Comparison of motor parameters and output characteristics of IPMSMs with concentrated and distributed windings

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Abstract — The purpose of this paper is to study the effect of main motor parameters such as inductance and back emf by winding configuration. Two IPMSMs(Interior Permanent Magnet Synchronous Motor) with distributed winding and concentrated winding having identical output power, stator and rotor outer diameter, air gap length, axial length, etc., are designed and fabricated. With two IPMSMs, basic motor parameters, such as inductances, back emf, phase resistances, and output performances are compared and results are discussed.

***Index Terms*—IPMSM, Concentrated windings, Distributed windings**

I. Introduction

The application of IPMSM(Interior Permanent Magnet Synchronous Motor) is extending due to high power density and wide operating speed range with the help of reluctance torque and field weakening control. In order to maximize the advantage of its high power density, distributed windings is the reasonable choices for windings designs, because almost unit winding factor can be achieved. However, PM machines with distributed windings have several disadvantages such as difficulty in winding automation, long end windings, larger copper loss than concentrated windings, etc. Comparing to distributed windings, concentrated windings enables easy windings automation and have short end windings, smaller copper loss, and require smaller space than distributed windings. However, winding factor of concentrated windings is generally smaller than distributed windings [1].

To improve output torque of PM machines with concentrated windings, many researches dealing with improving output torque of PM machines are undergoing. In design aspects, to improve the output torque, unequal tooth width of stator and appropriate choice of slot and pole number are introduced and the researches achieved improvement of output power of PM machines with concentrated windings or gives the direction in initial design stage [1-4]. However, the researches are concerned only with SPM motor with concentrated windings. Unlike to the SPM motors, inductances vary with rotor position and current phase angle in IPMSM, and this variation have significant effects on motor performances.

The purpose of this paper is to study on the characteristics of IPMSM when distributed winding is designed to concentrated windings. From basic parameter to output characteristics, both motors are compared. IPMSM with distributed winding (DIS) is designed, then that of concentrated winding(CON) is designed for identical output power and with stator volume.

II. Analysis model

A. Structure and Specifications

Fig. 1 show the models studied in this paper. Both distributed and concentrated winding are designed. (a) is DIS with 4poles and 24slots and (b) is CON with 4 poles and 6slots. The major geometric parameters are identical; axial length, air gap length, rotor outer radius, stator outer radius, permanent magnet volume, etc. Series turn number of CON is adjusted to have identical concentrated winding model is larger than that of distributed one due to low winding factor of concentrated winding. Therefore almost identical back emf is achieved with identical permanent magnet volume and the effect of windings configuration on the motor performance can be easily observed.

To improve THD of back emf and reduce torque ripple, rotor eccentricity is used in DIS and tooth shape is optimized for CON.

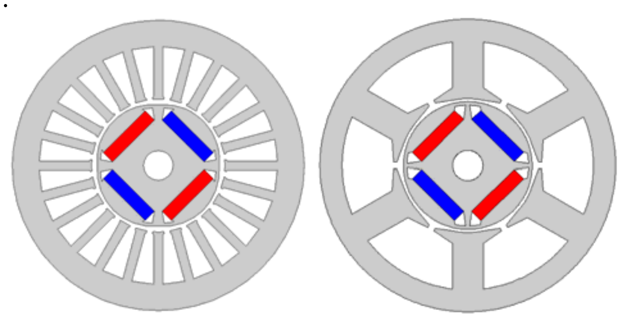

(a)DIS (b)CON
Fig. 1. Configuration of designed model

Fig. 2 shows the torque and power versus speed characteristics of both motors. Until 4,000rpm, constant torque of 0.6 Nm is maintained and from 4,000rpm to 7,000rpm, 250W of output power is maintained. In the constant torque region, maximum torque per ampere control is considered and maximum efficiency control with field weakening is used in the constant power region.

Table I shows specification of the models. By redesigning windings configuration from distributed windings to concentrated windings, resistance of CON is lowered.

