means of direct drive and reduce the weight of the motor system by using a high-speed motor with a reducer. The propulsion motor can be powered mainly by the battery or turboelectric generator system. If the turboelectric generator system (as shown in dashed box) is canceled, it will turn into an all-electric propulsion system.

It is noted that electrical machines occupy a pivotal position whether in the hybrid or electric propulsion systems. The electric propulsion system needs a motor to provide the equivalent thrust of the original engine. Table II gives the thrust of several typical aircraft types. As shown in Fig. 2 [14], the
design speeds and power ratings of the machines for electric propulsion aircraft application reach an almost critical state, which brings a great challenge to motor design.

B. Propulsion Motors

Based on the survey results, the high-power machines are listed in Table III. Although the surveyed high-power machines do not meet all the requirements of aircraft electric propulsion systems, their design methods and data can help us accelerate the design procedure of high-power machines for electric propulsion systems. It can be seen that high-speed and high-power machines mainly includes: radial flux permanent-magnet (RFPM) machines, induction machines (IMs), switched reluctance machines (SRMs), and AFPM machines. The power density is closely related to the cooling system and operating speed. Compared with the other topologies, the RFPM machines have higher power density.

III. IRONLESS STATOR AFPM MOTORS FOR AIRCRAFT ELECTRIC PROPULSION

A. Design considerations of propulsion motor

The aircraft electric propulsion systems require large rated power with constraints, including space, weight, and efficiency. The achievement of 13 kW/kg power density is regarded as a key milestone for megawatt-class propulsion motors in the development of future hybrid-electric aircraft [15]. To achieve high-power ratings with a reduced weight, propulsion motors are always designed with high operating speed. Parasitic effects, including mechanical strength, vibration and noise, always become a significant concern when designing a high-speed electrical machine. In order to satisfy the high requirements of aircraft electric propulsion systems, the main design considerations of propulsion motor are analyzed and described as follows.

(1) High power density topologies

High power density motor topology is the key technology to propulsion motors. The high-speed rotor often needs a high tensile sleeve, which causes an increase of main air-gap length in conventional inner-rotor PM machines. The increase of main air-gap length would lead to a decrease in electromagnetic performance due to the decrease of air-gap flux density. It is known that both outer-rotor and AFPM machines are featured of high torque and power density. Meanwhile, the sleeve would not affect the air gap and the mechanical design is relatively easy in outer-rotor and AFPM machines. Halbach array can be used to reduce the weight of rotor yoke and improve the air-gap flux density further.

(2) Loss analysis and cooling system design

One of the key challenges of high power density propulsion motor is the optimization of loss and efficiency. In conventional PM machines, the losses mainly include stator core loss, armature winding copper loss, PM loss, sleeve loss, rotor core loss and stray loss. The slotless stator structure can be used to reduce stator core loss, rotor core loss and PM loss. The Halbach array can also reduce the harmonic components of air-gap flux density, which can reduce the losses further. The large losses in a compact space would cause a serious temperature rise, which needs a high-performance cooling system design.

(3) Modularity and fault-tolerance

It is known that the design, manufacture and experiments of high-power motor are difficult and expensive. Fault tolerance is always a key issue in PM machine design, especially in some safety-critical applications. The large-power motor can be modularized by breaking the whole up into several modular motors, which can be controlled by several independent control units to realize fault-tolerance.

B. High-power propulsion motor design
Considering these constraints and design considerations of aircraft electric propulsion systems, high-power propulsion motor design is challenging. In [30]-[33], Kiruba Haran et al. designed a 1 MW, 15000r/min outer-rotor slotless PM propulsion motor, as shown in Fig. 3. Table IV presents the specifications of the outer-rotor slotless PM propulsion motor.

With respect to the space constraint and fault-tolerance, a 1MW, 15000r/min ironless stator AFPM propulsion motor is proposed and designed with the same space constraint of the outer-rotor PM motor. As shown in Fig. 4, the 1MW, 15000r/min AFPM motor consists of four 250kW, 15000r/min modular AFPM motors. The physical separation between the four modular AFPM motors realizes favorable fault-tolerance. In order to simplify the design, manufacture and experiment procedures, the validation of the 1 MW, 15000r/min ironless stator AFPM propulsion motor can be demonstrated by a 250kW, 15000r/min modular AFPM motor.

The specifications of the proposed ironless stator AFPM motor are listed in Table V.

