Investigation and Comparison of System Efficiency on the PMSM Considering Nd-Fe-B Magnet and Ferrite Magnet

Tao Sun, Soon-O Kwon, Jeong-Jong Lee, Jung-Pyo Hong
Department of Automotive Engineering, Hanyang University
E-mail: laplace_sun@hotmail.com, hongjp@hanyang.ac.kr

Abstract — This paper studies the influence of permanent magnet on the total system efficiency of permanent magnet synchronous motors (PMSM). Two PMSM with Nd-Fe-B and Ferrite magnets which have same Back-EMF and output power have been designed. First, the dynamic simulation is performed with these two motors' parameters. The current waveforms and switching losses of transistors can be evaluated. And then, by means of the obtained current waveforms and a series of numerical methods, the iron losses of these two motors will be calculated. Finally, comparing the sum of the switching losses and iron losses, the result can be used to reflect the influence of the magnet on the total motor system efficiency.

I. Introduction

Ferrite and Nd-Fe-B (NdFeB) magnets have been widely used in permanent magnet synchronous motors (PMSM) for a few decades. The ferrites, as known, are produced by powder metallurgy. Their theoretical chemical formulation may be expressed as $BaO{\cdot}6(Fe_2O_3)$, $SrO{\cdot}6(Fe_2O_3)$, or $PbO{\cdot}6(Fe_2O_3)$. The remanent flux density of ferrite magnets usually is under 0.5 T, and the relative high operating temperature and low cost are their advantages. The NdFeB is a type of rare-earth magnet. It is made from an alloy of neodymium, iron, and boron to form the $Nd_2Fe_{14}B$ tetragonal crystalline structure. According to manufacture techniques, the NdFeB magnets are classified to Sintered type and Bonded type. The remanent flux density of Sintered type NdFeB magnet can achieve maximum 1.4 T. In the PMSM design, by using NdFeB magnet, the high power density can be easily achieved. The demagnetization curves of the ferrite and NdFeB magnets are shown in Fig. 1 in order to describe and compare their typical characteristics. [1]

One of the drawbacks of NdFeB magnet is the great cost due to the using of rare-earth. Therefore, there is a compromise issue between the performance and cost when design the PMSM using ferrite or NdFeB magnets. As the same back electromotive force (Back-EMF) and output power, the motor with ferrite magnet may have higher inductance than the one with NdFeB magnet because of its more winding turns. The different inductance and resistance will lead to the different time constant which affects the switching efficiency of the motor drive and current waveforms. Additionally, the different current waveforms may produce different iron losses of motors.

In order to investigate the influence of magnet on the motor system efficiency, this paper studies two PM motors with Ferrite and NdFeB magnets which have same Back-EMF

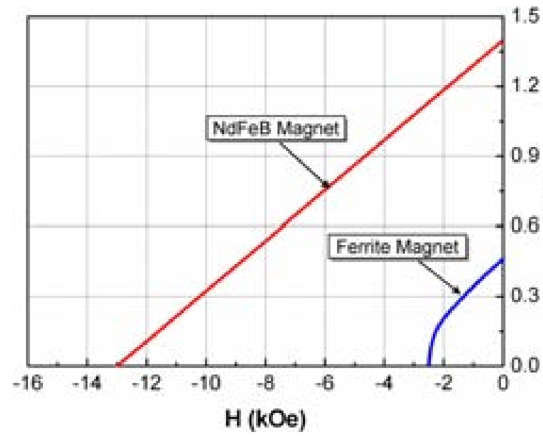


Fig. 1 Typical demagnetization curve of ferrite and NdFeB magnets

and output power, and compares their difference on the losses of switching inverter and iron losses of motors. An indirect coupled field-circuit method is used to deal with these problems. In the evaluation of switching losses, a dynamic simulation program considering PWM current regulation is processed with the parameters of these two motors. Using the obtained flowing current of IGBT, freewheeling current of diode, and other inherent parameters, the switching losses can be estimated [2] and [3]. And then, depending on an experiment data table and a finite elements method, the iron losses of the motors can be calculated [8]. Finally, the influence of the magnet on the total system efficiency can be reflected by comparing the total losses of these two motors. The analysis result will be helpful to the determination of permanent magnet in the PMSM design.

II. Analysis Motor Models

Two PMSM motors with ferrite and NdFeB magnets have been design for using in refrigerator compressor. The cross-section and specifications of these two motor models can be seen in Fig. 2 and Table I. In Fig. 3, the torque, output power, line-to-line voltage and line current of these two motors are compared in the total operation range. It is observed that the two motors are almost same in the characteristics.

