$$L=\begin{bmatrix} L_{aa} & L_{ab} & L_{ac} & L_{af} \\ L_{ab} & L_{bb} & L_{bc} & L_{bf} \\ L_{ac} & L_{bc} & L_{cc} & L_{cf} \\ L_{af} & L_{bf} & L_{cf} & L_{f} \end{bmatrix}, \quad R=\begin{bmatrix} r & 0 & 0 & 0 \\ 0 & r & 0 & 0 \\ 0 & 0 & r & 0 \\ 0 & 0 & 0 & r_f \end{bmatrix}, \quad I=\begin{bmatrix} i_a \\ i_b \\ i_c \\ i_f \end{bmatrix}$$

where the inductance matrix contains the self and mutual inductances between the armature windings and the mutual inductances between armature and excitation windings.

Equation (2) can also be written as:

$$\frac{dI}{dt}=-[L^{-1}(R+\frac{dL}{dt})]I+L^{-1}U \tag{3}$$

With substituting the corresponding calculated inductance and resistance parameters into (3), the differential equation can be solved by using the numerical integration method, and hence the current waveforms, the propulsion and the levitation forces can all be obtained. When the internal fault occurs, we only need to recalculate the inductance and resistance matrix according to the different fault type and the short circuit ratio, but the mathematical model keeps the same, the simulation results in section Ⅲ are derived from this method.

III. Simulation Results

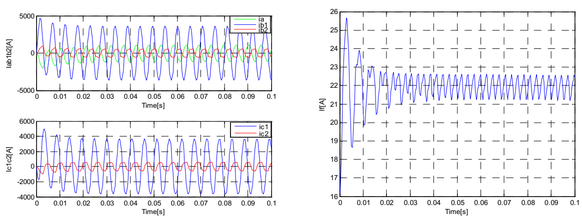
It's likely to occur three typical types of internal fault in LSM, single-phase and double-phase short circuit and single phase open circuit. As an example, the double-phase short circuit is discussed here. The internal fault voltage equation can be described as:

$$\left[U'\right]=\left[R'\right]\left[I'\right]+\left[L'\right]\frac{d}{dt}\left[I'\right]+\frac{d}{dt}\left[L'\right]\left[I'\right]$$

where
$$\left[U'\right]=\left[U_a,U_{b1},U_{b2},U_{c1},U_{c2},U_f\right]^T \tag{4}$$
$$\left[I'\right]=\left[I_a,I_{b1},I_{b2},I_{c1},I_{c2},I_f\right]^T$$

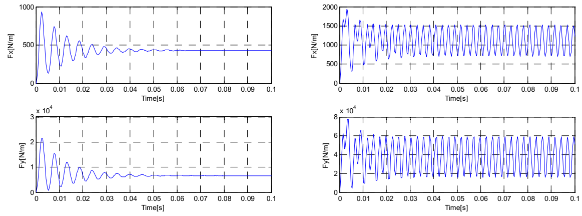
An equivalent circuit of the faulty coil is formed. The corresponding inductance matrix should be recalculated due to the short circuit ratio of phase bc .

Fig.2 shows us the current waveforms, the propulsion and the levitation forces under 50% double-phase short circuit. And with the increment of short circuit ratio, the amplitude of the waveforms increases and the harmonic components also strengthen. The more the number of short turns is, the more differences can be observed between normal phase and faulty phase. These simulation results are the basis of analysis of further fault diagnosis.



(a) the armature currents (b) the excitation current

Fig .2 The simulation results of the 50% ratio of double-phase short circuit currents



(a) under normal condition; (b) double-phase short circuit condition under 50% ratio;

Fig .3 The simulation results of the propulsion and levitation forces

In Fig.3 (a), it can be seen that when the maglev train system operates in steady-state, that is to say the speed and the system power angle keep constant, the propulsion and levitation forces also tend to stabilize. However, the electromagnetic force can't keep stable when double-phase short circuit occurs shown in Fig.3 (b).

According to the simulation results of LSM under normal and internal faults conditions, the fault law can easily be found. Whatever the fault happens, the waveforms of fault currents and electromagnetic forces all appear a certain extent oscillation. Through specific wavelet packet transforming, the harmonic components can be obtained, which can also be used for fault diagnosis.

IV. Conclusions

In this paper, a useful internal fault model is proposed based on the winding function theory. This method has distinctive advances compared to the previous ones. The calculation of the impedance matrix mainly including inductances under normal and internal fault conditions is not only simpler but also accurate. Furthermore, the programmed software package for LSM internal fault simulation and analysis can realize the man-machine conversation.

V. Reference

[1] Xiaoping Tu, Louis-A.Dessaint, Nicolas Fallati, etal. "Modeling and Real-Time Simulation of Internal Faults in Synchronous Generators With Parallel Connected Windings" [J]. *IEEE Trans on industrial electronics.* Vol, 54. No.3, Jun 2007,pp:1400-1409

[2] Iman Tabatabaei, Jawad Faiz, Lesani, et,al. "Modeling and Simulation of a Salient-Pole Synchronous Generator With Dynamic Eccentricity Using Modified Winding Function Theory". *IEEE Trans on magnetics.* Vol, 40. No. 3, May 2004,pp:1550-1555

[3] N. A. Al-Nuaim H.A. Toliyat, "Simulation and Detection of Dynamic Air-Gap Eccentricity in Salient-Pole Synchronous Machines"[J].,*IEEE Trans. on Industry Applications,* Vol. 35, No. 1, Jan/Feb 1999,pp. 86-93.

