Performance comparison of IPMSM with distributed and concentrated windings

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Abstract— **Performance comparison of IPMSMs with distributed and concentrated windings is presented in this paper. Two IPMSMs have been designed with identical rotor dimensions, air gap length, series turn number, stator outer radius, and axial length except winding configuration. Basic parameters and output characteristics, such as inductances, resistances, back emf, output torque, and efficiency, are compared. Design strategy about winding configuration is discussed.**

Keywords-component; IPMSM, Distributed windings, Concentrated windings,2D-FEA, d-q equivalent mode

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 winding can be one of the reasonable choices for winding designs, because almost unit winding factor can be achieved. However, PM machines with distributed winding have several disadvantages such as difficulty in winding automation, long end windings, and larger copper loss than concentrated windings, etc. Comparing to distributed windings, concentrated windings enables easy winding 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.

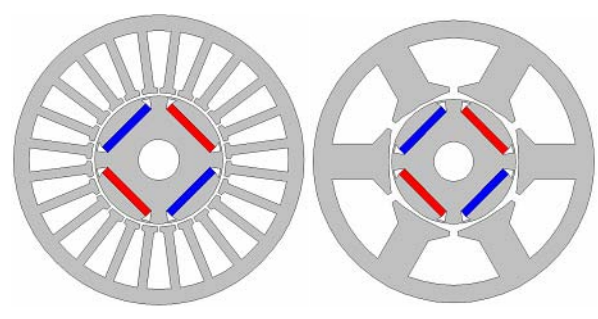
The purpose of this paper is to study the effects on the characteristics of IPMSM when distributed winding is designed to concentrated winding. From basic parameter to output characteristics, both motors are closely compared. Initially, DIS(IPMSM with distributed windings) for high speed application is designed, then CON(IPMSM with concentrated windings) is designed with identical rotor part of DIS. From the basic motor parameters and characteristics, such as inductances, resistances, back emf, output torque, and efficiency, are compared and design strategy about winding configuration is discussed.

II. ANALYSIS MODEL

A. Specifications and structure

Fig. 1 show the models studied in this paper. Both DIS and CON are designed for high speed application. (a) is distributed winding model with 4poles and 24slots and (b) is concentrated winding model with 4 poles and 6slots. The major geometric parameters of DIS and CON are identical; axial length, air gap length, rotor outer radius, stator outer radius, etc. and the only difference is the winding structure. Therefore, the effect of winding configuration on the motor performance can be easily observed.

Generally, concentrated winding machines have higher THD of back emf than distributed winding, therefore, CON is designed to have minimized THD of back emf by teeth tip and slot open width design.



(a) DIS (b) CON
Fig. 1 Comparison of basic stator and rotor configuration

Fig. 2 shows the torque and power versus speed characteristics of both DIS and CON. Until 6,000rpm, constant torque of 17.5 Nm is maintained and from 6,000rpm to 20,000rpm, 11kW 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 1 shows specification of the models. By redesigning winding configuration from distributed winding to

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concentrated winding, resistance of CON is lowered with lower current density. Lower current density could be achieved due to efficient filling factor of DIS.

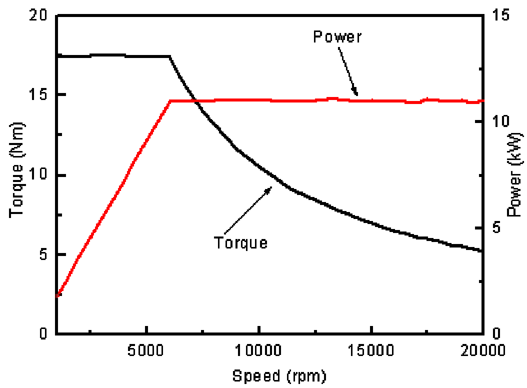


Fig. 2 Torque and power versus speed of designed IPMSMs

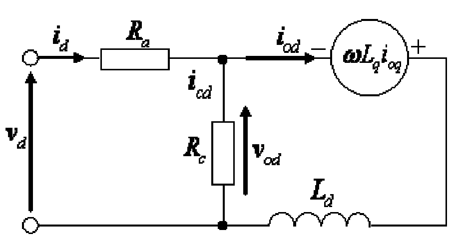
TABLE I. SPECIFICATION OF IPMSMS

	DIS	CON
Output power (kW)	11	11
Max. Torque (Nm)	17.5	17.5
Max. speed(rpm)	20,000	20,000
Number of poles/slots	4/24	4/6
Number of phases	3	3
Series turns	40	40
Number of coils	17	9
Number of parallel circuit	1	2
Resistance (mΩ)	45.7	37
Skew angle (°)	15	15

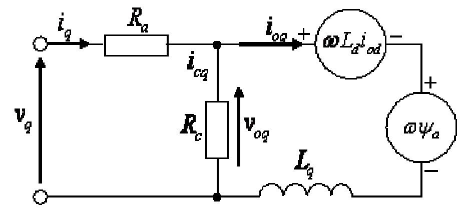
III. BASIC THEORY

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, and motor characteristics are 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 winding 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 iron 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.