Due to the low remanent flux density of ferrite magnet, the motor with ferrite magnet should have more turns of coil per phase in order to generate similar Back-EMF to the motor with NdFeB magnet. The more turns of coil per phase, hence, result into higher inductance. The d- and q-axis inductances of

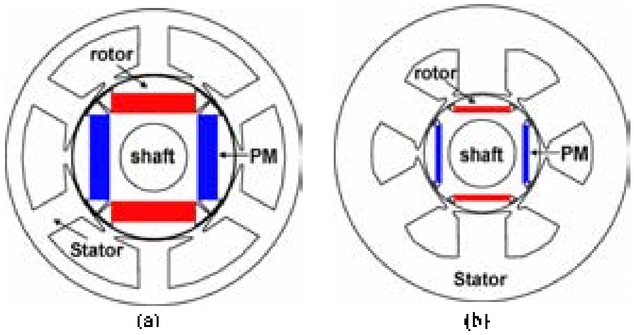
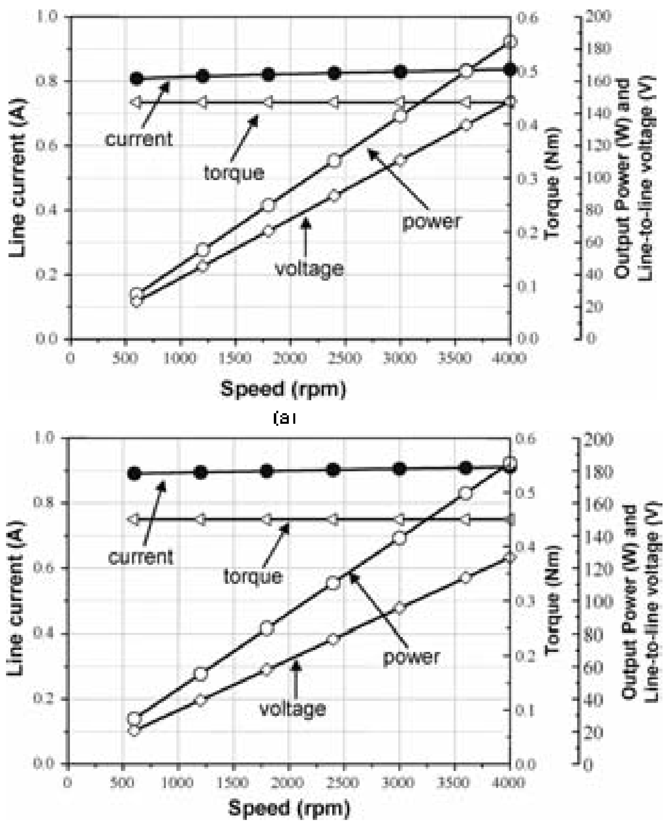


Fig. 2 Cross-section of analysis models: (a) motor with ferrite magnet; (b) motor with NdFeB magnet.



(b)

Fig. 3 Comparison of characteristics: (a) motor with ferrite magnet; (b) motor with NdFeB magnet

TABLE I
SPECIFICATION OF MOTORS

Parameters	Motor with ferrite magnet	Motor with NdFeB magnet
Out radii of stator	135 mm	
Inner radii of rotor	65 mm	45 mm
Air-gap/Stack length	0.7 mm / 45 mm	
Volume of magnet	$7.5\times33\times45$ mm^3	$2\times22\times45$ mm^3
Remanent flux density	0.46 T	1.3 T
Material of core	PNSE	
No. of turns per phase	310	196
Rated output power	184.5 W	
line to line Back-EMF (@1000 rpm)	32.13 Vrms	30.48 Vrms
d-/q-axis inductance	32.57 / 72.54 mH	16.72 / 26.21 mH

these two motors are compared in Table I.

III. INDIRECT COUPLED FIELD-CIRCUIT METHOD

The purpose of this paper is to investigate the influence of PM on the total system efficiency. Therefore, two domains: circuit and magnetic field should be calculated. The coupled field-circuit analysis method is satisfied to this case. The coupled field-circuit method includs direct method and indirect method. In the direct coupled field-circuit method, the equations of circuit domain and field domain are built into one simultaneous matrix and solved, while the equations of the two domains are built and solved separately in the indirect method. Although the direct method has higher precision than the indirect, its computation time also is much longer. [5] In this paper, the indirect coupled field-circuit will be used.

