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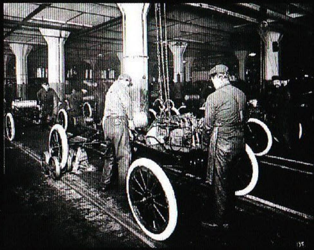

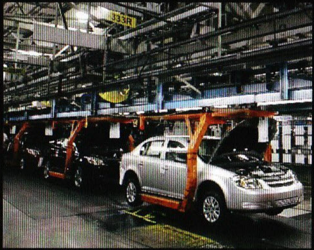

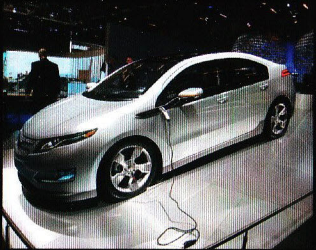

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Characteristics and Radial Magnetic Force of Interior Permanent Magnet Synchronous Motor According to Pole/slot Combinations

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Abstract— **This paper presents motor characteristics and radial magnetic force (RMF) of interior permanent magnet synchronous motors (IPMSM) according to pole/slot combinations. Three IPMSM of 15, 18, 24 slots with 16 poles are selected; 16 poles 15 slots and 18 slots provide high winding factor and 16 poles 24 slots is a general pole-slot combination. Using finite element analysis (FEA) and equivalent circuit analysis, output characteristics and motor parameters such as back electro-motive force (bemf), inductance, etc. are compared, and RMF in air gap causing noise and vibration is investigated. It is expected that presented study results help with appropriate choice of pole and slot number of IPMSM.**

Keywords-component; Interior Permanent Magnet Synchronous Motor (IPMSM); winding factor, radial magnetic forces.

I. INTRODUCTION

Permanent magnet motors have a wide application because they offer excellent maintainability, controllability, and environmental endurance while providing high-efficiency operation with high power factor[1]. Especially, IPMSM has high power density because it utilizes magnetic torque as well as reluctance torque and provides wide speed range by field weakening control. Therefore, a lot of interests are focused on IPMSM.

In designing IPMSM, appropriate choice of pole and slot number takes important parts as well as winding configuration. The winding layouts of motor generally are divided into concentrated winding and distributed winding. The concentrated winding has the advantages of short end-coil and simple structure suitable for high volume automated manufacturing in comparison with the distributed winding[2], however, problems, generally lower winding factor, higher torque ripple and cogging torque than distributed winding, should be solved.

Depending on the pole/slot combinations of concentrated winding, winding factor, torque ripple and cogging torque can be dramatically improved without detailed design. However, instead of improvements, other motor characteristics can be worse. In some fractional pole/slot combinations, if the machine has parallel circuits, circulating current induced and this increase the electric noises and additional copper loss.

Noise and vibration are also important characteristics and RMF is one of the sources. RMF varies with pole/slot combinations and should be investigated in designing stage. In some cases of pole/slot combinations, unbalanced RMF occurs and it damages bearings and finally leads to system failure.

Therefore, this paper investigates motor parameters and RMF in air gap for pole/slot combination. Among various pole number, 16poles are chosen since it provide fractional pole/slot with unbalanced, balanced, and conventional combinations, 16poles 15slots (16p15s), 16poles 18slots (16p18s), 16poles 24 slots (16p24s) respectively.

II. THEORY

A. $d-q$ model of IPMSM

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

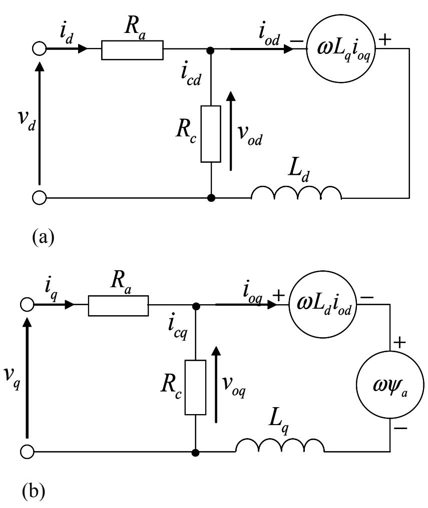


Figure 1. *d-q* equivalent circuit; (a) *d*-axis equivalent circuit, (b) *q*-axis equivalent circuit

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

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

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

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.