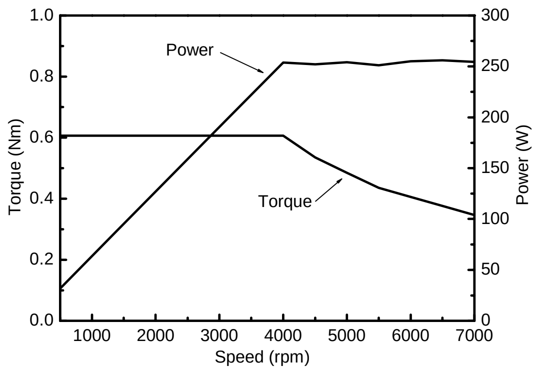


Fig. 2. Output Power characteristics

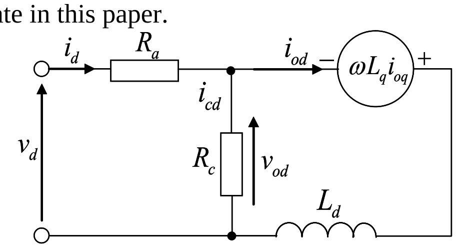
TABLE I. SPECIFICATION OF IPMSMS

	DIS	**CON**
Output power (W)	250	
Max. Torque (Nm)	0.6	
Max. speed(rpm)	7,000	
Number of poles/slots	4/24	4/6
Series turns	52	58
Number of parallel circuit	1	2
Resistance (mΩ)	106.36	81.76

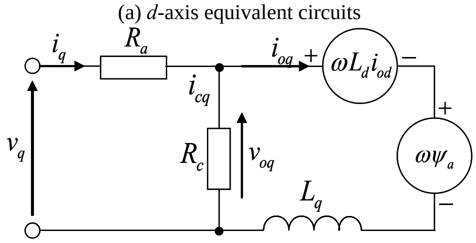
III. BASIC THEORY

A. *d - q model of IPMSM*

For the performance analysis of IPMSM, *d-q* model is generally used. Equivalent circuits for IPMSM based on a synchronous *d-q* model considering core losses are presented in Fig. 3. The mathematical model of the equivalent circuits is given by (1), (2), and (3) considering core loss [5]. By solving equations (1) ~ (3), characteristics of IPMSM is calculated in steady state in this paper.



(a) *d*-axis equivalent circuits



(b) *q*-axis equivalent circuits

Fig. 3. *d-q* equivalent circuit

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_a \begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \left(1+\frac{R_a}{R_c}\right)\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} + p\begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}\begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} \quad (1)$$

$$\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} = \begin{bmatrix} 0 & -\omega L_q \\ \omega L_d & 0 \end{bmatrix}\begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega\psi_a \end{bmatrix} \quad (2)$$

$$T = P_n\left\{\psi_a i_{od} + \left(L_d - L_q\right) i_{od} i_{oq}\right\} \quad (3)$$

where, i_d and i_q are d- and q-axis armature current, i_{cd} and i_{cq} are *d*- and *q*-axis iron loss current, v_d and v_q are *d*- and *q*-axis voltage, R_a is armature windings resistance per phase, R_c is iron loss resistance, Ψ_a is flux linkage by permanent magnet at no load, L_d and L_q are *d*- and *q*-axis armature self inductance, and P_n is pole pair.

B. *Core loss calculation*

Fig. 4 shows the procedure of core loss calculation using core loss data of magnetic material [5]. After calculating total iron loss, w_{total}, the core loss resistance R_c is calculated by (4).

$$R_c = v_0^2 / w_{total} \quad (4)$$

where, v_o is terminal voltage at no load and speed of core loss is calculated.