A. Modeling in Magnetic Field Domain

In the proposed indirect coupled field-circuit method, the 2D magneto-static field finite element method (FEM) is used in 2 calculation step:

Step 1: calculating the motor inductances and equivalent iron-loss resistance in total operation range; [4]

Step 2: calculating the magnetic field distribution with the known current waveforms and time steps.

The governing equation of the magneto-static field FEM for PMSM, i.e. the nonlinear Possion equation, is described in (1).

$$\nabla\times\upsilon(\nabla\times A)=J+\nabla\times(\upsilon\mu_0 M) \qquad (1)$$

where A is the magnetic potential vector, J is the current density vector, M is the magnetization vector, υ is the reluctivity, and μ_0 is permeability of air.

B. Modeling in Circuit Domain

After obtaining the motor parameters, a dynamic simulation based on the equation of circuit domain is processed. The control algorithm and pulse width modulation (PWM) current regulation are considered in this step. The generated current waveforms will be loaded to the magneto-static field FEM again as mentioned above to calculated the magnetic field distribution in operation condition.

1) Modeling of PMSM

According to the Park's transformation, the state space equations of the PMSM can be described as (2)-(4). And the corresponding d- and q-axis equivalent circuits are shown in Fig. 4 (a) and (b), respectively. [4]

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_a\begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \left(1+\frac{R_a}{R_c}\right)\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} + p\begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix}\begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} \qquad (2)$$

$$\begin{bmatrix} v_{od} \\ v_{oq} \end{bmatrix} = \begin{bmatrix} 0 & -\omega L_q \\ \omega L_d & 0 \end{bmatrix}\begin{bmatrix} i_{od} \\ i_{oq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega\psi_a \end{bmatrix} \qquad (3)$$

$$T = P_n\left[\psi_a i_{oq} + \left(L_d - L_q\right) i_{od} i_{oq}\right] \qquad (4)$$

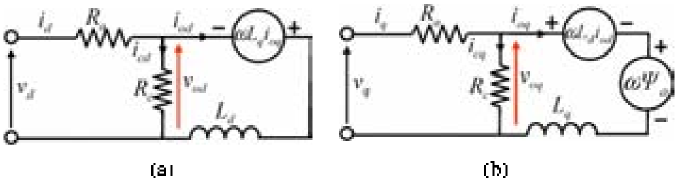


Fig. 4. Equivalent circuits of PMSM: (a) d-axis equivalent circuit, (b) q-axis equivalent circuit

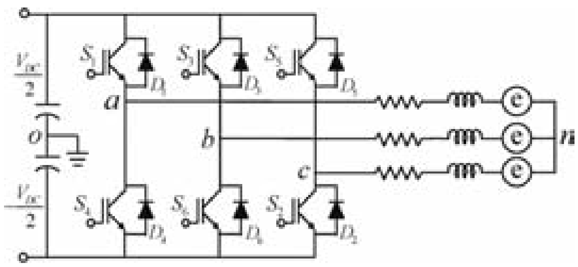


Fig. 5. Equivalent circuit of a full bridge inverter and PMSM

where R_a is the phase winding resistance, R_c is the resistance of iron losses, P is the number of pole pair, ω is the electrical angular velocity, ψ_a is the flux linkage of permanent magnet, i_{od} and i_{oq} are the d- and q-axis load current, respectively.

2) Modeling of Inverter

In order to considering the PWM current regulation influence, the modeling of the voltage source inverter and PWM are necessary. The voltage source inverter is modeled by using of the switch function concept which is introduced in [6]. As shown in Fig. 5, the pole voltage can be calculated by the following switching functions (5).

$$\begin{cases} v_{ao} = \frac{V_{DC}}{2}\times\left(SF_{A\_top} - SF_{A\_bottom}\right) \\ v_{bo} = \frac{V_{DC}}{2}\times\left(SF_{B\_top} - SF_{B\_bottom}\right) \\ v_{co} = \frac{V_{DC}}{2}\times\left(SF_{C\_top} - SF_{C\_bottom}\right) \end{cases} \quad (5)$$

where v_{ao}, v_{bo} and v_{co} are the 3-phase pole voltage. V_{DC} is the DC link voltage. SF_{x_top} and SF_{x_bottom} are the switching function of the top switch and bottom switch of corresponding phase, respectively. And . SF is 1 or 0 when the gate is on or off. After obtaining the pole voltages, the phase voltages can be expressed by the pole voltages as (6).

