Proceedings

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The 12th International Conference on Electrical Machines and Systems (ICEMS 2009), Tokyo, Japan

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Design and Optimization of External-Rotor Torque Motor
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Huazhong University of Science and Technology, China

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Simple Modeling and Prototype Experiments for a New High-Thrust, Low-Speed Permanent Magnet Disk Motor
Genevieve Patterson[1], Takafumi Koseki[1], Yasuaki Aoyama[2], Kentaro Sako[1]
[1]*The University of Tokyo, Japan,* [2]*Hitachi, Ltd., Japan*

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Satoshi Kikuchi[1], Akeshi Takahashi[1], Hiroyuki Mikami[1], Shin'ichi Wakui[1], Hakuei Kou[2], Keiji Tanaka[2], Masashi Miyake[2], Tomio Yoshikawa[2], Kenji Tojo[2]
[1]*Hitachi, Ltd., Japan,* [2]*Hitachi Appliances, Inc., Japan*

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K. Y. Hwang, B. I. Kwon
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DS2G1-9
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Jin Wang[1], Libing Zhou[1], Tong Yang[1], Yue Wang[2]
[1]*Huazhong University of Science and Technology, China,* [2]*Zhejiang Electric Power Dispatching and Communication Center, China*

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Liang Fang, B. H. Lee, J. J. Lee, H. J. Kim, Jung-Pyo Hong
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Multi-Objective Optimal Design for In-Wheel Permanent Magnet Synchronous Motor
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Design of Multi-Phase Permanent Magnet Motor for Ship Propulsion
Ho-Yong Choi[1], Sun Jung Park[2], Young Kyung Kong[2], Jae Goo Bin[1]
[1]*Hyosung Corporation, Korea,* [2]*Agency for Defense Development, Korea*

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Highly Effective Brushless DC Motor in which the Unidirectional Current Flows
Yasuhiro Komatsu, Tur-Amgalan Amarsanaa, Yosihiko Araki
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Byoung-Ook Son[1,2], Young-kwan Kim[3], Ju Lee[1]
[1]*Hanyang University, Korea,* [2]*Daesung Electric co., Korea,* [3]*Samsung Electric co., Korea*

Session DS2G2
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Time: 13:30-14:45
Venue: Room G
Chairs: Petr Blaha
Brno University of Technology, Czech Republic
Kichiro Yamamoto
Kagoshima University, Japan

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PM Motor Sensorless Position Detection Based on Iron B-H Local Hysteresis
Omar Scaglione, Miroslav Markovic, Yves Perriard
Ecole Polytechnique Fédérale de Lausanne (EPFL), Institute of Microengineering (IMT), Integrated Actuators Laboratory (LAI), Switzerland

DS2G2-2
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
Meiji University, Japan

DS2G2-3
Sensorless Control Performance of IPMSM with Over-Modulation Range at High Speed
Shunsuke Shimizu, Shigeo Morimoto, Masayuki Sanada
Osaka Prefecture University, Japan

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Accurate Estimation of Initial Rotor Position for Brushless DC Motor Position Sensorless Drive
Kentarou Hatakeyama, Shinsuke Nakano, Nobuyuki Kurita, Takeo Ishikawa
Gunma University, Japan

Study on High-Efficiency Characteristics of Interior Permanent Magnet Synchronous Motor With Different Magnet Material

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***Abstract*--This paper presents a study on interior permanent magnet synchronous motors (IPMSM) design with different PM materials, ferrite and NdFeB magnet, for achieving high efficiency performance. The high efficiency performance for IPMSM is analyzed based on energy losses balance analysis between iron losses, copper loss and mechanical loss. In addition, the important machine characteristics are also analyzed. The finite element analysis (FEA) is used to precisely calculate machine parameters, and then the equivalent circuit method (ECM) is performed for predicting motor performances. The calculated results are confirmed by testing the two type Ferrite/NdFeB IPM synchronous motors. In final, the high-efficiency IPMSM design process is concluded.**

***Index Terms*— ECM, Ferrite/NdFeB magnet, FEA, high-efficiency IPMSM.**

I. INTRODUCTION

Interior permanent magnet synchronous motors (IPMSM) have widely applications to household goods, due to their superior performance characteristics, such as high torque density, high efficiency and wide operation range characteristics [1].

In the structural point, the IPM motors have PM segments 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, magnet torque and reluctance torque, 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, which benefits to the high efficiency performance of IPMSM [2].