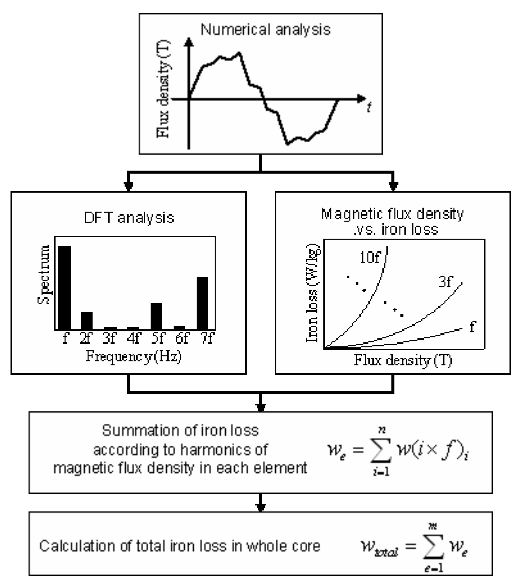


Fig. 4 Procedure of iron loss calculation.

C. Consideration of skew effect

To reduce torque ripple, THD of back emf, and cogging torque, skewing rotor or stator is general. Consideration of skew with 2D FEA can be simply achieved by shifting wave forms to the skew angle with a number of slices then average value is calculated and used.

IV. COMPARISON OF CHARACTERISTICS

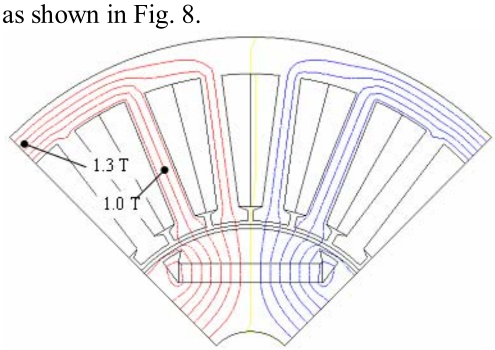
A. Comparision of basic characteristics

Flux densities of DIS and CON at no load are compared in Fig. 5. CON shows lower flux density in the stator yoke than DIS, considering identical yoke thickness, that leads to smaller flux linkage of CON. Therefore, lower back emf and core loss of are produced.

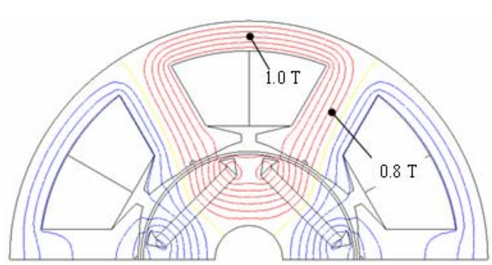
No load back emfs are shown in Fig. 6. Due to pole/slot combination and winding configuration, CON shows 86.6 % of back emf to DIS having almost unit winding factor[1]. Due to skew effect and THD reduction design, both models show low THD.

No load core losses are compared in Fig. 7. Due to lower THD of back emf and flux densities, CON shows lower core loss at entire speed region.

Generally distributed winding with large slot numbers shows lower cogging torque than concentrated windings. In this study, CON designed to have minimum cogging torque within limitations, however it has still much higher cogging torque than DIS as shown in Fig. 8.