$$\begin{cases} V_{an} = V_{ao} - \frac{V_{ao}+V_{bo}+V_{co}}{3} \\ V_{bn} = V_{bo} - \frac{V_{ao}+V_{bo}+V_{co}}{3} \\ V_{cn} = V_{co} - \frac{V_{ao}+V_{bo}+V_{co}}{3} \end{cases} \quad (6)$$

where v_{an}, v_{bn} and v_{cn} are the corresponding phase voltages. The calculated phase voltage then will be converted to the dq frame of reference by Park's transformation, and excite the PMSM model. In addition, a current vector controller also is considered in the modeling of circuit domain. In this paper, the motor with ferrite magnet is controlled at 15° current vector angle, while the motor with NdFeB magnet has 6° degree current vector angle in order to get maximum torque.

IV. Losses Calculation Methods

As mentioned before, this paper investigates the total system efficiency which means both the losses in the inverter and losses in the PMSM should be considered.

A. Iron Losses Calculation Method

The dominant losses in PMSM usually consist of copper loss, iron losses and mechanical losses. The copper loss is determined by winding resistance which is constant in a given temperature. The mechanical losses can be calculated by a function of proportion with speed.[4] The general expression of iron losses which include the hysteresis loss P_h, eddy current loss P_e and a anomalous component P_a as shown in (9) [7]

$$P_c = P_h + P_e + P_a = k_h f B_m^{\alpha} + k_e f^2 B_m^2 + k_a f^{1.5} B^{1.5} \quad (9)$$

where the coefficients k_h, k_e, k_a and α are the function of frequency and amplitude of flux density. However, only sinusoidal variable is suitable for this formula. In practice, the special and temporal distributions of the flux density may be distorted. In this paper, a method which was proposed and verified in [8] is used to calculate the iron losses. It is described in Figure 6.

B. Switching Losses Calculation Method

As the transistors in switching-on or switching-off states, four kinds of losses are produced [2]. They are current conduction losses and switching losses in transistors and freewheeling diodes, respectively. Based on [2] and [3], The simplified calculation equations of these four losses are shown in (5)-(8).

$$P_{M1} = I_{M1} V_{CES}\left(\frac{1}{8}+\frac{M}{3\pi}\cos\theta\right) \quad (5)$$

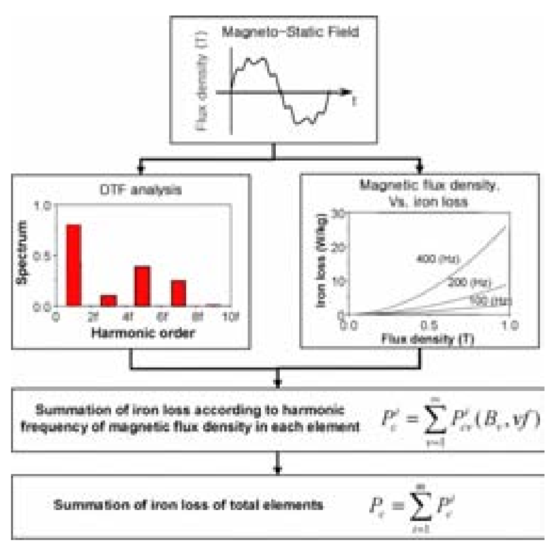


Fig. 6 Process of motor iron losses calculation method

$$P_{DC} = I_{MP} V_F \left(\frac{1}{8} - \frac{M}{3\pi} \cos\theta \right) \tag{6}$$

$$P_{TS} = \left(E_{on} + E_{off} \right) f_{SW} \frac{1}{\pi} \tag{7}$$

$$P_{DS} = \frac{1}{4} f_{SW} Q_{rr} V_{DC} \tag{8}$$

where P_{TC} and P_{DC} are the power losses of the transistor and diode in conduction statet. P_{TS} and P_{DS} are the power losses of the transistor and diode at switching states. I_{MP} is the flowing current. V_F is the voltage drop on freewheeling diode. V_{CES} is the voltage drop on switching device. E_{on} is the loss at switching-on. E_{off} is the loss at switching-off. Q_{rr} is the reverse-recovery charge. M is the modulation index. V_{dc} is the DC Link Voltage. $\cos\theta$ is the power factor, and f_{sw} is the switching frequency. The value of these parameters in this paper is listed in Table II.