The properties of magnet materials significantly affects the machine performance [3]. In this paper, ferrite magnet and rare-earth magnet (NdFeB) are used in the IPMSM designs for high efficiency performance. As well known, the ferrite magnet is less expensive and available for forming the PM in various shapes, but the magnetic flux density is low, therefore hindering the reduction in size of the rotor core. On the other hand, the NdFeB magnet has a high magnetic flux density, so that the reduction in size of the rotor core is easy, but the shape of the PM is limited by difficulty of forming. In addition, the NdFeB magnet is more expensive than the ferrite magnet. Due to the different attribute of ferrite and NdFeB PM material, the electric field and magnetic field reacted inside IPMSM are quite different. It results in the different balance between the energy losses produced at each part, such as the iron loss in the yoke part and teeth part of stator, copper loss in armature windings, and the mechenical loss.

With both use and cost consideration, the efficiency performance of IPMSM with different PM materials, ferrite and NdFeB are studied, for investigating the energy losses balance with high-efficiency performance. [4]. Each of energy loss component should be considered for improving the motor efficiency peformance in the motor design.

In the study, the machine parameters and performances are calculated by using finite element method (FEM) coupled with equivalent circuit method (ECM). And the experiment is setup to confirm the presnet analysis. Finally, the IPMSM characteristics with adopting different PM material are compared to investigate the motor high efficiency performance.

II. ANALYSIS MODELS AND METHOD

A. Ferrite/NdFeB IPMSM Models

In this study, two 4-pole/6-slot IPMSMs are designed with ferrite and NdFeB PM material, for achieving required high efficiency performance [>92%] at main operation speed [1800 rpm, 3600rpm]. Fig. 1 shows the basic model of IPMSM stator and rotor structure with buried magnets. TABLE I lists the specification of the two designed IPMSMs. The differece of B_r characteristic of ferrite PM and NdFeB results in the different amount of PM usage for generating similar air gap field.

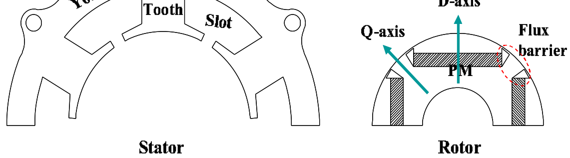


Fig. 1. Configuration of basic 4-pole/6-slot IPMSM model

TABLE I
DIMENSION AND SPECIFICATION OF FERRITE / NDFEB IPMSM

Machine Item	Ferrite IPMSM	NdFeB IPMSM	Unit
Stator outer diameter	117	117	mm
Rotor outer diameter	64	46	mm
Stack length	45	45	mm
Air-gap	0.7	0.7	mm
Br (@20~25°C)	0.45	1.3.	T
Amount of PM (/pole)	248*45	44*45	mm^3
DC link voltage	310	310	V_{rms}
Rated output power	185	185	W
Max. current	1	1	A_{rms}
Rated speed	1800 / 3600	1800 / 3600	Rpm
Rated torque	4.5	4.5	Kgf·cm

B. Efficiency Performance Analysis

Equivalent circuits for IPMSM based on a synchronous *d-q* reference frame including iron losses are presented in Fig. 2. 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.

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

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

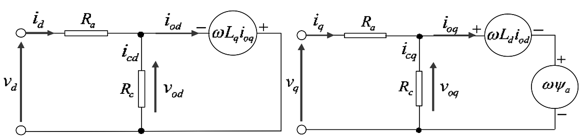
$$V_a = \sqrt{v_d^2 + v_q^2}, \quad I_a = \sqrt{i_d^2 + i_q^2} \quad (3)$$

$$\begin{aligned} T &= P_n \left\{ \psi_a I_a \cos\beta + \frac{1}{2}(L_q - L_d) I_a^2 \sin 2\beta \right\} \\ &= P_n \left\{ \psi_a i_{od} + (L_d - L_q) i_{od} i_{oq} \right\} = T_M + T_R \end{aligned} \quad (4)$$

$$W_{loss} = W_{iron} + W_{copper} = \frac{\left(v_{od}^2 + v_{oq}^2\right)}{R_c} + \left(i_d^2 + i_q^2\right) R_a \quad (5)$$

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

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.