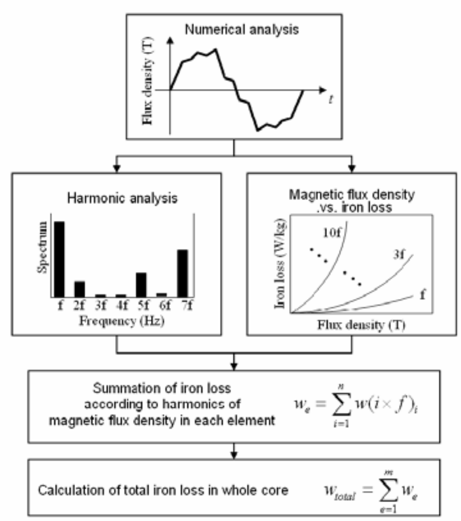


Fig. 4. Procedure of core loss calculation.

IV. COMPARISON OF CHARACTERISTICS

A. *Comparison of basic characteristics by 2D FEA*

Cogging torque, *d*-axis inductance, saliency ratio, and output torque are calculated by 2D FEA and compared from Fig. 5 to Fig. 7. As generally kwon, cogging torque of CON is higher than DIS. In the inductance comparison DIS shows higher value and it is expected it will show less currents in the field weakening region.

In order to calculate L_d and L_q, 2D FEA is used. Flux linkages at no load, and each current and current phase angle are calculated. From the comparison, it is found that redesigning distributed windings to concentrated windings results in decrease of saliency ratio. Especially, the increase of L_d significantly affects to the decreased saliency ratio, while the effect of decreased L_q is small.

Average torque and torque ripple are compared in Fig. 7. Even though CON is optimized to have low torque ripple, it still shows higher torque ripple than DIS, however the difference is not significant.

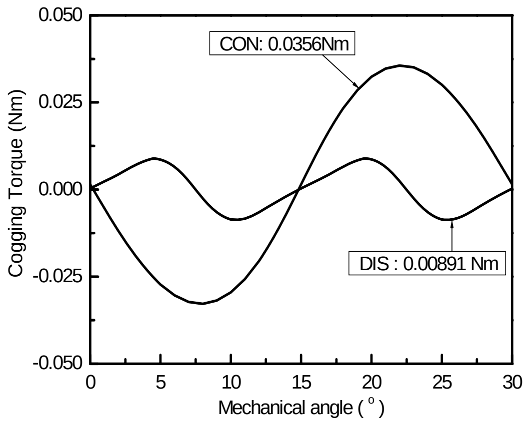
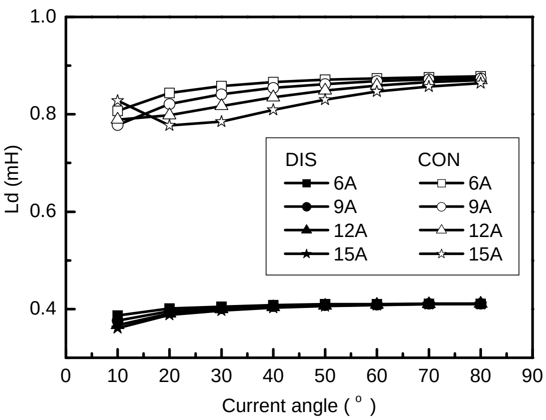
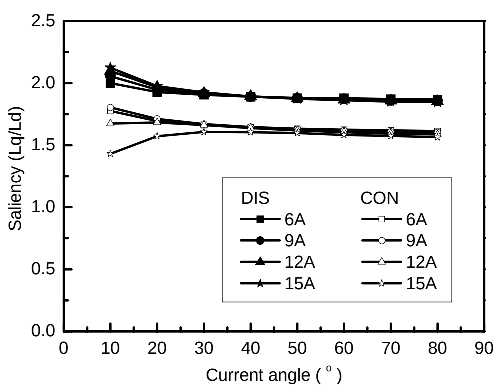