[4] Hamid A. Toliyat, Shailesh P. Waikar, Thomas A. Lipo, "Analysis and Simulation of Five-Phase Synchronous Reluctance Machines Including Third Harmonic of Airgap MMF".*IEEE Trans. on Industry Applications,* Vol. 34, No. 2, Mar/Apr 1998,pp. 332-339.

[5] V.A.Kinisty. " Calculation of Internal Fault Currents in Synchronous Machines".*IEEE Trans PAS*，Vol.84，No.5，1965：381~389

[6] N. L. Shmitz and D.W. Novotny, Introductory Electromechanics[M]. New York: Roland, 1965.

Effects of Magnetic Saturation on Spindle Motor Characteristics

Jaenam Bae, Seung-Joo Kim, Sung-Chul Go, Dong-Woo Kang, Sang-Hwan Ham, and Ju Lee
Hanyang University
17 Haengdang-dong, Sungdong-gu, Seoul, 135-111, South Korea
Baejn81@hanyang.ac.kr

***Abstract* — In spindle motor for disk memory devices, constant torque is very important. There are three kinds of source for the torque ripple viz. harmonics, cogging torque, reluctance torque. Because the motor has uniform airgap and a permanent magnet for the motor is magnetized on the special fixture, the effect of harmonics and reluctance torque is not considerable but cogging torque is the most influence to the torque ripple. However, when the ferromagnetic material is saturated, we get unexpected results such as torque fluctuation. In this paper, effect of magnetic saturation on spindle motor is presented. FPM is used to consider the saturation in FEA simulation.**

I. INTRODUCTION

M brushless DC motors are widely used for the spindle motor in disk memory devices such as a CD-ROM drive system. In current disk drive system, the motor with slotted laminations and NdFeB magnets is the most common for use as the spindle motor [1]. Because an ODD speed and torque characteristics depends on spindle motor, it is very important the spindle motor has constant torque independent of the rotor position.

There are three sources for torque pulsation. First is the field harmonic torque due to non-ideal spatial distribution of flux density in the airgap and another is cogging torque or detent torque and third is reluctance torque, produced due to unequal reluctances of the d- and q- axis [2]–[4]. Because a magnet for the spindle motor is magnetized very sinusoidal, spatial distribution of flux density in the airgap is also sinusoidal. Moreover most of them have a fractional pole-slot combination which results in filtering high frequency component of induced voltage. Besides it has uniform airgap and equal reluctances of the d- and q-axis therefore it doesn't have reluctance torque. In conclusion, the most important source in the spindle motor is cogging torque in three of them.

There are several researches about cogging torque reduction in [5][6]. However they don't take into account magnetic saturation. As known, an important part of electrical machines is made of ferromagnetic materials. These materials consist of nonlinear magnetic characteristics. When the total magnetic motive force in the machine increases saturation of the ferromagnetic parts appears [7]. The result of the saturation effects is a variation of the stator and rotor inductances. For an optimized design of electrical machines, it needs designing the machines near the saturation point. Therefore the magnetic saturation effects should be considered.

Kwak et al. suggests Fixed Permeability Method (FPM) to get more accurate motor parameters (d- and q-axis inductance, back-EMF constant) by dividing the total magnetic flux linkage into the flux linkage due to the PM and to the stator current in [8]. The method can be also applied in a magnetic saturation effects. In this paper, an effect of the magnetic saturation on the motor characteristics is investigated using the FPM.

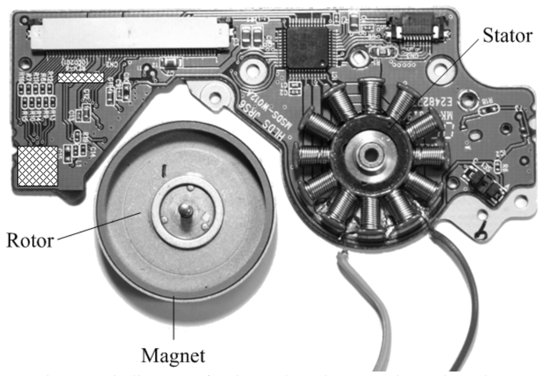


Fig. 1. Spindle motor for the study. It has 16 poles and 12 slots

II. STUDY MODEL

Fig. 1 shows the spindle motor for the study. The motor has 16 poles and 12 slots and the NdFeB bonded magnet is mounted on the rotor inner surface. Ring magnet is used for cost reduction and it is magnetized on a special magnetizing fixture for sinusoidal distribution. Actually the magnet has both of radial and tangential components on its body, but only radial component is considered in the study because influence of the tangential component is very lower than that of the radial component. The radial component of the magnetization is defined as (1)

$$M_r = \frac{B_r}{\mu_0 \mu_r} \cos\left(\frac{N_p}{2}\theta\right) \tag{1}$$

where μ_0 and μ_r is permeability of the free space and relative permeability of the magnet respectively, B_r is residual flux density of the magnet and N_p is the number of poles.

III. TORQUE CONSIDERING MAGNETIC SATURATION

Voltage equation for a phase is given by