Study of Saturation Effects in Brushless DC Spindle Motors Using Harmonics Analysis Method

J. T. Li, Z. J. Liu and C. Bi

Abstract—**In analysis of brushless dc (BLDC) motors, the effect of saturation needs to be appropriately considered especially in the case of small disk format where the housing space is very limited for the spindle. In this paper, we propose a practical method for analysis of saturation effects in BLDC spindle motors. The model is based on the comparative analysis of the harmonics contents in the air-gap field in the saturated and non-saturated situations. This method is useful for analysis of the magnetic forces and other parameters taking into account the saturation effects.**

Index Terms—**Brushless DC Spindle Motor, Saturation.**

I. INTRODUCTION

The brushless dc (BLDC) motors are widely used in industries nowadays, particularly in the data storage industry as spindle motors in hard disk drives (HDDs). The thickness of the back yoke and the stator yoke are relatively small due to limited housing space, so it is necessary to consider the saturation effects to give more accurate results for the performance evaluation. In the design phase, it is very important to understand how the saturation affects the magnetic fields and forces, which are critical characteristics to the performance of the assembly. Quite a few analytical solutions were provided for the air-gap fields and the magnetic forces in the PM spindle motors [1-4]. In previous work [5], the effect of magnet poles passing over slot opening was carefully studied to give a more accurate solution. Nevertheless, it's very hard for the analytical methods to account for the saturation effect.

In this paper, we propose a practical method for analysis of saturation effects in BLDC spindle motors. The model is based on the comparative analysis of the harmonics contents of the air-gap field in the saturated and non-saturated situations. The flux density in saturated situation can be obtained by modulating the air-gap field calculated using the previous analytical solution with correction factors, which are determined by the harmonic analysis. In particular, this method is also useful for analysis of other motor parameters taking into account the saturation effects.

Manuscript received 15 Oct. 2010

J. T. Li is with the School of Electrical Engineering, Xi'an Jiaotong University, P. R. China, 710049.

Z. J. Liu and C. Bi are with the Data Storage Institute, P. R. Singapore, 117908.

II. SATURATION EFFECTS ON THE AIR-GAP FLUX DENSITIES

The magneto-motive force (MMF) consumptions in the magnetic materials will increase when saturation occurs. Thus, the MMF drop across the air gap will reduce compared to the non-saturated case. In the spindle motors used in HDDs, the tooth body is often designed to be merely saturated and the tooth face is normally not saturated. In the viewpoint of the magnetic circuit theory, the saturation in the back yoke and the tooth body will reduce the magnitude of the air-gap field. When the saturation occurs on the tooth tips, the flux lines will not go vertically into the slot walls, which will slightly change the waveform of the flux density in the slot opening region.

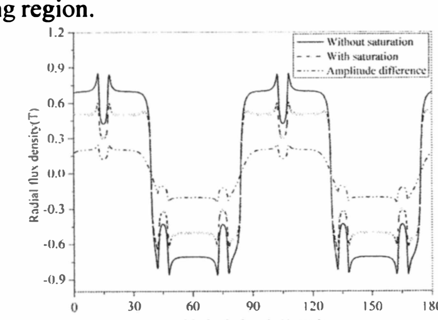

Fig. 1 Flux densities comparison with saturated and unsaturated back yoke

Fig.1 shows the comparison of the radial air-gap flux densities in saturated and non-saturated situations in an 8-pole 12-slot exterior-rotor PM spindle motor. It is clear that the amplitude of the flux density reduces and the shape of the waveform deformed only a little bit around the slot opening region. A method based on the comparison of the harmonic components to investigate the saturation effects on the harmonics of the air-gap flux density are described as follows.

III. HARMONICS ANALYSIS

Fig.2 shows the comparison of the harmonic contents of the radial flux densities in saturated and non-saturated situations. It is clear that the harmonic components are exact the same in both cases except the amplitudes. It is also noted that the dominant harmonic components appear to be the odd multiples of the 4^{th} harmonic component which are induced by the magnet poles flux. Therefore, the ratio of the fundamental harmonic in saturated flux densities to non-saturated flux densities can be used for a first-round modulating for the air-gap field in non-saturated case. Fig.3 shows the comparison between the saturated air-gap flux density and the first-round modulated flux density. It is found that the average amplitudes of these two waveforms are very close to each other.