(a) *d*-axis equivalent circuit (b) *q*-axis equivalent circuit
Fig. 2. Equivalent circuit of IPMSM model in d-q reference frame

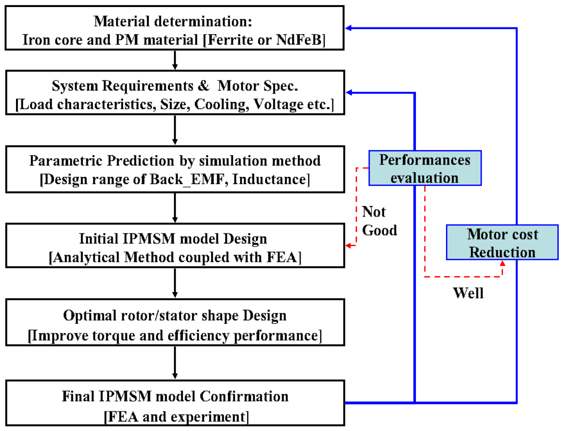


Fig. 3. Flowchart of design process of IPMSM with cost consideration

III. IPMSM DESIGN PROCESS

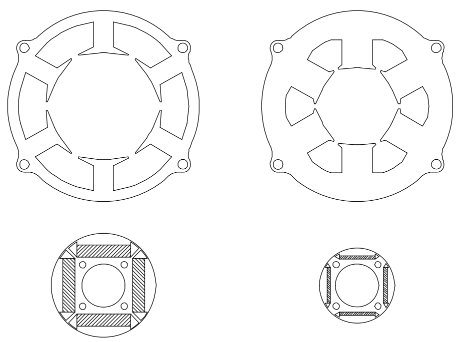
In this paper, the IPMSM design focuses on high efficiency performance at main operation situation (1800rpm and 3600rpm). In addition, the cost of final motor is considered for the further cost reduction design. The IPMSM design process is illustrates as given flowchart in Fig. 3, that beginning from material to the IPMSM structure optimal design, including machine performance evaluation and cost analysis.

A. Stator design

In the stator part structure design, the slot region is determined with considering the fill factor of armature windings concentrated arrangement [6]. Then, the resistance of copper winding can be calculated. Consequently, the other part is investigated with varying the ratio of thickness to determine teeth and yoke design for minimizing the iron losses in the stator iron core. As the above analysis, the stator structure design significant relates to motor efficiency performance according to the balance of energy losses of copper loss and iron losses.

B. Rotor design

Since different ferrite and NdFeB magnet materials are used in the IPMSM designs, the rotor should be designed with fully considering the properties of magnet materials since the motor characteristics are quite sensitive to the inner structure of IPM rotor, such as flux-barriers and PM positions. As mentioned, the high flux density NdFeB PM causes small size of rotor, as Fig. 4 shows.



(a) Ferrite magnet IPMSM model (b) NdFeB magnet IPMSM model
Fig. 4. IPMSM 4-pole/6-slot designs with different magnet material

IV. Results And Discusses

The IPMSM model designed with ferrite and NdFeB materials are analyzed by performing the presented equivalent circuits, and the machine characteristics are calculated by using 2-dimensional FEA. Their Back-EMF and d-q axis inductances characteristics are compared in Fig. 5 and Fig. 6. It is found that the Back-EMF characteristic with similar fundamental component is produced for achieving required high efficiency performance. As well as the large differences of inductance reacted due to different material properties of ferrite and NdFeB. With same rated output torque, the efficiency performances are compares as Fig. 7 shows. The lower mechanical loss due to smaller rotor size helps NdFeB IPMSM to achieve high efficiency performance.