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**Table IV [33]**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>1.0 MW</td>
</tr>
<tr>
<td>Rated speed</td>
<td>15000 r/min</td>
</tr>
<tr>
<td>Poles/slots</td>
<td>20/120</td>
</tr>
<tr>
<td>No. of phase</td>
<td>3</td>
</tr>
<tr>
<td>No. of turns</td>
<td>3</td>
</tr>
<tr>
<td>No. of parallel circuits</td>
<td>10</td>
</tr>
<tr>
<td>Air gap</td>
<td>1.15 mm</td>
</tr>
<tr>
<td>Machine outer radius</td>
<td>159.13 mm</td>
</tr>
<tr>
<td>Stack length</td>
<td>241.4 mm</td>
</tr>
<tr>
<td>core material</td>
<td>silicon steel</td>
</tr>
<tr>
<td>PM remanent B</td>
<td>1.2 T</td>
</tr>
<tr>
<td>shell material</td>
<td>aermet</td>
</tr>
</tbody>
</table>

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**Table V**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rated power</td>
<td>1.0 MW (250kW*4)</td>
</tr>
<tr>
<td>Rated speed</td>
<td>15000 r/min</td>
</tr>
<tr>
<td>Poles/slots</td>
<td>10/12</td>
</tr>
<tr>
<td>No. of phase</td>
<td>3</td>
</tr>
<tr>
<td>No. of coil-group</td>
<td>5</td>
</tr>
<tr>
<td>Air gap</td>
<td>1 mm</td>
</tr>
<tr>
<td>Machine outer radius</td>
<td>160 mm</td>
</tr>
<tr>
<td>Effective axial length</td>
<td>240 mm (60mm*4)</td>
</tr>
<tr>
<td>PM remanent B</td>
<td>1.2 T</td>
</tr>
</tbody>
</table>

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**Fig. 3.** The outer-rotor permanent magnet motor in [30]. (a) Axial view. (b) 3D description.

**Fig. 4.** Proposed axial flux permanent magnet motor topology. (a) Integrated structure. (b) Module structure.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Number of Slot/pole</td>
<td>12/10</td>
</tr>
<tr>
<td>Outer Radius</td>
<td>320 mm</td>
</tr>
<tr>
<td>Inner Radius</td>
<td>200 mm</td>
</tr>
<tr>
<td>Non-magnetic distance</td>
<td>20 mm</td>
</tr>
<tr>
<td>Axial thickness of PM</td>
<td>25 mm</td>
</tr>
<tr>
<td>Actual air-gap</td>
<td>1.0 mm</td>
</tr>
<tr>
<td>Axial length of one coil</td>
<td>6 mm</td>
</tr>
<tr>
<td>Radians of one coil</td>
<td>0.049</td>
</tr>
<tr>
<td>Number of coil-group</td>
<td>5</td>
</tr>
<tr>
<td>Midline pitch radian of coil-group</td>
<td>0.157</td>
</tr>
<tr>
<td>Layer Number of stator windings.</td>
<td>2</td>
</tr>
<tr>
<td>Output Power</td>
<td>250 kW</td>
</tr>
<tr>
<td>Rated speed</td>
<td>15000 rpm</td>
</tr>
<tr>
<td>Phase back-EMF</td>
<td>200 V</td>
</tr>
<tr>
<td>Current density</td>
<td>&lt;25 A/mm²</td>
</tr>
<tr>
<td>Effective Axial-Length</td>
<td>60 mm</td>
</tr>
</tbody>
</table>
The propulsion motor solution are shown in Table V. The volume of the proposed ironless stator AFPM propulsion motor is consistent with that of the outer-rotor slotless PM propulsion motor. The axial length can be optimized further by integrated design.

### IV. DEVELOPMENT OF 250 KW IRONLESS STATOR AFPM MODULAR MOTOR

#### A. Electromagnetic design

If the distribution of the air-gap magnetic field is sinusoidal, the average flux density for AFPM machines can be calculated by

\[
B_{avg} = \frac{1}{p/2} \int_{-p}^{p} B_y \sin(p\alpha) d\alpha
\]

\[
= -\frac{p}{\pi} B_{g1} \left[ \frac{1}{p} \cos(p\alpha) \right]_{-p}^{p}
\]

\[
= -\frac{p}{\pi} B_{g1} [\cos p - \cos 0] = \frac{2}{\pi} B_{g1}
\]

where \( p \) is pole pairs, \( B_{g1} \) is the fundamental component.
amplitude of air-gap flux density.

The phase back electromotive force (EMF) can be predicted by the following equation.

\[ E_{ph} = 2\pi fN_{ph}k_w\phi_f = 2\pi fN_{ph}k_w\frac{B_{r_1}(r_2^2 - r_1^2)}{P_n} \]

\[ = \frac{1}{30}\pi nN_{ph}k_wB_{r_1}(r_2^2 - r_1^2) \]  

(2)

where \( N_{ph} \) is number of turns per phase winding per layer, \( n \) is rotational speed, \( k_w \) is winding factor.