Fig. 5. Cogging torque comparison



(a) L_d



(b) Saliency ratio

Fig. 6. Comparison of inductance and saliency ratio at rated current

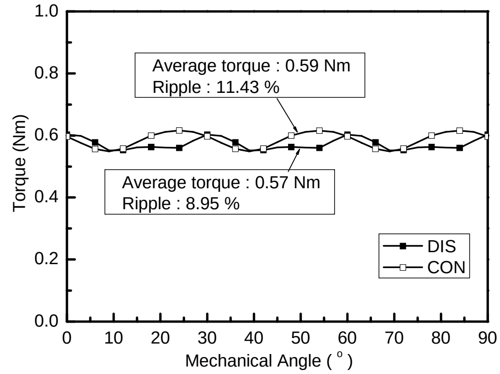


Fig. 7. Output torque and torque ripple at rated current

B. *Comparison of output characteristics by experiments*

Fig. 8 shows fabricated DIS and CON. Rotor eccentricity of DIS and tooth shape of CON are shown.

No load back emfs are shown in Fig. 9. Due to pole/slot combination and windings configuration, CON would show 86.6 % of back emf to DIS, therefore, series turn number of CON is increased to have identical back emf.

No load-loss is compared in Fig. 10. Due to higher flux density of CON, it shows higher core loss at entire speed region.

d and *q* - axis current are compared in Fig. 11 for the output power shown in Fig. 2. Due to the slightly higher back emf, CON requires less input current than DIS, however, efficiency of DIS in the entire region is higher than CON. That is due to higher no load loss of CON.

Fig. 8. Fabricated DIS and CON model

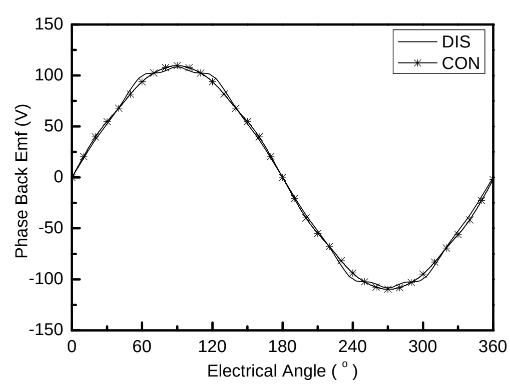


Fig. 9 Comparison of phase back emf and THD at 1000rpm

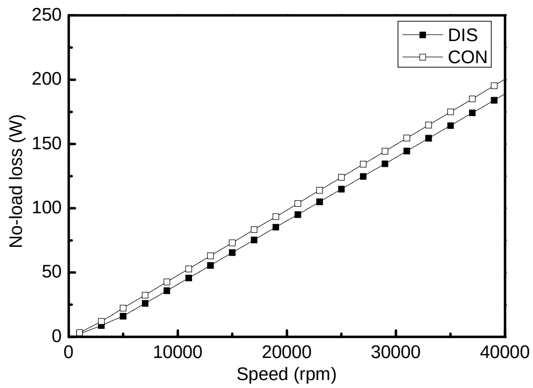


Fig. 10. No-load loss

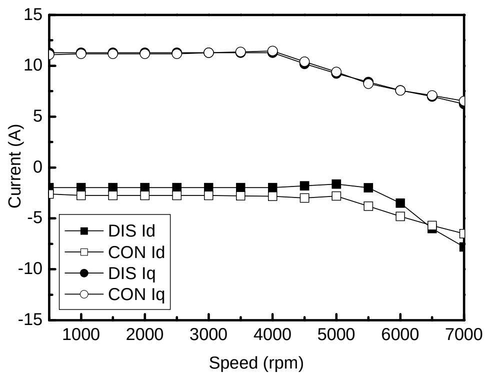


Fig. 11. Comparison of current

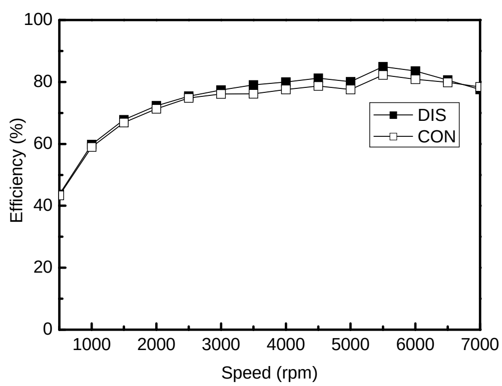


Fig. 12. Efficiency

V. Conclusion

Two IPMSMs with concentrated and distributed windings are designed, fabricated, and characteristics are compared. The motors are designed with identical stator volume, stack length, permanent magnet volume, and output power.