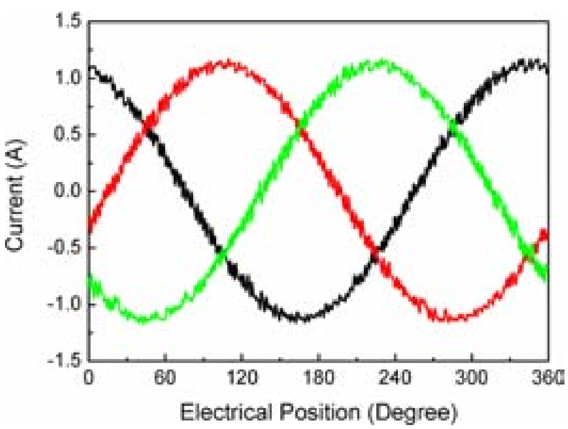
TABLE II
PARAMETERS OF SWITCHING LOSSES CALCULATION

Parameters	Motor with ferrite magnet	Motor with NdFeB magnet
V_{CES}	1.5 (V)	
V_F	1.5 (V)	
E_{on}	3 (mJ)	
E_{off}	3 (mJ)	
Q_{rr}	1.16 (μC)	
M	1.1	
$\cos\theta$	94.6%	98.4%
f_{sw}	3000 Hz	3000 Hz

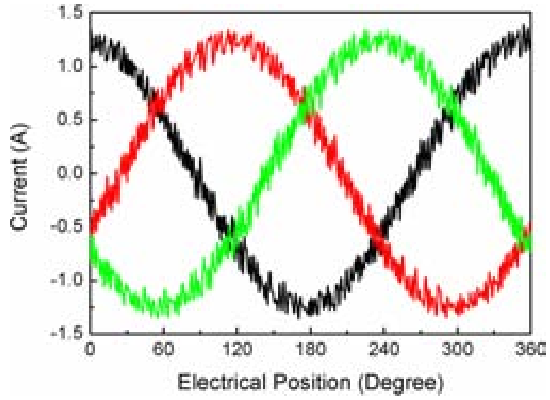
V. ANALYSIS RESULTS AND DISCUSSIONS

The current waveforms of the two analysis motors calculated in the model of circuit domain are shown in Fig. 7 (a) and (b). The load torque is 0.44 Nm, the operating speed is 3000 rpm, and the PWM frequency is 3000 Hz. It is obvious that the current waveforms of the motor with ferrite magnet are smoother than those of the motor with NdFeB magnet, which verified the inductance influence mentioned before.

The currents of the two analysis motors flowing in an upper transistor and the corresponding freewheeling diode are compared in Fig. 8. The power losses produced by these conduction currents are shown in Fig. 9.

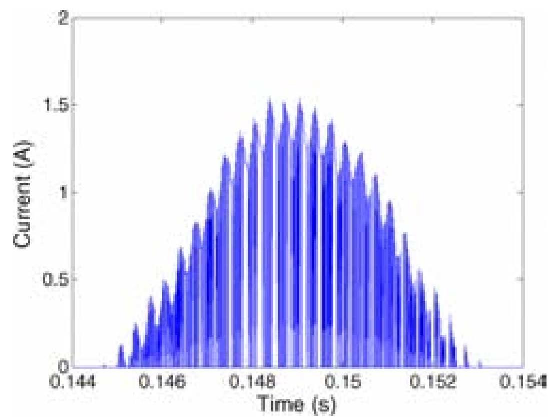


(a)

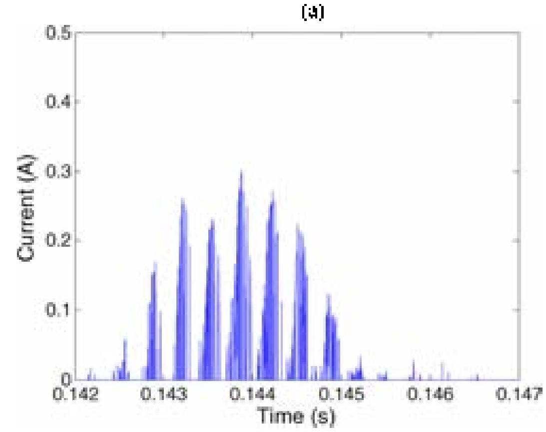


(b)

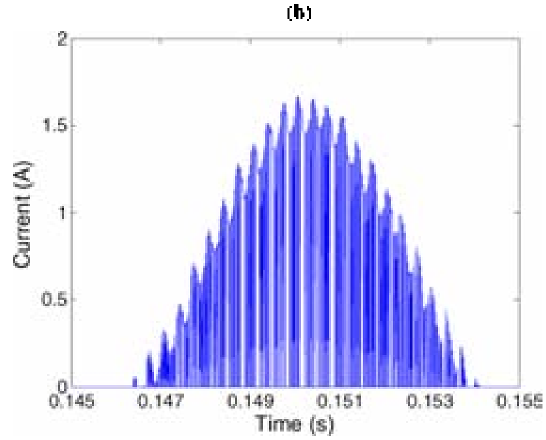
Fig. 7 Current waveforms: (a) motor with ferrite magnet; (b) motor with NdFeB magnet.



