

Design of a Novel Topology for an Axial Flux Wound Rotor Synchronous Motor

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Electric vertical take-off and landing (eVTOL) aircraft designed for urban environments rely on distributed electric propulsion systems to enhance safety and reliability. These systems necessitate electric propulsion solutions that combine high power density with superior efficiency. To address these demands, this study presents a novel axial flux wound rotor synchronous motor (AFWRSM) with an innovative design and operating principle, specifically developed for eVTOL propulsion. The proposed AFWRSM is a rare-earth-free motor that uses field windings on the rotor, eliminating the reliance on permanent magnets. To further improve power density and fault tolerance, the motor incorporates a dual-stator configuration. The design process is thoroughly detailed, with a focus on distinguishing the proposed motor from conventional designs in terms of structure and operation. Finally, the motor performance was validated using three-dimensional finite element analysis, demonstrating its suitability for eVTOL applications.

Index Terms—Axial flux motors (AFMs), finite-element method (FEM), motor design method, wound rotor synchronous motors (WRSMs)

I. INTRODUCTION

Urban air mobility (UAM) has emerged as a promising eco-friendly solution to mitigate traffic congestion from growing urban populations [1], [2]. Among the various types of aircraft designed for UAM, electric vertical take-off and landing (eVTOL) aircraft are notable for employing distributed electric propulsion systems for safety, making them well-suited for densely populated urban environments [3], [4]. Consequently, eVTOL propulsion systems demand electric motors with low torque ripple, high power density, and high efficiency.

While permanent magnet motors are known for their high power density, they are susceptible to demagnetization, reducing output and limiting the flight reliability of eVTOL aircraft, potentially compromising safety.

This study introduces a novel axial flux wound rotor synchronous motor (AFWRSM) topology specifically designed for eVTOL propulsion. The AFWRSM is an axial flux motor, characterized by magnetic flux flowing axially through the air gap. Additionally, it eliminates reliance on rare-earth materials by using field windings to generate the field flux. The motor's design was guided by the D²L method, with key considerations including the rotor structure and dual-stator configuration. Parameters such as Carter's coefficient, no-load magnetomotive force (MMF), load MMF, and armature reaction MMF were carefully analyzed during rotor design. To distinguish the AFWRSM from conventional motors, its novel structure and operating principles are detailed. Finally, a precision analysis of the motor was conducted using finite element analysis (FEA) to validate its performance.

II. DESIGN PROCESS AND PRINCIPLE OF THE NOVEL TOPOLOGY

A. Topology of the Proposed Machine

The proposed AFWRSM features 14 poles and 12 slots. Its structure comprises a rotor core, two stator cores, and windings,

as illustrated in Fig. 1. To enhance power density, the stator incorporates a dual-stator design. Concentrated windings are utilized as the winding method.

B. Operating Principle of the AFWRSM

The operating principle of the AFWRSM is shown in Fig. 2. The motor employs a dual-stator configuration, with the stators symmetrically positioned above and below the rotor. The rotor forms poles depending on the direction of the direct current supplied to the field windings. Meanwhile, the armature windings are supplied with three-phase current, generating a rotating magnetic field. The magnetic flux produced by the field windings is evenly distributed across the two air gaps, enabling constant torque production through electromagnetic interaction between the magnetic flux and the rotating magnetic field. Fig. 2 illustrates the alignment process between the rotor and stator, which varies according to the rotor's rotation angle.

C. Design Process using the D²L Method

The proposed motor was designed using the D²L method, with the target specifications provided in Table 1. This method determines key parameters, such as the outer diameter, inner diameter, and overall design specifications of the stator core. The outer diameter of the stator core is calculated using (1). In designing the rotor, the flux density is optimized using Carter's coefficient, and a squared form is applied to account for the

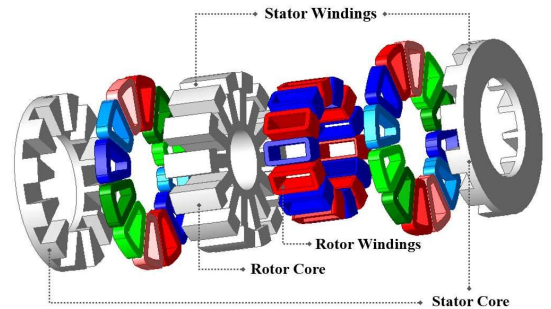


Fig. 1. Exploded view of the axial flux wound rotor synchronous motor.