For the AFPM machines, the Lorentz magnetic force on single conductor in axial magnetic field can be expressed as

\[ \vec{F} = (R_s - R_f) \cdot (i \times \vec{B}) \]  

(3)

The Lorentz magnetic force on total windings in the radial direction can be calculated by the following equation.

\[ F_r = 2p \int_0^{\pi/p} B_{r_1} \cos(p\theta - \alpha) \left( \frac{3}{2} \sqrt{2} N_r \sin(p\theta) \right) d\theta \]

\[ = \frac{3}{8} \sqrt{2} \pi B_{r_1} IN_r (r_2^2 - r_1^2) \sin(\beta) \]

(4)

The electromagnetic torque can be calculated by

\[ T_e = \frac{3}{8} \sqrt{2} \pi B_{r_1} IN_r (r_2^2 - r_1^2) \sin(\beta) \cdot \frac{2\pi n}{60} \]

\[ = \frac{\sqrt{2}}{80} \pi^2 k_{mc} \frac{1}{k_{mm} k_{mc}} I_r (r_2^2 - r_1^2) \cdot n \]

(5)

\[ P = T_e \cdot \Omega = \frac{3}{8} \sqrt{2} \pi B_{r_1} IN_r (r_2^2 - r_1^2) \cdot \sin(\beta) \cdot \frac{2\pi n}{60} \]

\[ = \frac{\sqrt{2}}{80} \pi^2 k_{mc} \frac{1}{k_{mm} k_{mc}} I_r (r_2^2 - r_1^2) \cdot n \]

where \( J \) is current density, \( l_a \) is axial length, \( k_{mc} \) is axial strength coefficient, \( k_{mm} \) is peripheral strength coefficient.

On the basis of sizing equation, the basic calculation process is shown in Fig. 5. According to the size of outer-rotor PM machine in Table IV, the calculated results of ironless stator AFPM machine are given in Table VI. Fig. 6 shows the FEA model of 250kW modular AFPM motor with internal ironless stator. In order to improve the air-gap flux density, the Halbach-array is adopted in the design and composed of forty PM pieces. The magnetization direction of the forty PM pieces varies 45° in turn.

Fig. 7 shows the three-dimensional air-gap flux density distribution with respect from the center line of the air gap. It can be seen that the air-gap flux density waveform is relatively sinusoidal.

Fig. 8 gives the phase back EMF waveform of ironless stator AFPM machine at 15000r/min, it can be seen that the fundamental amplitude of back-EMF for the ironless stator AFPM machine is about 390V.

The average torque variation of the ironless stator AFPM machine along with phase current is shown in Fig. 9. The torque increases linearly with phase current in the ironless stator AFPM machine. The torque-current ratio is about 0.34N·m/A and the output power is about 250kW when the phase current is about 450A at 15000r/min.

B. Mechanical Design Considerations and High-speed Operational Issues

The mechanical construction of the proposed ironless stator AFPM machine is shown in Fig. 10. When the speed is increased further in pursuit of high power density design, the mechanical design constraints would become more serious and even limit the design.

In order to improve the mechanical strength of rotor, a new hybrid protective sleeve is proposed. The carbon fiber sleeve is mounted on the stainless steel sleeve to enhance mechanical strength further. Since the carbon fiber material is sensitive to bending force, the carbon fiber sleeve avoids direct contact with the stainless steel screws in rotor design.

The tangential stress of PM and the equivalent stress of dual rotors at 90℃, 15000r/min are analyzed by 3D FEM, and the results are shown in Fig. 11. It can be seen that the maximum tangential stress of PM is about 48.9MPa, and the maximum equivalent stress of dual rotors is about 355MPa. The maximum allowed compressive stress of rotor is about 650MPa, and the maximum allowed tensile stress of PM is 80MPa.
C. Oil immersed Forced cooling

In order to enhance the output performance of machine, an oil immersed forced cooling system is applied in the machine. The aim of oil immersed force cooling system is to transfer the heat of the copper losses and eddy losses to the oil.

The construction of the ironless stator and winding shape is shown in Fig. 12. In order to improve electromagnetic performance, each phase winding divided into two layers is fixed with epoxy support. All windings are placed in the cooling oil, the cooling oil is sealed with two epoxy baffle plates.

