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Venue: Room G
Chairs: Petr Blaha
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Kichiro Yamamoto
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Ecole Polytechnique Fédérale de Lausanne (EPFL), Institute of Microengineering (IMT), Integrated Actuators Laboratory (LAI), Switzerland

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Improvement of Current Waveforms of Position Sensor-Less Vector Controlled Permanent Magnet Synchronous Motor at High Frequency Region
Noboru Koshio, Hisao Kubota, Ichiro Miki, Kouki Matsuse
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Sensorless Control Performance of IPMSM with Over-Modulation Range at High Speed
Shunsuke Shimizu, Shigeo Morimoto, Masayuki Sanada
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Accurate Estimation of Initial Rotor Position for Brushless DC Motor Position Sensorless Drive
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Performance Improvement by Making Holes of Interior Permanent Magnet Synchronous Motor

Tae-geun Lee, Do-jin Kim, Jung-Pyo Hong
Department of Automotive Engineering, Hanyang University, Seoul, South Korea
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***Abstract*—This paper discusses a study on Interior permanent magnet synchronous motor(IPMSM) which has high power density. The focus is placed on applications where the centrifugal forces due to high-speed operation are the major mechanically limiting design factor. In order to improve efficiency performance of IPMSM, this paper presents a study by making hole around barrier. The suitable hole disperses rib stress that is concentrated by the centrifugal force. And the use of hole can be reduced rib thickness of IPM rotor and it can help reduction of the PM[Permanent Magnet] leakage flux. And saliency ratio can be also increased. For this study, structure analysis of rotor is performed by finite element method (FEM). And electromagnetic parameters of the improved IPMSM are calculated by using the equivalent circuit method (ECM) and finite element method (FEM). And characteristic analysis is performed and we confirm that efficiency is improved. This example presents that it is possible to significantly improve the rotor's structural integrity and motor efficiency using the techniques described in this paper.**

***Index Terms*— Centrifugal force, Hole, IPMSM(Interior permanent magnet synchronous motor), Rib stress, Stress dispersion.**

I. Introduction

The interior permanent magnet synchronous motors (IPMSM) have wide applications to household goods, industrial use, and electric and hybrid vehicle propulsion. Because of their superior performance characteristics, that including high efficiency, high torque density, and wide constant power operating range, the IPMSM is to be a good machine for vehicle propulsion.

In IPM motors, the PM are buried insider the rotor core, which is not only for avoiding the separation of PM caused by the centrifugal force at high speed, but also for employing a hybrid torque generation, that including magnet torque and reluctance torque. The magnet torque is produced by the permanent magnets, and the reluctance torque is generated from the unique rotor structure[1]. Fig. 1(a) illustrates a conventional IPM rotor structure, that the axis directly along the d-axis exhibits high reluctance due to the low permeability of PM, while along the q-axis that between the flux-barriers inside the IPM rotor, there exists no magnetic barrier, that having low reluctivity to magnetic flux. This variation of the reluctance around rotor creates rotor saliency effect, which can generate reluctance torque in addition to the magnet torque[2]. By utilizing the unique hybrid torque generation, the high efficiency performance can be achieved[3].

According to the analysis of hybrid torque characteristics above, the increase of reluctance torque production due to higher rotor saliency can compensate the decrease of magnet torque production when generating specific torque production. In general, the higher the rotor saliency creates, the lower the dependency on magnet torque. As a result, the currents fed to the stator windings can be reduces and the copper loss caused in armature windings decreases correspondingly, which is helpful to improve motor efficiency performance.

First, this paper presented a study by rotor structure analysis. As previous mention, IPM rotor core was affected by the centrifugal force at high speed. The force is generally concentrated in rib. Therefore the rib must be thick. However the more rib is thick, the more magnetic flux leakage is increased. If rib is thick, structural safety is good. But efficiency is bad. Therefore in IPMSM design, structure analysis of rotor is important because of avoiding the separation of PM and motor performance at high speed.

Second, this study presented that concentrated stress of IPMSM Rotor dispersed by drilling holes around barriers. Because of this application, concentrated stress of rib was dispersed and rib thickness was reduced.

Third, the machine parameters and performances are calculated by using finite element method(FEM) and equivalent circuit method(ECM).