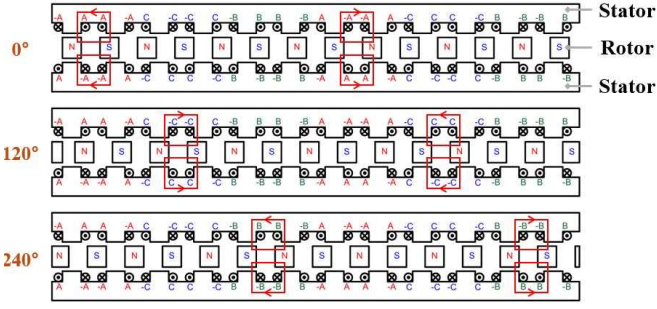


Fig. 2. Operation principle of the AFWRSM.

dual-stator configuration, as shown in (2). The load MMF is derived by combining the no-load MMF and the armature reaction MMF, as detailed in (3)–(5). Based on these calculations, the specifications of the field windings are determined, and the final design results of the AFWRSM are summarized in Table 1.

$$D_{out} = \sqrt[3]{\frac{\varepsilon P_{out}}{\pi^2 k_d k_w n B_m A_m \eta \cos \theta}} \quad (1)$$

where D_{out} represents the outer diameter of the stator, ε is the ratio of phase EMF to phase voltage, P_{out} denotes the output power, k_d is the ratio of the stator's inner to outer diameter, k_w represents the winding factor, n is the rotor's rotation speed, B_m is the magnetic flux density in the air gap, A_m is the linear current density in the air gap, η is the efficiency, θ is the phase angle between voltage and current.

$$k_c = \left(\frac{t_1}{t_1 - 2\gamma g} \right)^2 \quad (2)$$

where k_c represents the Carter's coefficient, t_1 is the average slot pitch, γ denotes the fictitious air-gap coefficient, and g is the air-gap length.

$$AT_{f0} = AT_{ag} + AT_{st} + AT_{rt} + \frac{1}{2}(AT_{sy} + AT_{ry}) \quad (3)$$

where AT_{f0} denotes the no-load MMF, AT_{ag} is the MMF of the air-gap, AT_{st} represents MMF of the stator teeth, AT_{rt} is the MMF of the rotor teeth, AT_{sy} is the MMF of the stator yoke, AT_{ry} is the MMF of the rotor yoke.

$$AT_a = \frac{\sqrt{2} cm N_1 k_w I_a}{\pi p} \quad (4)$$

where AT_a is the armature reaction MMF, c denotes the compensation coefficient, m is the number of phases, N_1 is the number of turns in series per phase, and I_a represents the armature current.

$$AT_f = \sqrt{AT_{f0}^2 + k^2 AT_a^2 + 2k AT_a \sin \theta} \quad (5)$$

where AT_f represents the load MMF, and k is the saturation coefficient.

D. Finite Element Analysis

To validate the performance of the motor designed using the D²L method, three-dimensional FEA was performed. The no-load back electromotive force (EMF) at 1,000 rpm was measured at 9.21 V, with a total harmonic distortion (THD) of 4.60%. The load analysis results indicated an average torque of

TABLE I
THE PARAMETERS OF THE AFWRSM

	ITEMS	Unit	Value
Target Specifications	Output Power	kW	71.8
	Rated Voltage	V	500
	Frequency	Hz	1167.67
	Rated Speed	rpm	10,000
	Efficiency	%	92
Stator	Power Factor	-	0.92
	Outer diameter	mm	293
	Inner diameter	mm	170
Rotor	Outer diameter	mm	293
	Inner diameter	mm	120
	Air-gap length	mm	1
	Lamination	mm	120

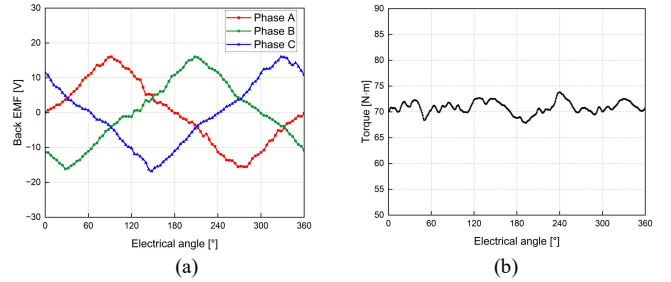


Fig. 3. Back EMF and Torque waveforms. (a) Back EMF and (b) Torque.

70.57 N·m and an efficiency of 94.57%. These results confirmed that the average torque exceeded the target value of 68.52 N·m. The waveforms of the back EMF and average torque are presented in Fig. 3.

III. CONCLUSION

This study proposed the AFWRSM, a rare-earth-free motor featuring a novel structure and operating principle, as a propulsion system for eVTOL aircraft. The motor design process, structure, and operating principles were detailed to highlight its differences from conventional motors. FEA validated the motor performance, demonstrating an average torque of 70.57 N·m and an efficiency of 94.57%, thereby meeting the target specifications.

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