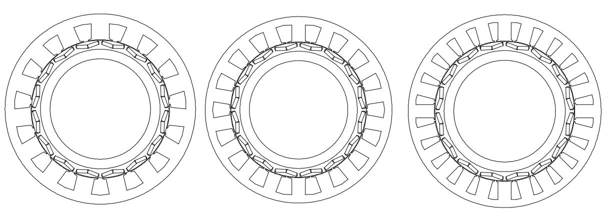
III. STUDY MODEL

A. Study Model and Specification

Basic specifications of study model are listed in Table I and rotor and stator geometries are shown in Figure2. Three models have identical rotor size and permanent magnet volume, with 15, 18, 24 slots. Yoke and tooth width are designed to have identical filling factor of coil with identical current density for each model without detailed design.

TABLE I
BASIC SPECIFICATION

Contents \ Model	16p15s	16p18s	16p24s
Output Power (kW)		12	
Stator Outer Diameter (mm)		277	
Stack Length (mm)		32	
Air gap Length (mm)		0.8	
Rotor Outer diameter (mm)		200	
Series Turn Per Phase		52	
Parallel Circuit	5	6	8



(a) (b) (c)

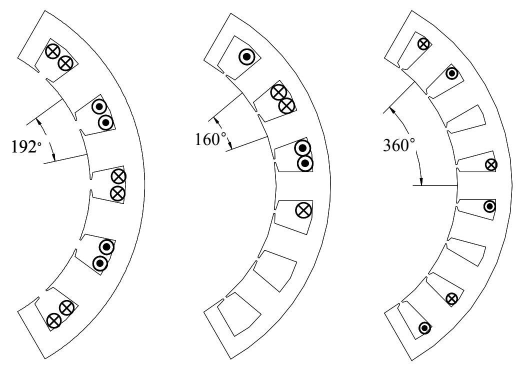
Figure 2. Study model; (a) 16p15s, (b) 16p18s,(c)16p24s

B. Winding Configuation

Winding configurations of three models for one phase are shown in Figure 2. Winding configuration affected by pole/slot combination, and this leads to the winding factor variation. Winding factor of 15slots, 18slots, 24slots with 16poles are calculated as 0.951, 0.931, 0.866 respectively [2], [5].

Another important factor is circulating current when parallel circuit is used. As shown in Figure 3, due to different slot pitch in electrical degree, angular positions of each coil of one phase in 15 and 18 slots are different. Therefore, circulating currents occurs in 15 and 16slots. Circulating currents decreases efficiency and increases electric noise Therefore, parallel circuits should be avoided in 15 and 18 slots with 16 poles.

In addition, it is general for 24slots models using 1/8 models on the basis of periodicity, while 15 does full model and 18slots does 1/2 model. This should be considered in the planning stage of design since detailed design with full modeling requires huge computation with FEA.



(a) (b) (c)

Figure 3. Winding configuration of one phase (1/3 model)

IV. COMPARISON OF PARAMETERS

A. Back EMF, THD, Cogging Torque

Figure 4 shows harmonic components of line - line bemf of three models by FEA at 1000rpm. With identical series turn per phase, 16p15s provides the highest fundamental bemf due to high winding factor with low harmonic components.

Cogging torques of three models are presented in Figure 5. Large least common multiple of pole and slot number of 15slot leads to minimum cogging torque among three models.