Two IPMSMs show close characteristics of input current and efficiency. Concentrated winding model shows higher torque ripple, however the difference is not significant. Therefore winding configuration shows no differences of performances in this case.

For the comparison of total space usage, overall axial length is compared in Fig. 13. As generally known axial length of concentrated winding is shorter than distributed winding. Therefore considering identical output characteristics with close efficiency, concentrated winding would be better space effective.

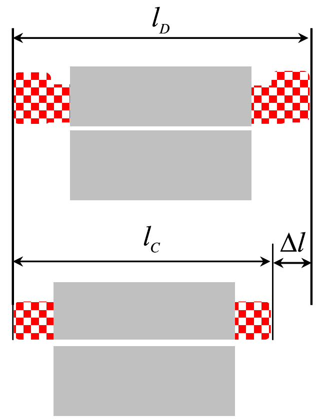


Fig. 13. Comparison of axial length of endwinding

References

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Sincerely,

Prof. Ichiro Miki
ICEMS 2006 Conference Chairman
October 23, 2006

Session DS3F1
PM Machines and Drives (5)

Date: Wednesday, 22 November 2006
Time: 14:00-15:20
Venue: Room F

DS3F1-01
PDF

Magnetic Field Analysis of Permanent Magnet Synchronous Motor Using the Transfer Relations

Seok-Myeong Jang, Kyoung-Jin Ko, Han-Wook Cho, Jang-Young Choi
Chungnam National University, Korea

DS3F1-02
PDF

A Torque Ripple Reduction Drive Strategy for Permanent Magnet BLDC Motor with Imperfect Back-EMF

Tao Sun [1)], Geun-Ho Lee [2)], Jung-Pyo Hong [1)]
[1)]Changwon National University, Korea, [2)]Namhae College, Korea

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DS3F1-03
PDF

The Design and Analysis of a High Efficiency Permanent Magnet Reluctance Motor

Peng Zhang, Soon-O Kwon, Jung-Pyo Hong
Changwon National University, Korea

DS3F1-04
PDF

Comparison of Motor Parameters and Output Characteristics of IPMSMs with Concentrated and Distributed Windings

Soon-O Kwon, Su-Beom Park, Zhang Peng, Liang Fang, Jung-Pyo Hong
Changwon National University, Korea

DS3F1-05
PDF

Robust Flux-Weakening Control of Permanent Magnet Synchronous Machines Incorporating Speed Regulation

Song Chi [1)], Longya Xu [1)], Jinsheng Sun [2)]
[1)]The Ohio State University, USA, [2)]Hebei Polytechnic University, China

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DS3F1-06
PDF

Design and Experimental Investigation of Permanent Magnet for Room Temperature Magnetic Refrigerator

Zheng Zhang, Yumei Du, Hui Guo, Guobiao Gu
Institute of Electrical Engineering of Chinese Academic Science, China

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DS3F1-07
PDF

Magnetic Characteristic Analysis of a Dual-Rotor Type Generator Taking Account of Two-Dimensional Vector Magnetic Property

T. Todaka, A. Ikariga, K. Shuto, H. Shimoji, M. Enokizono
Oita University, Japan

DS3F1-08
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Study on the Static Characteristics of a Hybrid Stepping Motor by Combining Magnetic Circuit Method and Numerical Magnetic Field Analysis

Yiping Dou [1)], Youguang Guo [2)], Jianguo Zhu [2)], Zhongwei Jiang [3)]
[1)]Nanjing Normal University, China, [2)]University of Technology, Australia, [3)]Nanjing University of Aeronautics and Astronautics, China