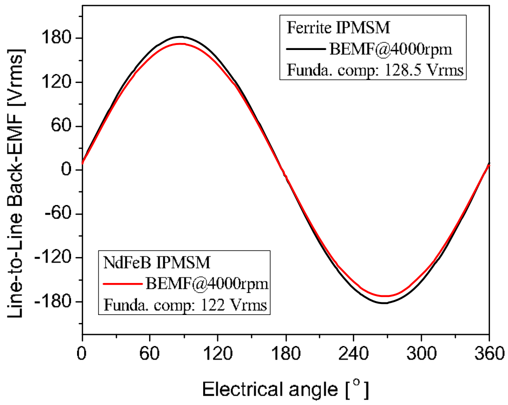


Fig. 5. Back-EMF characteristic comparison

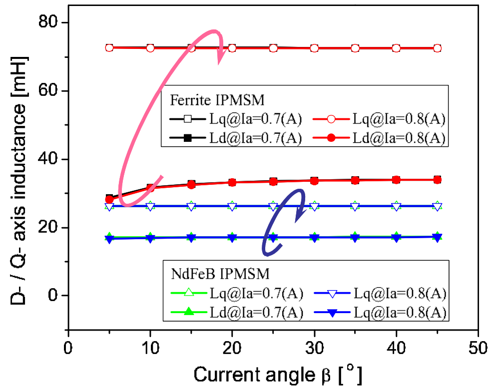


Fig. 6. D-axis and q-axis inductance characteristic comparison

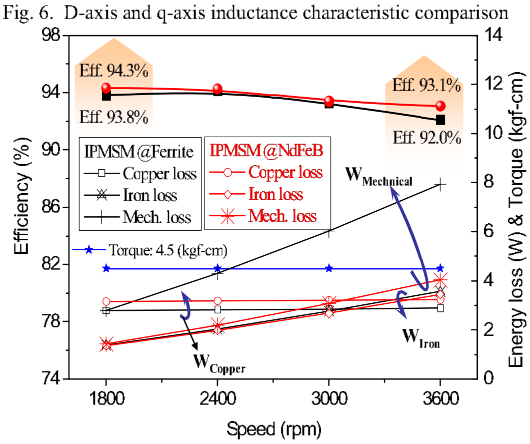


Fig. 7. Torque, efficiency performances and energy losses comparison.

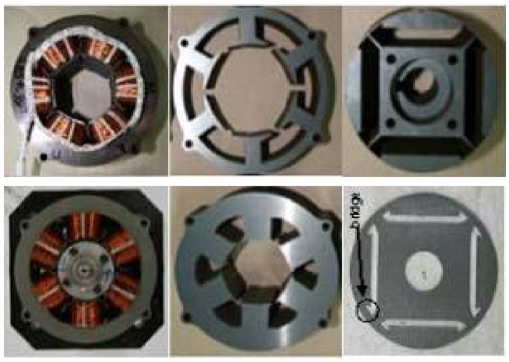


Fig. 8. Fabricated 4-pole/6-slot IPMSMs (ferrite and NdFeB magnet)

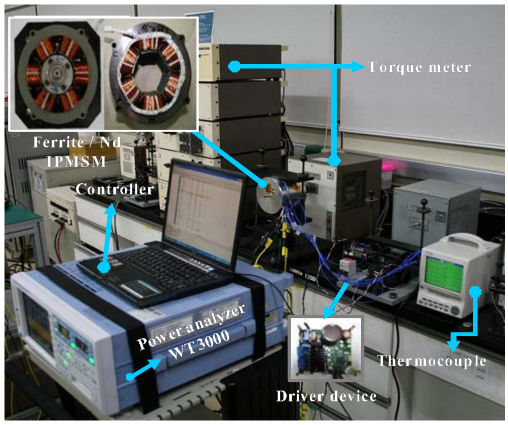


Fig. 9. Experiment setup for test characteristic of IPMSM.

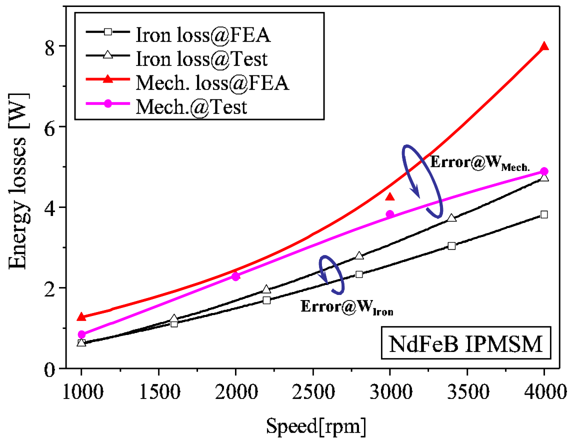


Fig. 10. Iron losses and mechanical loss confirmation by test

As Fig. 8 shows, both of the designed ferrite and NdFeB IPMSMs are fabricated. And then, they are tested using the experiment setting shows in Fig. 9. It is found that NdFeB IPMSM model has better efficiency performance due to the lower iron losses and mechanical loss. Therefore, the iron losses and mechanical loss are tested for confirming the presented ECM analysis, as Fig. 10 illustrated. A general good agreement is obtained.

On the other hand, NdFeB and ferrite IPMSMs are manufactured costing about [0.85:1] with all material consideration. From cost reduction standpoint, the high cost NdFeB magnet is chosen for final IPMSM design.

V. CONCLUSION

This paper presented a study on ferrite and NdFeB PM excited, two IPMSM designs for achieving high efficiency performance requirement within the same frame size. The different balance ratio between each components of energy loss is analyzed with motor efficiency. Compare with ferrite IPMSM, the NdFeB IPMSM design benefits to higher efficiency and lower manufacture cost is observed.

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