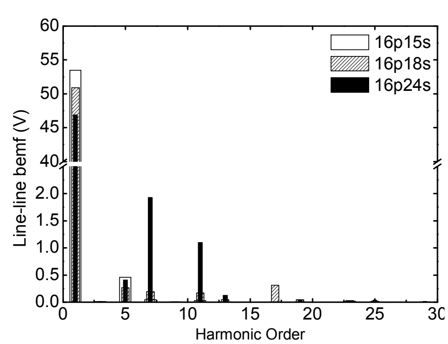


Figure 4. The comparison harmonic component of line to line bemf

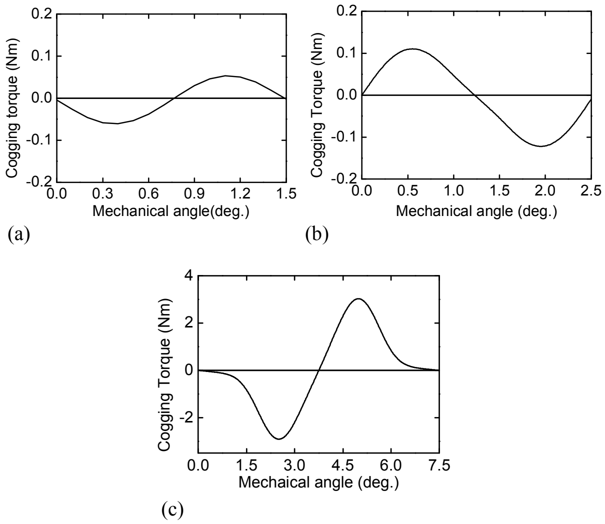


Figure 5. The comparison of cogging torque; (a) 16p15s, (b) 16p18s, (c) 16p24s

B. *Inductances*

In addition to bemf, *d* - *q* inductances are important parameters in IPMSM, since they directly affect to field weakening ability and maximum torque. *d* - *q* axis inductances are calculated by FEA on the basis of Figure 6 and (1) in steady state. Figure 7 shows the comparison of the d-q inductances and saliency at rated current.

Due to high winding factor, 16p15s shows highest inductances. Especially *d*-axis inductance is high with low saliency ratio. Therefore, 16p15s have lower reluctance torque with the larger magnetic torque than 16poles 24slots. The analysis results of *d* - *q* equivalent circuit analysis are shown in Figure 9. In constant torque region below 2000rpm, maximum torque per ampere (MTPA) control method is applied and field weakening control with maximum efficiency is applied. 16poles 15slos model requires minimum current in MTPA region, while 16p18s does in field weakening region.

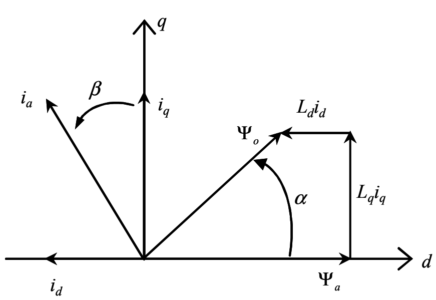


Figure 6. Vector diagram of IPMSM

$$L_d = \frac{\Psi_o \cos\alpha - \Psi_a}{i_d}, \quad L_q = \frac{\Psi_o \sin\alpha}{i_q} \tag{4}$$

where, ψ_a is flux linkage by permanent magnet, ψ_o is resultant flux linkage by permanent magnet and armature reaction , id is d-axis current, iq is q-axis current, α is phase angle between ψ_a and ψ_o, β is current phase angle respectively.