(a) Flux density in the yoke and teeth of DIS



(b) Flux density in the yoke and teeth of CON

Fig. 5 Flux density comparison

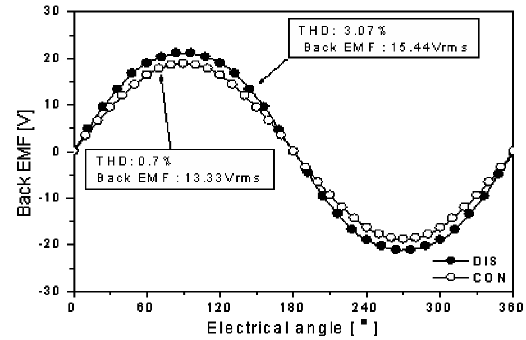


Fig. 6 Comparison of back emf and THD at 1000rpm

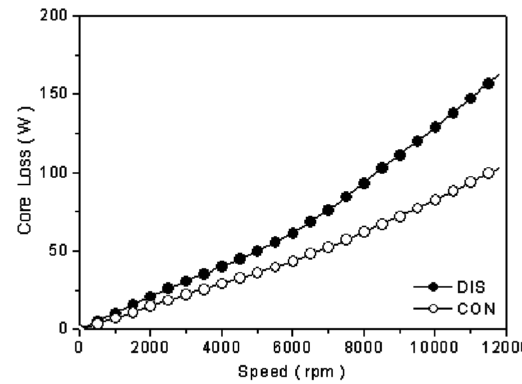


Fig. 7 Core loss comparison

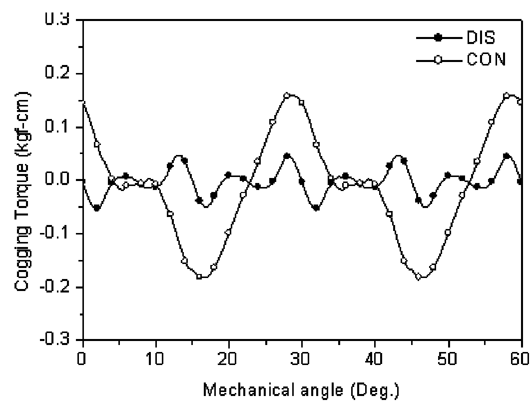
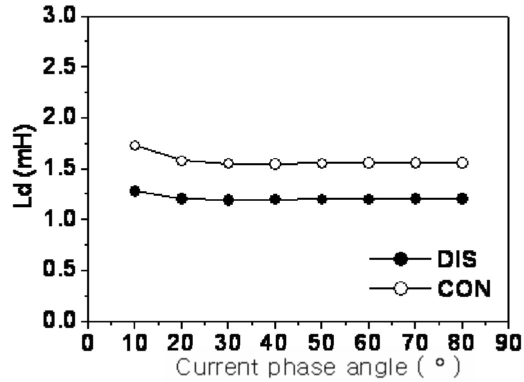
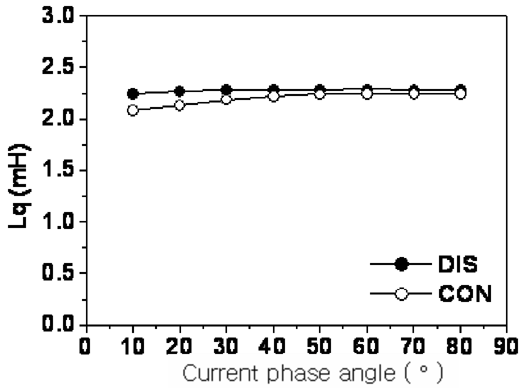


Fig. 8 Cogging torque comparison

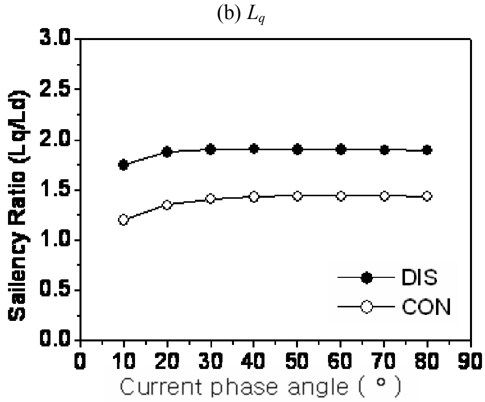
In Fig. 9, saliency ratio, L_d, and L_q are compared. To calculate L_d and L_q, 2D FEA is used. Flux linkages at no load, and each current and current phase angle are calculated. From the comparison, it is found that redesigning distributed winding to concentrated winding results in decrease of saliency ratio. Especially, the increase of L_d significantly affects to the decreased saliency ratio, while the effect of decreased L_q is small.



(a) L_d



(b) L_q



(c) Saliency ratio

Fig. 9 Comparison of inductance and saliency ratio at rated current (43Arms)

B. *Comparision of output characteristics*

When both DIS and CON shows output powers shown in Fig. 2, other characteristics such as current, loss, line to line voltage, etc. are compared.

Fig. 10 shows current and voltage characteristics. Because CON has lower back emf and saliency ratio, it needs more current than DIS to produce required output torque in the constant torque region. However, when the back emf is saturated, CON requires less current due to smaller back emf to weaken.