Finally, the machines characteristics between the prototype IPMSM model and the IPMSM model applied hole are compared to investigate the improvement of motor performance.

II. Theory

A. Model and The centrifugal force of Rotation Machine

In rotating machine, stress of rotor can be divided by tangential stress (1) and radial stress (2) in a homogenous annulus of uniform thickness with inner radius, *Ri*, outer radius, *Ro*, spinning at angular velocity, ω [5]. And the ρ is the density and v is the poisson's ratio of material. Fig. 1(b) shows stress direction of element for rotating machine.

And the mechanical stress of the rib is mainly in the

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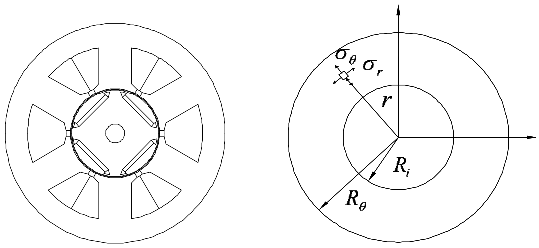
form of tangential tensile stress. So mainly this tangential stress formula (1) is used to find analytical method of rib stress in IPMSM[4]. But the formula is applied for Homogenous annulus of uniform thickness. Rotor which we analyzed isn't annulus of uniform thickness. Therefore there is all difference between analytical results and FEM (Finite Element Method) analysis. So this study used FEM analysis and formula (1), (2) is only used to decide design direction of improved model.

$$\sigma_\theta(r) = \frac{3+\upsilon}{8}\rho\omega^2\left[R_0^2 + R_i^2 + \frac{R_0^2 R_i^2}{r^2} - \frac{1+3\upsilon}{3+\upsilon}\right] \quad (1)$$

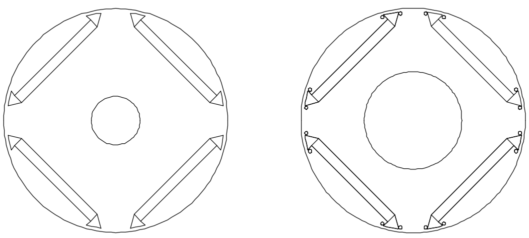
$$\sigma_r(r) = \frac{3+\upsilon}{8}\rho\omega^2\left[R_0^2 + R_i^2 - \frac{R_0^2 R_i^2}{r^2} - r^2\right] \quad (2)$$

TABLE I
SPECIFICATION OF ANALSIS MODEL

	Value
Voltage [Vdc]	120
Current Limit [Arms]	6
Max.Torque [Nm]	3.35
Max.Power [W]	700
Base speed / Max speed	2000 / 6000



(a) Prototype IPMSM (b) Stress component of rotating machine
Fig. 1. Motor



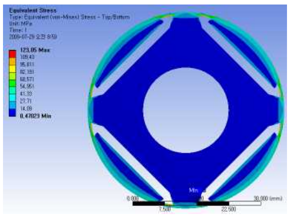
(a) Prototype Rotor (b) Rotor applied hole
Fig. 2. Rotor

B. Structure analysis using for FEM

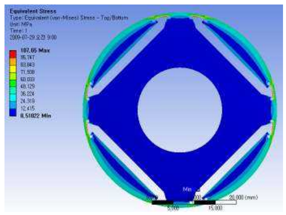
First, Fig2. (a)'s structure analysis was performed. And then it is analyzed. As we anticipated analysis result, stress concentration showed around rib. We focused on dispersion of concentration stress. So we made a hole around barrier and stress of rib was dispersed. TABLE1 is specification of analysis model. Table II appears Max. stress of rib. Generally the more rib thickness reduces, the more increase concentration stress of rib become. But we could reduce rib thickness from 0.7mm to 0.6mm by making holes at same Max. stress of rib. And table II presented that rib 0.6mm_Hole's model acted on the lowest stress. Fig3 showed distribution of rib stress. This analysis was performed to model that don't inserted permanent magnet. And rib maximum stress is based on safety factor '2'.