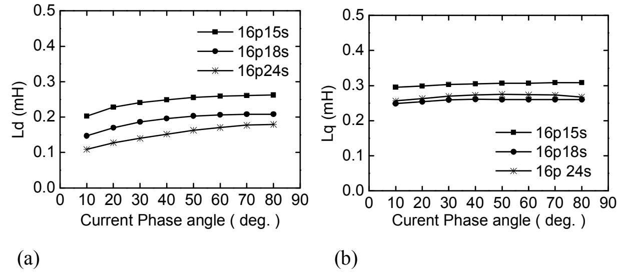


Figure 7. Comparison of inductance at rated current

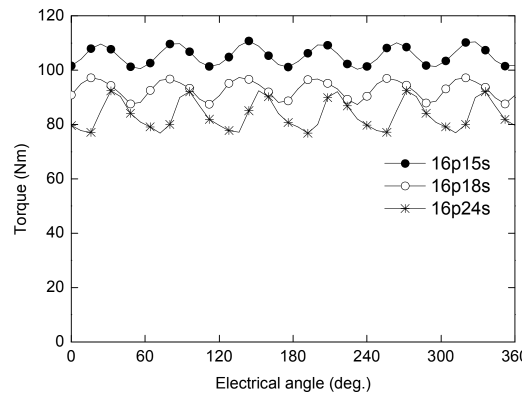


Figure 8. Comparison of output torque

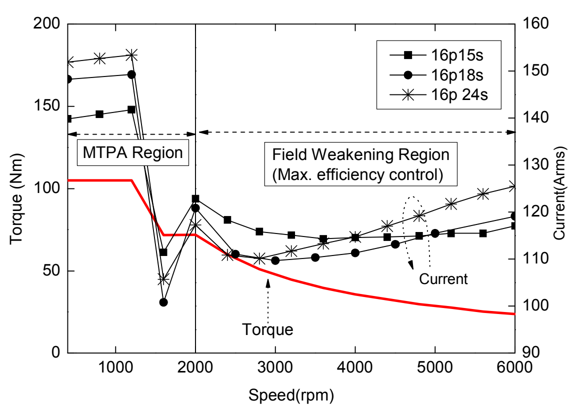


Figure 9. Input current according to speed and torque

C. *Torque and Ripple*

In order to compare torque and torque ripple, identical current with zero current phase angle (β) are applied to three models, and Figure 8 shows the torque and torque ripple of three models. 16p15s shows the largest torque with the smallest torque ripple. To improve torque ripple of IPMSM, pole angle, position of permanent magnet, etc. are available design parameters and this requires large number of FEA [4]. The result shows that improvement of torque and torque ripple can be easily achieved by choosing appropriate pole/slot combination

V. RADIAL MAGNETIC FORCE

Magnetic noise results from RMF that make the stator vibrate. RMF are attractive forces between the stator and rotor while tangential forces act on the rotor to produce torque. The forces that generate magnetic noise are mostly the radial forces [3]. Generally, RMF of rotation machines cancel each other but 16p15s as shown Figure 2 which has asymmetry winding arrangement generates unbalanced RMF.

FEA is used to calculate the RMF. The computation relies on the Maxwell Stress method. For this computation, only the normal component of the flux density is taken into account.

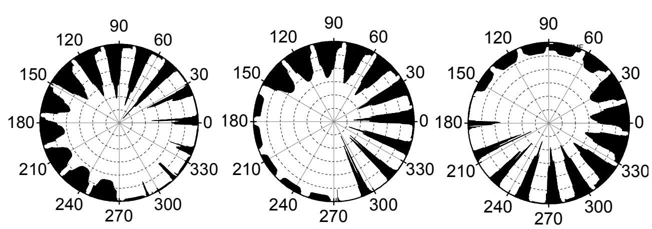
$$\sigma(\theta,t) = \frac{1}{2\mu_0} B_n(\theta,t)^2 \quad (\text{N/m}^2) \tag{5}$$

where σ is RMF density, θ is the angular coordinate, t is the time, μ_0 is the permeability of free space, and B_n is the radial component of the air gap flux density respectively.

Figure 10 and Figure 13 show RMF distribution and harmonic analysis results of 16p15s. Due to the asymmetric winding configuration, RMF distributions become unbalanced, and this results in serious noise, vibration, especially damages on bearings.

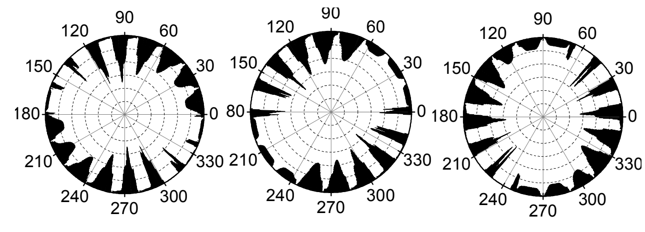
Figure 11 and 14 show RMF distribution of 16poels 15 slots. RMF distributions are symmetric and peak RMF is smaller than 16p18s. Although the RMF distributions 16p18s are symmetric, since high RMF components are distributed only 2 sides along air gap, relatively high noise and vibration are expected than 16poles 24slots. The frequency of fundamental component is 2 times of 16p15s.

Figure 12 and 15 show RMF distribution and harmonic component of 16poles 24slots. The frequency of fundamental component of RMF is 8 times of 16p15s. It is found that 16p24s provides relatively low winding factor, high cogging torque, and THD of back emf, however, RMF distribution in air gap is symmetric, periodic, and balanced.



