Detailed Electromagnetic Analysis of a High Specific Power Slotless Permanent Magnet Motor with Imbalanced Armature Windings

Han-Wook Cho[1,2], *Member, IEEE*, Andy Yoon[2], Nathaniel J. Renner[2], and Kiruba S. Haran[2], *Fellow, IEEE*

[1]Chungnam National University, Yuseong-gu, Daejeon 34134 Korea, hwcho@cnu.ac.kr, hwcho@illinois.edu
[2]University of Illinois at Urbana-Champaign, Champaign, IL 61820 USA, kharan@illinois.edu

As a result of stronger demand for improved fuel efficiency, environmental concerns, and emissions, there is a growing trend to substitute turbo-electric propulsion technologies for conventional jet fuel engines in aircraft application. This paper presents a detailed electromagnetic analysis of high specific power permanent magnet(PM) motors for aircraft propulsion applications. The high-pole count surface mounted permanent magnet synchronous machine(SPMSM) with slotless/Halbach array and air-cored high-speed machine is proposed and analyzed. In particular, the influence of imbalanced armature windings on machine performances are presented by finite element analysis(FEA). It will be shown that the proposed analysis strategy is very effective for the prediction of machine performance in special purpose electric machines.

***Index Terms*—Aircraft application, electromagnetic analysis, finite element analysis, Halbach array, high-speed high-frequency.**

I. Introduction

IN a rigorous attempt to meet projected national aviation goals in noise, emissions, and performance, NASA(National Aeronautics and Space Administration) conducted an N+3 case study intended to foster advanced aircraft concepts and technologies projected to enter service in the 2030 to 2045 time frame[1]. Engineers are constantly working to make aircraft more fuel efficient and more environmentally friendly, and several new technological innovations may finally make the future of flight a sustainable one. Thus, NASA has identified a key enabling technology of turbo-electric propulsion system as electric motors with four times the power density of the current state-of-the-art(SOA)[2]. In order to satisfy a final goal from NASA, the design utilizes high frequency, high pole-count, Halbach arrays, and slotless winding to minimize the use of heavy iron alloy. Furthermore, outer rotor topology is adopted to minimize effective airgap[3]. In case of slotless winding machine, the adversely effects of leakage flux which decrease the performance of cannot be ignored because permanent magnet(PM) motor with large airgap structure has a relatively much leakage flux than conventional slotted winding motor. Therefore, to confirm the performance and reliability of PM motor, 3-D electromagnetic performance analysis should be necessarily performed. This paper presents a detailed electromagnetic analysis of PM motor to meet NASA's output power, power density, and efficiency goals. 3-D finite element analysis(FEA) software is utilized to reduce the analysis errors which are caused by leakage flux in end-region of airgap slotless winding. In particular, we consider the effect of imbalanced armature windings which are designed to easy manufacturing of high-frequency litz wire coils. First of all, magneto-static performance and basic parameters of PM motor have been analyzed including imbalanced armature windings, after that torque-speed characteristics and efficiency analysis have been performed. Finally, we will show that the proposed machine is very effective for the purpose of reducing the weight and increasing the efficiency in aircraft system during high-speed high-frequency operation.

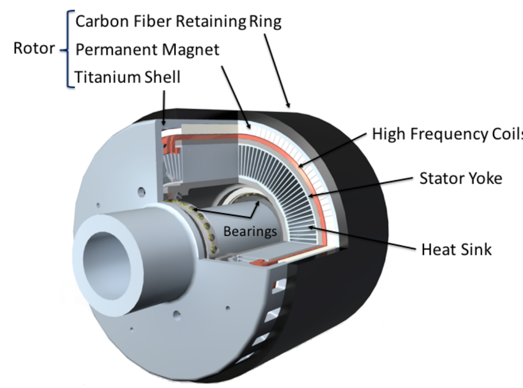

Fig. 1. Proposed PM motor for turbo-electric propulsion system of N3-X hybrid wing body(HWB) aircraft.

TABLE I
System Requirements and Key Specifications

Item	Specifications	Unit
Rated Power	1	MW
Rated Speed	14,000	r/min
Maximum Phase Voltage	379.4	Vrms
Rotor Outer Diameter	337.2	mm
Airgap Length	1	mm
Active Length	223.5	mm
Number of Poles	20	counts
Fundamental Frequency	2.5	kHz
Permanent Magnet	N45SH	
Stator Core	Hiperco 50 Alloy	
Rotor Shell	Titanium	

II. 3-D FEA considering Imbalanced Armature Windings

A. Machine Topology and Specifications

Fig.1 shows the full drawing architecture of the PMSM for turbo-electric propulsion system of N3-X hybrid wing

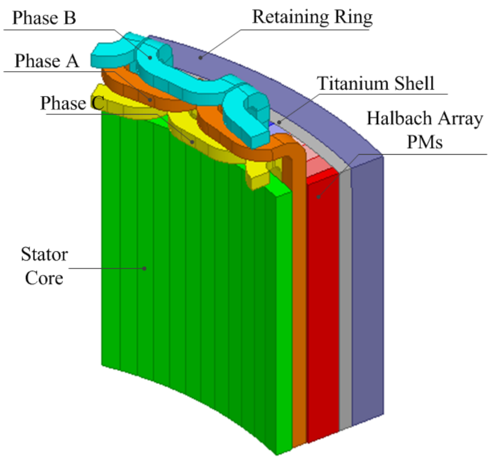

Fig. 2. 3-D FEA model for PM motor with slotless imbalanced armature windings.