TABLE II
RIB STRESS

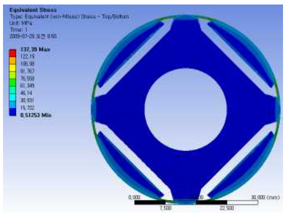
	Rib0.7mm	Rib0.7mm _Hole	Rib0.6mm	Rib0.6mm _Hole
Rib Thickness [mm]	0.7	0.7	0.6	0.6
Hole	no	Yes	no	Yes
Max. Speed [rpm]	18000			
Material	S18			
Y.P [Mpa]	270			
Rib Stress [Mpa]	123.05	107.65	137.4	120.7
Safety Factor	2			



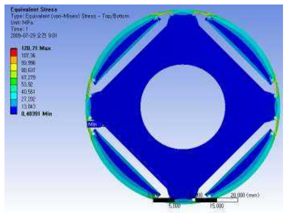
(a) Rib 0.7mm



(B) Rib0.7mm_Hole



(b) Rib 0.6mm



(B) Rib0.6mm_Hole

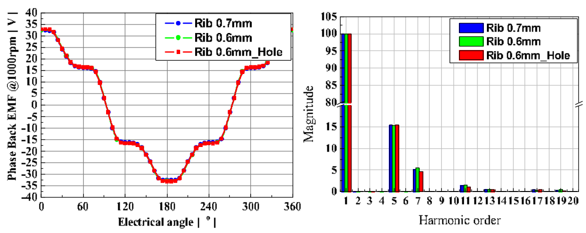
Fig. 3 Stress of rotor

C. Back electromotive force (BEMF) and Total harmony distortion(THD)

Using the FEM, BEMF and THD of model (Rib0.7mm, Rib0.6mm and Rib0.6mm_Hole) was calculated. Fig5. showed BEMF and THD. Generally the more rib thickness reduce, the more increase BEMF become. Table III appeared influence of rib thickness and holes.

TABLE III

	Rib0.7mm	Rib0.6mm	Rib0.6mm _Hole
Phase BEMF [Vrms]	21.18	21.35	21.37
THD[%]	16.38	16.38	16.16

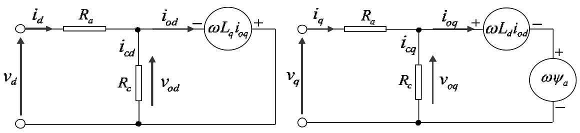


(a) Bemf (B) THD
Fig. 4. Bemf and THD

D. Equivalent Circuits Method (ECM)

Equivalent circuits for IPMSM based on a synchronous d-q reference frame including iron losses are presented in Fig. 3. By using this method, the efficiency performance of IPMSM can be quickly predicted, while the motor characteristics can also be investigated at the same time.

The mathematical model of the equivalent circuit is given as following equations. Iron loss is considered by equivalent resistance R_c[5]. The d- and q-axis voltages and currents are given by equations (1), (2) and (3), and hybrid torque, energy loss and motor efficiency are given by equations (4), (5) and (6) respectively.



(a) *d*-axis equivalent circuit (b) *q*-axis equivalent circuit

Fig. 5 Equivalent circuit of IPMSM model in d-q reference frame

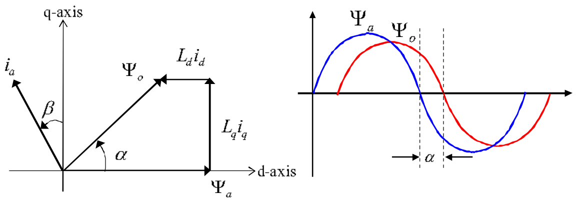


Fig. 6 Calculation of L_d and L_q by FEM

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

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

$$V_a = \sqrt{v_d^2 + v_q^2}, \quad I_a = \sqrt{i_d^2 + i_q^2} \quad (4)$$

$$T = P_n \left\{ \psi_a I_a \cos\beta + \frac{1}{2}(L_q - L_d) I_a^2 \sin 2\beta \right\}$$
$$= P_n \left\{ \psi_a i_{od} + (L_d - L_q) i_{od} i_{oq} \right\} = T_M + T_R \quad (6)$$

$$W_{loss} = W_{iron} + W_{copper} = \frac{\left(v_{od}^2 + v_{oq}^2\right)}{R_c} + \left(i_d^2 + i_q^2\right) R_a \quad (4)$$