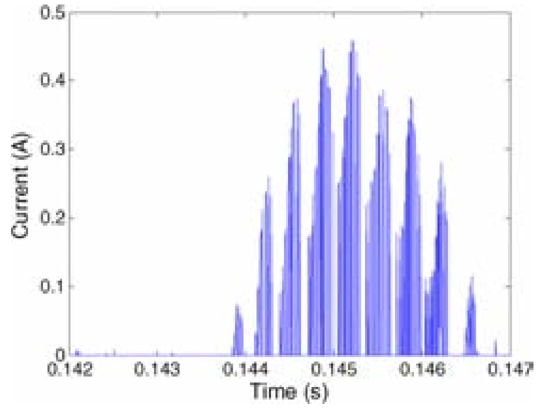
(a)



(b)

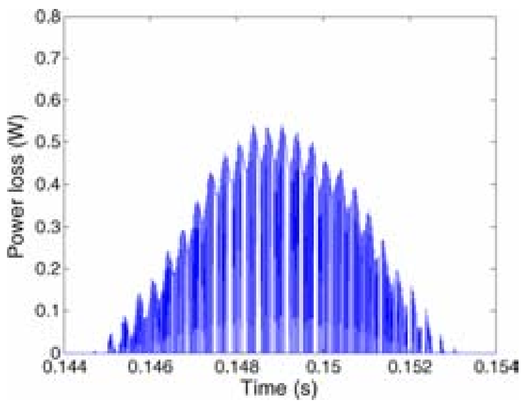


(c)

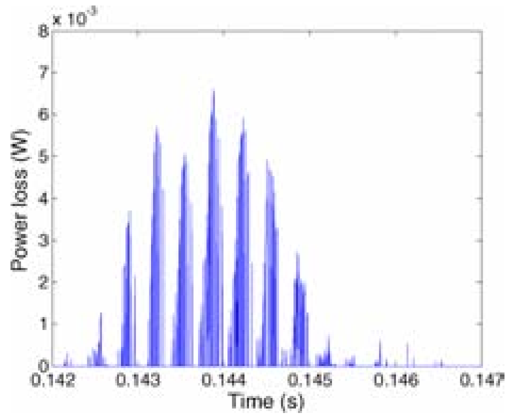


(d)

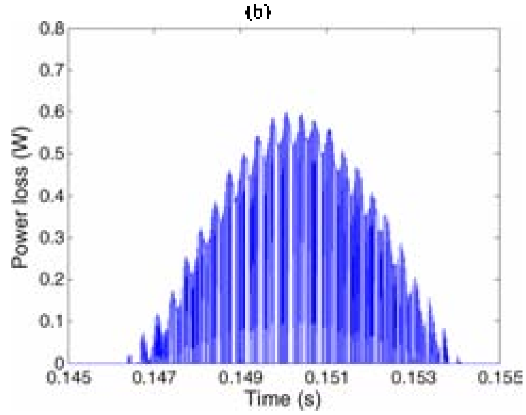
Fig. 8 Conduction currents: (a) and (b) conduction currents in transistor and diode of the motor with ferrite magnet; (c) and (d) conduction current in transistor and diode of the motor with NdFeB magnet.



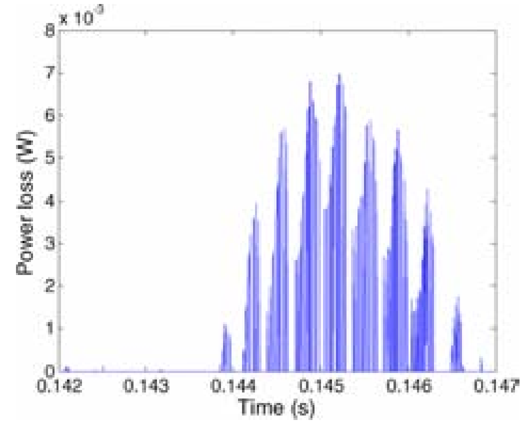
(a)