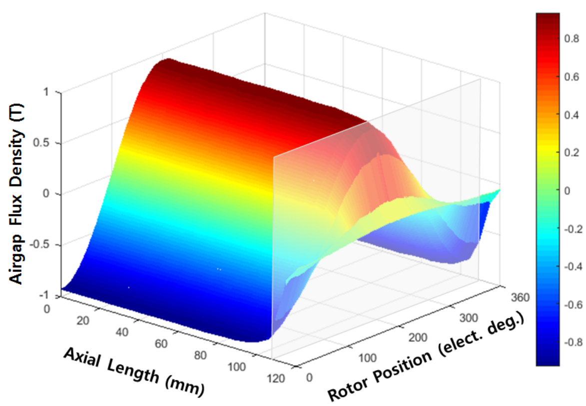

Fig. 3. Air-gap flux density distribution.

body(HWB) aircraft. The basic concept is inside-out, high pole-count PMSM with very high frequency drive. The system requirements and key specifications for high-speed high-frequency PMSM are listed in Table I. The required output power is 1MW at 14,000r/min, and the goals of power density and efficiency is >13kW/kg and >96%, respectively. To achieve the highest power density, high grade NdFeB PMs(N45SH) with Halbach array and high performance lamination steel(Hiperco 50 Alloy) have been employed in our machine. In addition, litz wire conductor is chosen as armature windings to reduce the skin effect of eddy current in copper wire.

B. Airgap Flux Density

Fig. 2 shows the 3-D FEA model for PM motor with imbalanced armature windings. It demonstrates the phase coil topologies that exist with large difference for the length of end-windings. The commercial FEA analysis software is used to simulate the machine. Fig. 3 shows the airgap flux density distribution due to PM source in the airgap region. The maximum value of airgap flux density is 0.93T when the machine operates at 100°C.

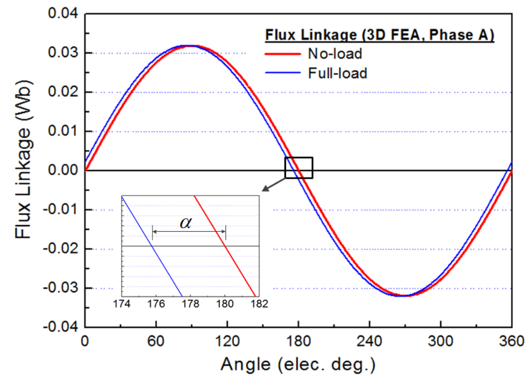

Fig. 4. Phase angle difference between no-load and full-load flux linkages by 3-D FEA

TABLE II
COMPARISON OF INDUCTANCE CALCULATION RESULTS

Analysis	2-D	3-D		
Item	All phases	Phase A	Phase B	Phase C
Full-load flux linkage[Wb]	0.0318	0.0320	0.0320	0.0319
Phase angle diff.[elec. deg.]	3.5926	4.2595	4.3558	4.2046
Input current[Arms]	1018.4	1018.4	1018.4	1018.4
Inductance[μH]	1.3837	1.6505	1.6877	1.6241

C. Flux Linkage and Inductances

Using the 3-D time-stepping FEA, the flux linkages with no-load and full-load are calculated and plotted to extract a phase angle α between them. The nonlinear inductance, L_s, are basically estimated from the voltage equation and phase diagram as

$$L_s = \frac{\lambda_o \sin\alpha}{i_q} \quad (1)$$

where, λ_o is full-load flux linkage, α is phase angle difference between no-load and full-load flux linkage, and i_q is q-axis current, respectively. Fig.4 shows the phase angle difference α between no-load and full-load flux linkage in Phase A from 3-D FEA. Table.II presents the full-load flux linkage λ_o, phase angle difference α and predicted inductances L_s from 2-D and 3-D FEA.

III. DISCUSSIONS

The results from 3-D FEA show the variation of the inductances according to the imbalance armature windings. The inductances of phase-A, -B, and -C are 19.20%, 21.97%, and 17.37% larger than 2-D FEA result. More detailed results and influences, such as resistance, power losses, torque-speed characteristics and efficiency, will be discussed in full paper.

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