$$\eta = \frac{P_{out}}{P_{out} + W_{loss}} \times 100\% \quad (6)$$

$$L_d = \frac{\psi_0 \cos\alpha - \psi_a}{i_d}, \quad L_q = \frac{\psi_0 \sin\alpha}{i_q} \quad (7)$$

$$i_q = I_a \cos\beta, \quad i_d = -I_a \sin\beta \quad (8)$$

Where i_d and i_q are d- and q-axis component of armature current, i_{cd} and i_{cq} are d- and q-axis component of iron loss current, v_d and v_q are d- and q-axis component of terminal voltage, R_a is armature winding resistance per phase, R_c is iron loss resistance, ψ_a is flux linkage of PM per phase(rms), L_d and L_q are d- and q-axis inductance, P_n is number of pole pairs, β is the lead angle of phase current ($\tan^{-1}(-i_d/i_q)$), the saliency ratio is defined as $\rho(L_q/L_d)$, η is the efficiency of IPMSM.

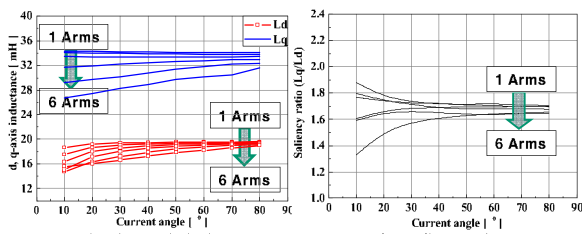
E. Inductance and Salient ratio

If rib thickness was reduced, rotor core is easily saturation. And the both d,q-axis inductance is decreased. But because reduction of d-axis inductance is greater than reduction of q-axis inductance, rotor saliency ratio is increased. And the improved rotor saliency changes the balance of magnet torque and reluctance torque in hybrid torque generation. And the increased reluctance torque production compensated the magnet torque production. Because of this reluctance torque, permanent magnet usage will be reduced.

The d,q-axis inductance and saliency ratio are calculated and compared separately in Fig. 7, 8, 9. Table IV showed parameters in main operating region[@ 4Arms, current angle 40°]. We knew that saliency ratio of rib0.7mm model is more good than rib0.6mm model. Saliency ratio was increased by d-axis saturation when rib thickness reduces from 0.7mm to 0.6mm. Table IV also looked like that saliency ratio wasn't influenced by the holes in same rib thickness because Rib0.6mm_hole model didn't perform optimization of holes position. This paper presented that saliency ratio was improved by rib thickness reduction through making the holes.

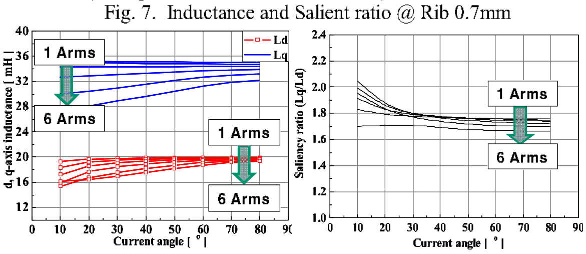
TABLE IV
SALIENT RATIO AND D, Q-AXIS INDUCTANCE
@ 4ARMS, CURRENT ANGLE 40°

	Rib0.7mm	Rib0.6mm	Rib0.6mm _Hole
d–inductance [mH]	19.1	18.8	18.5
q–inductance [mH]	32.9	33.3	32.4
Salient ratio [Lq/Ld]	1.71	1.76	1.75



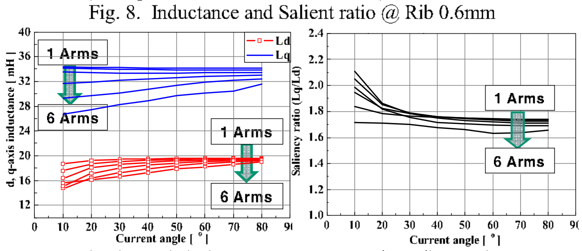
(a) d, q-axis inductance (b) Salient ratio