(b)



(c)



(d)

Fig. 9 Conduction losses: (a) and (b) conduction losses in transistor and diode of motor with ferrite magnet; (c) and (d) conduction losses in transistor and diode of motor with NdFeB magnet

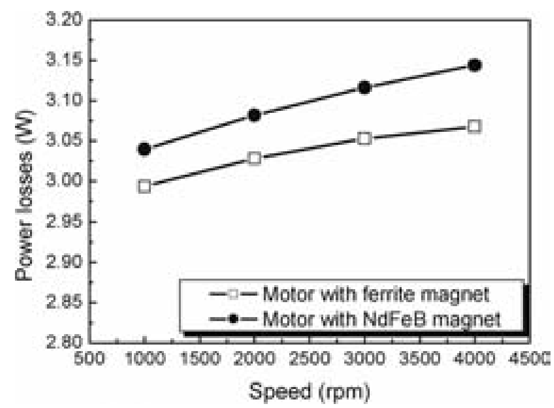
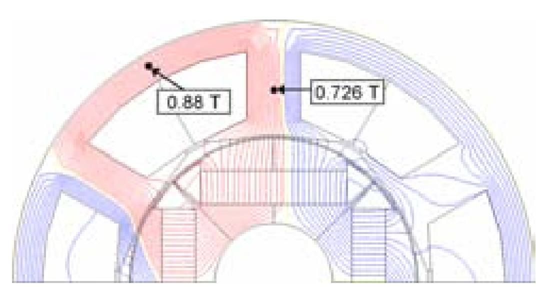


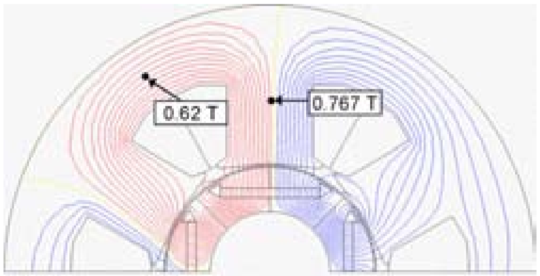
Fig. 10 Comparison of the inverter losses of the analysis motors

In Fig. 8 and 9, it can be seen that the current of the motor with NdFeB magnet has higher regulation frequency, and hence has more power loss during the unit time, although the peak value of the losses in the both motors are similar. The mean value of the inverter losses of the two motors in the same duration are compared in Fig. 10.

Using the current waveforms obtained from the model of circuit domain, the flux distributions are analyzed in 2D magneto-static FEM. Fig. 11 shows the model in FEM and flux densities of the stator teeth. It can be seen that the motor with ferrite magnet has higher flux density, especially in stator yoke part due to the narrow cross area. Although the motor with NdFeB magnet has wider stator tooth width, the higher remanent flux density of NdFeB leads that the flux density is higher.



(a)



(b)

Fig. 11 FEM model and flux distribution: (a) motor with ferrite magnet, (b) motor with NdFeB magnet.

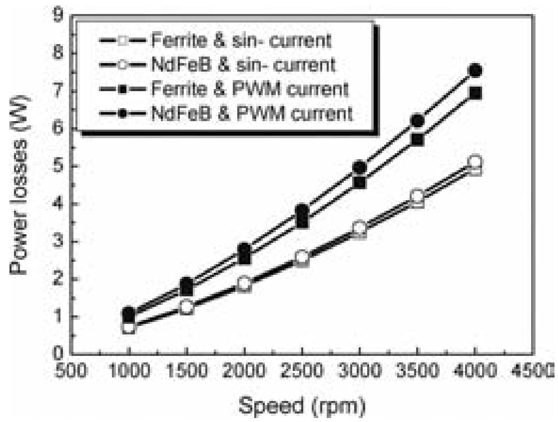


Fig. 12 Comparison of calculated motor iron losses excited by sinusoidal current waveforms and PWM current waveforms