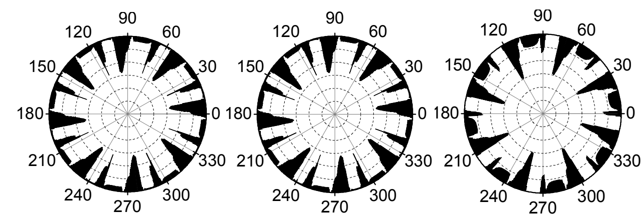
(a) (b) (c)

Figure 10. RMF of 16p15s (rated current, $\beta = 0°$); (a) $wt = 0°$, (b) $wt = 40°$, (c) $wt = 88°$



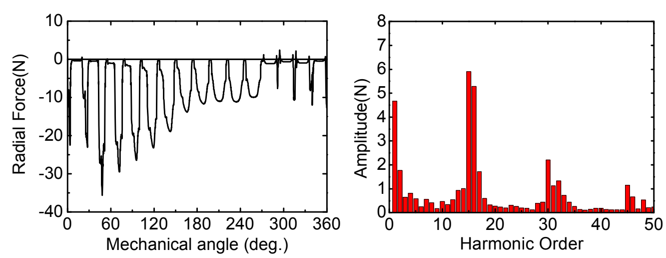
(a) (b) (c)

Figure 11. RMF of 16p18s (rated current, $\beta = 0°$); (a) $wt = 0°$, (b) $wt = 40°$, (c) $wt = 88°$



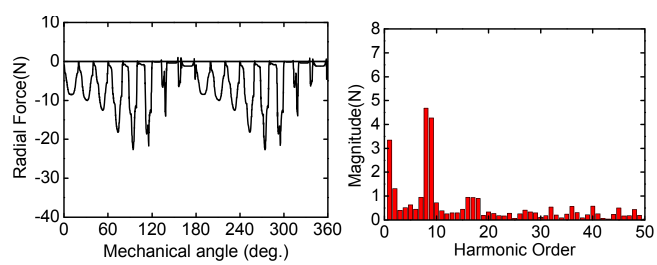
(a) (b) (c)

Figure 12. RMF of 16p18s (rated current, $\beta = 0°$); (a) $wt = 0°$, (b) $wt = 40°$, (c) $wt = 88°$



(a) (b)

Figure 13. RMF of 16p15s (rated current, $\beta = 0°$); (a) RMF distribution in airgap, (b) Harmonic analysis



(a) (b)

Figure 14. RMF of 16p18s (rated current, $\beta = 0°$); (a) RMF distribution in airgap, (b) Harmonic analysis

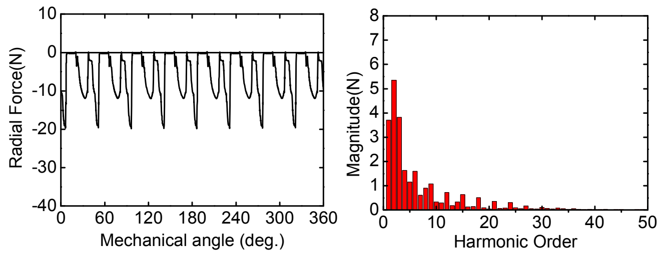


Figure 15. RMF of 16p24s (rated current, $\beta = 0°$) ; (a) RMF distribution in airgap, (b) Harmonic analysis

VI. Conclusion

By choosing appropriate pole/slot combination, required motor parameters such as bemf, cogging torque, and torque ripple reduction can be easily achieved without detailed design.

Inductances are important parameter especially in IPMSM since characteristics of output torque, operating speed, etc. are greatly influenced. Combinations providing high winding factor; 16p15s and 16p18s, give high d-axis inductance and better field weakening ability then 16poles 24slots.

Among three models, 16p18s shows best characteristics with high winding factor and field weakening ability, low cogging torque, and torque ripple with balanced RMF. However, circulating current occurs when parallel circuit is used. Moreover, relations between RMF and noise and vibration should be investigated. Comparisons of parameters and characteristics of the studied models are summarized in Table II.

TABLE II
COMPARISON OF PARAMETERS AND CHARACTERISTICS

Contents \ Model	16 p15 s	16p18s	16p24s
Winding factor	0.951	0.931	0.866
Normalized back emf	1	0.943	0.865
THD of bemf (%)	0.866	0.97	4.82
Cogging Torque (Peak-Peak, Nm)	0.11	0.25	6.08
Reluctance Torque(Nm)	1	2.81	6.52
Torque Ripple (%)	9.84	10.73	18.68
Ld(mH)	0.262	0.208	0.18
Saliency(Lq/Ld)	1.4	1.6	1.9
RMF distribution	Unbalanced	Balanced	
Resistance (mΩ)	15.18	11.49	12.73
Parallel circuit	Should be avoided to prevent circulating current		Available

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