Fig. 7. Inductance and Salient ratio @ Rib 0.7mm



(a) d, q-axis inductance (b) Salient ratio

Fig. 8. Inductance and Salient ratio @ Rib 0.6mm

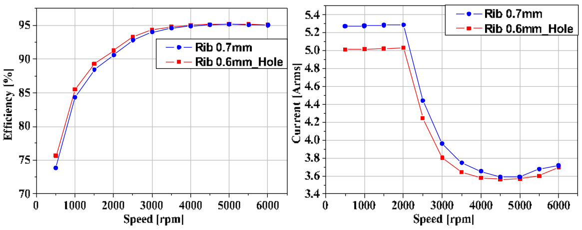


(a) d, q-axis inductance (b) Salient ratio

Fig. 9. Inductance and Salient ratio @ Rib 0.6mm_Hole

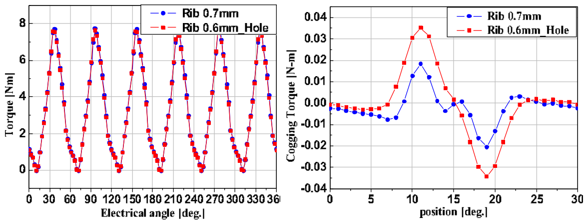
F. Characteristic Analysis

The efficiency and characteristic current at all operation resign is shown in Fig10. The Rib 0.6mm_hole that was applied to holes had more high performance than Rib 0.7mm model. Because of reduction of rib thickness d-axis flux path was saturated. And saliency ratio was improved. Increase of Saliency ratio caused improvement of reluctance torque. The increase of reluctance torque production due to higher rotor saliency can compensate the decrease of magnet torque production when generating specific torque production. In general, the higher the rotor saliency creates, the lower the dependency on magnet torque. As a result, the current fed to the stator windings was reduced and the copper loss caused in armature windings decreases correspondingly, which is helpful to improve motor efficiency performance. The parameters about torque all operation resign is shown in Fig11. Two models have small difference of torque ripple but those have some differences of cogging torque. Therefore IPM rotor design for an electric power steering system (EPS) application seems to be difficult to use the model applied the holes because motor for EPS have a sensibility for cogging torque.



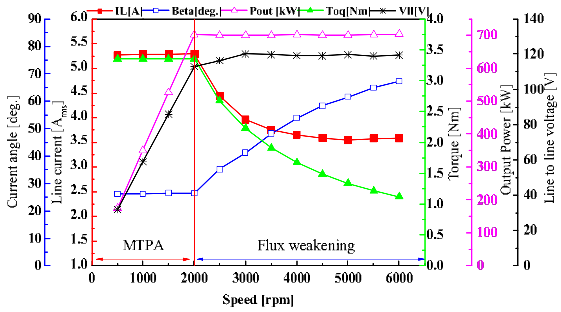
(a) Efficiency (b) Current

Fig. 10. Efficiency and Current at Operation resign

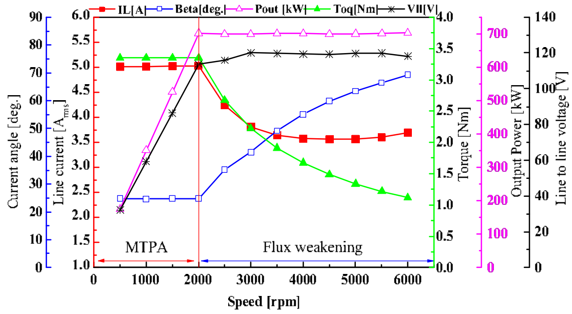


(a) Torque Ripple (b) Cogging Torque

Fig. 11. Efficiency and Current at Operation resign



(a) Rib 0.7mm



(b) Rib 0.6mm_hole

Fig. 12 Inductance and Sailancy ratio @1Arms

III. CONCLUSIONS

This paper has presented the rotor design to apply holes for improving efficiency performance in IPMSM. From the above analyzing based on characteristic comparisons between the prototype Rib 0.7mm model and the Rib 0.6mm_Hole model, we showed the efficiency performance improvement through rotor design to be applied holes. In conclusion to this study, rotor design which was applied holes can generate higher rotor saliency that is helpful to improve machine performances without increasing PM usage.

For IPM motor design it is important to determine holes position and rib thickness through structure analysis. Therefore electromagnetic and mechanical design for optimization design points have to be considered correspondingly.

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