The inlet velocity is 1.2m/s, and the inlet flow rate is 15L/min. The velocity distribution of cooling oil in each part of stator is shown in Fig. 13. It can be seen that the cooling oil flows along the windings and winding framework after the cooling oil is entered into the stator. The overall velocity is about 0.5~1.0m/s because of the winding arrangement is dense. The velocity of inlet and outlet exceeded 1.5m/s since the turbulence exists.
that the fundamental amplitude of back-EMF is about 261V.

9000r/min ironless stator AFPM machine with Halbach-array machine design and analysis method, the prototype of a 50kW, winding end is about 10
PM rotor is manufactured with the consideration of cost and
D.

simulation results of temperature distribution can only serve as a reference.

D. Experimental verification

To validate the feasibility of the ironless stator AFPM machine design and analysis method, the prototype of a 50kW, 9000r/min ironless stator AFPM machine with Halbach-array PM rotor is manufactured with the consideration of cost and processing cycle. The prototype and test platform are shown in Fig. 15. The prototype is driven by a 12000r/min, 100kW PMSM.

The prototype machine has been tested up to 9000r/min and the three-phase back-EMFs are measured at no load. The machine runs at the speed of 9000r/min for two hours, and the three-phase back-EMF is shown in Fig. 16(a). It can be seen that the fundamental amplitude of back-EMF is about 261V.

In addition, the electromagnetic characteristics at the rated load are tested. Fig. 16(b) shows the measured phase current waveform at 9000r/min. Fig. 17 shows the measured efficiency and output power under different load currents at 9000r/min. It is noted that the value of output power increases linearly with the increase of load current, and the maximum output power is about 53.8kW. It is worth noting that the efficiency is increased significantly at first and then reduced when the load current is increased. The maximum efficiency of the prototype ironless stator AFPM machine is about 97.4% when the load current is about 120A.

V. CONCLUSION

This paper has presented a feasible technology solution of propulsion motor for aircraft electric propulsion applications. A new ironless stator AFPM machine with oil immersed forced cooling system is proposed as a favorable candidate because of the advantages of high efficiency and power density, as well as the axial modularity and fault-tolerance.

The concept and design of a high-power 1 MW multi-stack ironless stator AFPM machine have been presented, which is composed of four 250kW modular motors by stacking in axial. The detailed electromagnetic, structural considerations and thermal design are presented and discussed. The research results indicate that the power density and efficiency of the proposed multi-stack ironless stator AFPM machine are over 13kW/kg and 96%, respectively. Furthermore, the unit prototype machine has been developed and tested up to 53.8kW at 9000 r/min. The maximum efficiency reaches 97.4% when the current density is about 10A/mm². Because the oil immersed forced cooling system is adopted, the electric load of ironless stator can be further increased by three times to improve torque density, which lays a good foundation for MW-level propulsion motor design and implementation.

REFERENCES


Zhuoran Zhang (M’09–SM’12) received the B.S. degree in measurement engineering and the M.S. and Ph.D. degrees in electrical engineering from Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2000, 2003 and 2009, respectively. Since 2003, he has been a member of the faculty at Department of Electrical Engineering, NUAA, where he is currently a full professor and vice director of Jiangsu Provincial Key Laboratory of New Energy Generation and Power Conversion. From Feb. 2012 to Jun. 2013, he was a visiting professor in Wisconsin Electric Machines and Power Electronics Consortium (WEMPEC), University of Wisconsin-Madison, U.S. His research interests include design and control of permanent magnet machines, hybrid excitation electric machines, and doubly salient electric machines for aircraft power, electric vehicles and renewable energy generation. He has authored or coauthored over 130 technical papers and one book, and is the holder of 34 issued patents in these areas.

Wewei Geng received the B.S. degree in electrical engineering from Nanjing Agricultural University (NJAU), Nanjing, China, in 2012. The M.S. and Ph.D. degree in electrical engineering from Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2014 and 2018 respectively. He has published more than 10 technical papers in journals and conference proceedings. He has eleven issued/published invention patents. His main research interests include PM machines and control, electric drive system for electric vehicles and hybrid propulsion.

Ye Liu received the B.S. degree in electrical engineering from Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China, in 2014. He is currently working toward the Ph.D. degree in electrical engineering at NUAA, Nanjing, China. His main research interests include design and control of permanent magnet and hybrid excitation electrical machines.

Chen Wang received the B.S. degree in electrical engineering from Xidian University, Xi’an, China, in 2010. The M.S. degree in 2013 from Jiangxi University of Science and Technology, Ganzhou, China, where he is currently working toward the Ph.D degree in electrical engineering at Nanjing University of Aeronautics and Astronautics (NUAA), Nanjing, China. His main research interests include structural design and vibration analysis of high speed machines.