Core loss and copper loss are shown in Fig. 11. It is found that currents of CON is higher in the constant torque region, however, copper loss becomes close to DIS, that is caused by lower phase resistance of CON.

Resultant efficiencies of both models are shown in Fig. 12. Due to low copper losses DIS shows higher efficiency in the constant torque region, but the difference is not significant. In the constant power region, due to low field weakening current, CON shows higher efficiency than DIS.

Output torque and ripples at 43Arms are calculated by 2D FEA and shown in Fig. 13, where maximum torque per ampere operation is considered. Due to lower back emf saliency ratio, CON shows lower output torque than DIS at identical input current. It is notable that maximum torque of CON is about 86.7% of DIS.

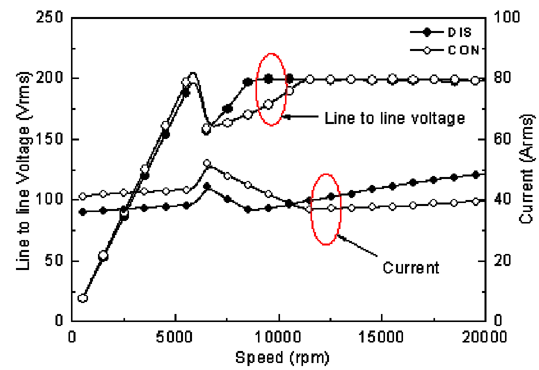


Fig. 10 Voltage and current comparison

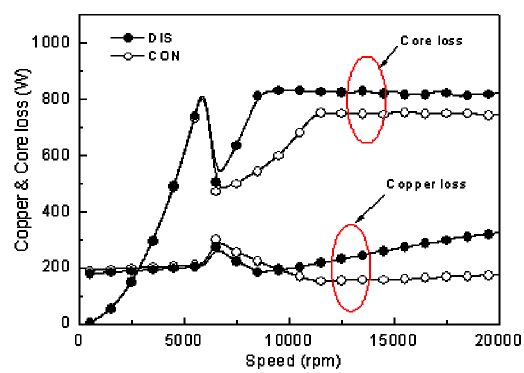


Fig. 11 Core loss and copper loss comparison

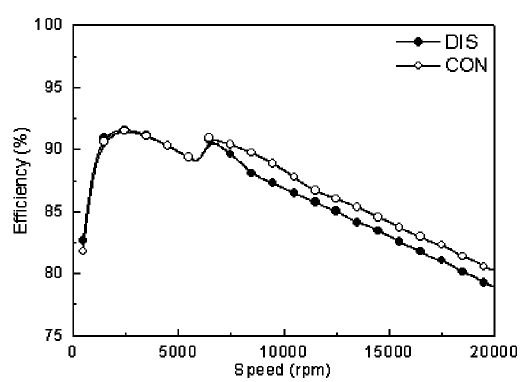


Fig. 12 Efficiency

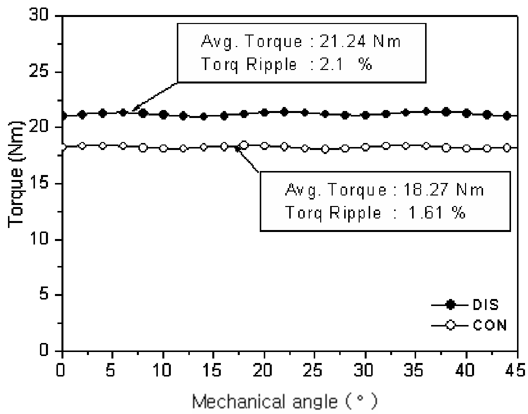


Fig. 13 Output torque and torque ripple at 43Arms

V. SUMMARY

Characteristics of IPMSMs with distributed and concentrated winding are compared in this paper.

More current is required for concentrated winding than distributed winding model due to lower back emf and saliency ratio in constant torque region. The reason for more input current is that the decrease of magnetic torque and reluctance torque. Magnetic torque is reduced by decreased winding factor and the decrease of reluctance torque is caused mainly by increase of L_d.

In the constant power region, lower current is required for concentrated winding due to lower back emf to weaken and increased d-axis inductance.

Therefore, even though more current is required for concentrated windings in the constant torque region, copper loss is close to the distributed winding and less current with high efficiency is achieved in the field weakening region due to low back emf and higher d-axis inductance, and it is expected that concentrated winding is more suitable than distributed winding when field weakening operation at high speed is used.

ACKNOWLEDGEMENT

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