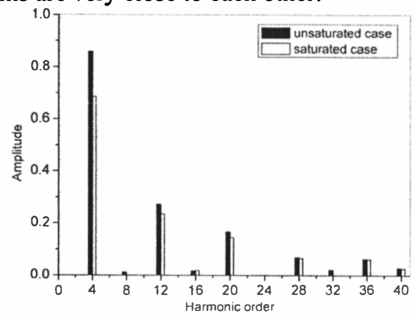

Fig.2 Comparison of harmonic components under saturated and unsaturated conditions

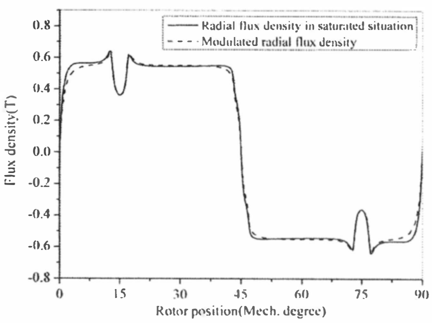

Fig.3 Comparison of the flux density modulated by correction factor and the calculated flux density in saturated case

The first-round modulation may provide acceptable results, but using a single value to modulate all the harmonics is not always reasonable especially for certain high harmonics which may contribute to the discrepancy in Fig.3. Therefore, it is necessary to investigate the individual correction factors for other dominant harmonics.

IV. HARMONICS FITTING

As mentioned before, the effect of the tooth body width can be considered as additional MMF consumption in the back yoke and the tooth tip is not possible very sharp and the depth of the tip will not have great effects on these correction factors. Therefore, the respective modulating factors are closely related to the slot opening, rotor position and the back yoke thickness. Response surface methodology (RSM)[6] is a possible and reliable way to get polynomial relationships between these factors and the structure parameters. Fig.4 shows the fitted response surface of the 12th harmonic correction factor vs. slot opening and the back yoke thickness. The correction factors for other harmonic contents can also be obtained in the same way. Using these correction factors, we can obtain the second-round modulation for the flux density as shown in Fig.5. It is clear the result is much more accurate.

With the air-gap field in hand, the motor performances such as the magnetic forces are able to be investigated quickly and accurately.

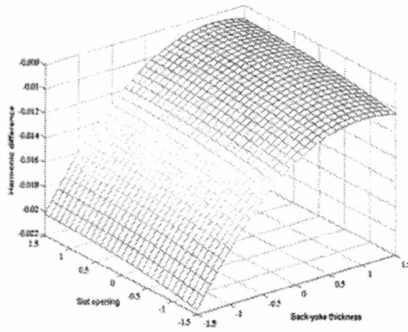

Fig.4 RSM surface of the Comparison of the 12th harmonic correction factor vs. slot opening and back yoke thickness.

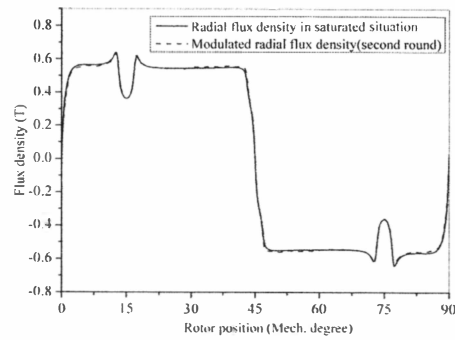

Fig.5 Comparison of the flux density modulated by correction factors and the calculated flux density in saturated case

V. CONCLUSION

In this paper, the influence of the saturation effects in on the harmonics components of the air-gap flux density is analyzed and discussed. The air-gap field can be obtained by modulating the dominant harmonics by correction factors which can be determined by the harmonic amplitude fitting using RSM. The proposed method in this paper is useful for quick evaluation of the magnetic filed and forces to predict the motor performance in the early design phase.

REFERENCES

[1] N. Boules, "Prediction of No-load flux density distribution in permanent magnet machines," *IEEE Tran. Ind. Appl.*, vol. IA-21, no. 4, pp. 633-643, May/June 1985.

[2] Z. Q. Zhu and D. Howe, "Instantaneous magnetic field distribution in brushless permanent magnet dc motors, part III: effect of stator slotting", *IEEE Trans. Magn.*, vol. 29, no.1, pp. 143-151, Jan, 1993

[3] K. F. Rasmussen, H. D. John, T. J. E. Miller, M. I. McGilp, and O. Mircea, "Analytical and numerical computation of air-gap magnetic field in brushless motors with surface permanent magnets," *IEEE Trans. Magn.*, vol. 36, no. 6, pp. 1547-1554, Nov./Dec. 2000.

[4] U. Kim and D. K. Lieu, "Magnetic field calculation in permanent magnet motors with rotor eccentricity: with slotting effect," *IEEE Trans. Magn.*, vol. 34, no. 4, pp. 2253-2266, July 1998.

[5] Z. J. Liu and J. T. Li, "Analytical solution of airgap field in permanent magnet motors taking into account the effect of pole transition over slot", in press, *IEEE Trans. Magn.*, Oct., 2007.

[6] Raymond H. Myers and Douglas C. Montgomery, Response Surface Methodology: process and product optimization using designed experiments, second edition, USA, 2002.