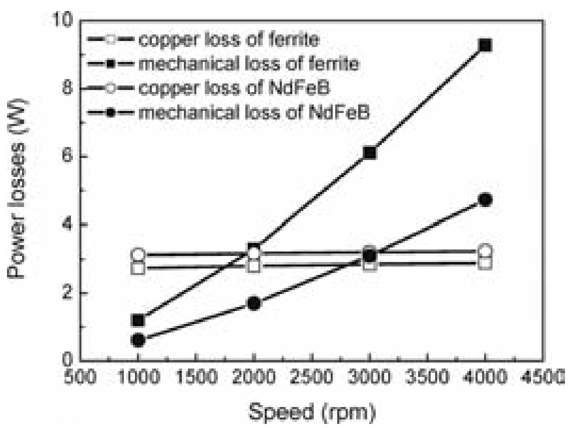


Fig. 13 Comparison of calculated system losses on the analysis two motors

Not only the PWM current waveforms, but also the ideal sinusoidal current waveforms are used to solve the magneto-static FEM. The iron losses of these two motors solved by sinusoidal and PWM current waveforms are compared in Fig. 12. In addition, the copper loss and mechanical loss as the same operation condition are calculated and shown in Fig. 13. Due the a little higher current, the motor with NdFeB magnet has higher copper loss. A large difference occurs between the mechanical losses of the two motors. This is because the much great radii of the motor with ferrite magnet increases the area of friction and windage.

The total system losses and efficiency are compared in Fig. 14. It can be seen that the motor with NdFeB magnet has higher efficiency in the total operation range. However, this

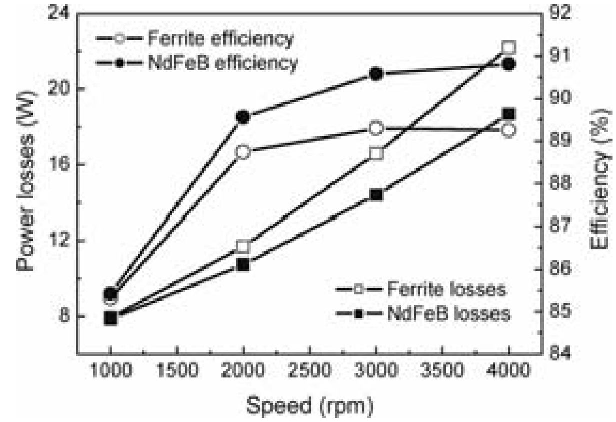


Fig. 12 Comparison of calculated motor iron losses excited by sinusoidal current waveforms and PWM current waveforms

predominance to the motor with ferrite magnet will be unregarded as the speed decreases. There is a great difference on the rotor structure so that the mechanical losses become dominant. However, in the case of the larger electrical power application, the advantage of the motor with ferrite magnet on the iron losses will be more significant.

VI. Conclusion

This paper investigate the influence of PM on the total PMSM system efficiency. Two motors with different magnet and same output power are compared. By using an indirect coupled field-circuit method, the problem is solved in circuit domain and magnetic field domain. The inverter switching losses, iron losses of PMSM are calculated. As shown in results, due to the higher inductance, the motor with ferrite magnet generates lower iron losses in the PWM current exciting. Although the total efficiency is lower than the motor with NdFeB magnet, considering great magnet cost, there is a compromise between the using of NdFeB and ferrite magnets as higher electrical power application and optimization structure design.

References

[1] Rollin. J. Parker. *Advances in Permanent Magnetism*. A Wiley-Interscience Publication, 1990, pp. 61-100.

[2] F. Blaabjerg, U. Jaeger, S. Munk-Nielsen, "Power losses in PWM-VSI inverter using NPT or PT IGBT devices," *IEEE Trans. Power Electron.*, Vol. 10, No. 3, pp. 358-367, May 1995.

[3] AN-IP9931E, Calculation of Major IGBT Operating Parameters, Infineon technologies, www.infineon.com, Aug. 1999

[4] Tao. Sun, J. P. Hong, etc., "Determination of Parameters of Motor Simulation Module Employed in ADVISOR," *IEEE Trans. Magn.*, Vol. 44, No. 6, pp.1578-1581, June 2008.

[5] L. Xu. and Ruckstadter E. "Direct modeling of switched reluctance machine by coupled field-circuit method," *IEEE Trans. Energy Convers.*, Vol. 10, No. 3, pp.446-454, Sept. 1995.

[6] W. T. Lee, J. P. Hong, etc., "Object oriented modeling of an interior Permanent Magnet Synchronous Motor Drives for Dynamic Simulation of Vehicular Propulsion," *IEEE Vehicle Power and Propulsion Conference, VPPC '06*, Sept. 2006.

[7] A. E. Fitzgerald and C. Kingsley, Jr., *Electric Machinery*. New York: McGraw Hill, 1952, pp. 124-158

[8] J. J. Lee, J. P. Hong, etc., "Loss distribution of three phase induction motor fed by pulsewidth-modulated inverter," *IEEE Trans. Magn.*, Vol. 40, No. 2, pp.761-765, March 2004