Effect of Magnetization on High-Speed Permanent Magnet Synchronous Motor Design

H. N. Phyu and Bi Chao
A*Star – Data Storage Institute, 5 Engineering Drive 1, Singapore 117608
Email: hla_nu_phyu@dsi.a-star.edu.sg

Abstract-- **This paper presents the influence of permanent magnet (PM) magnetization effect on high speed PM synchronous motor design and performances. Different PM magnetization fields applied to the electromagnetic field system of the motor are analyzed and their effects to the motor performances are investigated. Field-circuit-motion coupled Time-stepping finite element method is used to evaluate the effect of different PM magnetization fields to the nonlinear electromagnetic field system of the motor. Results show that magnetization orientation of the permanent magnet directly affects the motor efficiency, vibration and torque generation. Preliminary investigation of the effect of PM excitation is vital to optimize the motor performances and to identify proper driver circuit and control scheme.**

Index Terms—**PM magnetization, Field-circuit coupled system, Magnetization orientation, High speed permanent magnet motor.**

I. Introduction

High speed permanent magnet synchronous motors have high efficiency and high power density because of using permanent magnet (PM) as the source of magneto motive force (mmf) to provide the magnetic field against the armature field which interacts to rotate the motor. Hence, motor's reliability, efficiency and performances are heavily depends on the PM Field distribution of the motor. Different PM magnetization (in turn PM excitation field) can generate different magnetic field distribution in the system as well as different motor performances. Preliminary investigation of the effect of PM excitation to the electromagnetic (EM) field system of the PM synchronous (PMSM) is essential to get the optimum motor performances.

Radial magnetization is the most common type of PM excitation and widely used in most of the high speed motors. However, for special conditions and applications, parallel and sinusoidal magnetizations are also used. In this work, three common type of PM magnetizations such as Radial, Parallel and Sinusoidal are applied to the electromagnetic field system of the motor and analyzed the motor performances. Field-circuit-motion coupled Time-stepping finite element method is used to analyze the nonlinear electromagnetic field (EM) of the motor. Outer rotor type high speed PMSM is used as a working example. This type of motor is mostly used in high performance enterprise hard disk drive to rotate the read/write platters. Motor geometry and inverter circuit are shown in Fig.1. Detailed specifications are listed in Table. I.

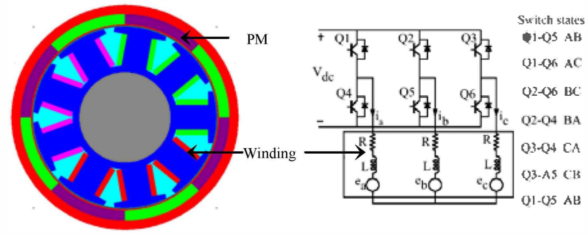

Fig. 1 Motor geometry and inverter circuit

TABLE I
MOTOR SPECIFICATIONS

Rotor outer diameter	24.85mm
Rotor inner diameter	22.85mm
Stator outer diameter	20.0 mm
Magnet thickness	1.15mm
Air gap	0.275mm
Rated speed	15000rpm
Permanent magnet	NdFeB
PM energy product	10MGOe

II. Nonlinear EM Field Model

Hard disk drive spindle motors are typical PMSM, and they are normally driven by voltage source inverter and require alternating phase currents. Commutation takes place between every 60 electrical degrees if motor operates in BLDC mode. An accurate modeling of the motor-inverter system requires direct coupling and simultaneous solutions of the time varying EM field, the characteristic of the inverter circuit, stator winding circuit and rotor rotational effect in time domain.

The time dependent nonlinear EM field in a motor can be represented by applying the Maxwell's equation as:

$$\nabla \times (\nu \nabla \times A) = \frac{i_s}{S} - \sigma \frac{\partial A}{\partial t} + \nabla \times (\nu B_r) \qquad (1)$$

In (1), the first term of the right side of represents for the stator conductor region, second term represents for iron cores region and the last term represents for permanent magnet region. Magnetization vector method is used to represent the permanent magnet in this FEM formulation. In (1), A is the magnetic vector potential, ν is the reluctivity of the material, i_s is the stator phase current, σ is the conductivity of the material and B_r is the remanence flux density of permanent magnet.

The stator phase circuit equation can be expressed as:

$$V_s = Ri_s + L_\sigma \frac{di_s}{dt} + e \tag{2}$$

where V_s is the stator phase voltage, R total equivalent resistance of the winding, i_s is the stator phase current, L_σ is the inductance of the end winding and e is induced voltage (back-emf).

Rotor motion can be represented by the mechanical equation as

$$J\frac{d\omega}{dt} = T_e - T_L + B\omega \tag{1}$$

where J is the moment of inertia, ω is the rotor speed, T_e is the electromagnetic torque, B is the damping coefficient and T_L is the load toque.

In inverter circuit, the settling time of the semiconductor devices is shorter than the time step length of the FEM. Hence, the semiconductor components can model as nonlinear resistor and the external circuits can be simplified as RLC circuits which directly coupled with stator phase circuit.

The solution of the field equations are obtained by minimizing the corresponding nonlinear energy functional. The minimization is performed by means of finite element method (FEM). Galerkin's method is used to derive the finite element equations and final global equations are solved by Incomplete Cholesky Conjugate Gradient (ICCG) method. Since field and circuit equations are solved simultaneously, magnetic vector potential A and stator phase current i_s are calculated directly from solutions of global system of equations. From which, motor torque is computed by Maxwell Stress Tensor Method. Detailed FEM formulation has been presented in Phyu et. al [1]-[2].

III. Analyzing the Effect of PM Magnetization

A. *Radial, Parallel and Sinusoidal PM Magnetization*

Multi-pole radial magnetization is widely used in high-speed PMSMs. Nonlinear isotropic magnetic material such as bonded NdFeB is commonly used for this type of magnetization. For parallel magnetization, anisotropic sintered magnetic material is applied which possess stronger magnetic field compare with isotropic material [3][4]. For sinusoidal magnetization, ideal Halbach magnetization [5][6] is applied in this work. In Halbach magnetization, each pole of the rotor magnet comprises a halbach array of permanent magnet segments. The orientations of the magnet segments are determined a priori and confirm by magnetic analysis using FEM to get the perfect sinusoidal magnetic field [7].

To check the PM magnetization pattern with the three different types of PM excitations, EM field calculation is carried out with FEM. Only PM ring and back iron are included in FEM calculation. NdFeB magnet with same energy product of 10MGOe is used for all three different types of PM magnetization. Results are shown in Fig.2 and Fig.3. In radial and parallel PM magnetization, magnitude of magnetic field is the highest at the magnet pole transition region where the magnetic field abruptly changes from one direction to another. In sinusoidal magnetization, PM surface field is smoothly changed from North Pole to South Pole and it is perfectly sinusoidal. Flux density distribution in the air gap is calculated. It can be seen that different magnetization patterns generate different air gap field profiles (as shown Fig. 4) and these are directly effect to the producing of motor torque, back-emf, UMP and motor efficiency. Detail analysis is carried out in next section.

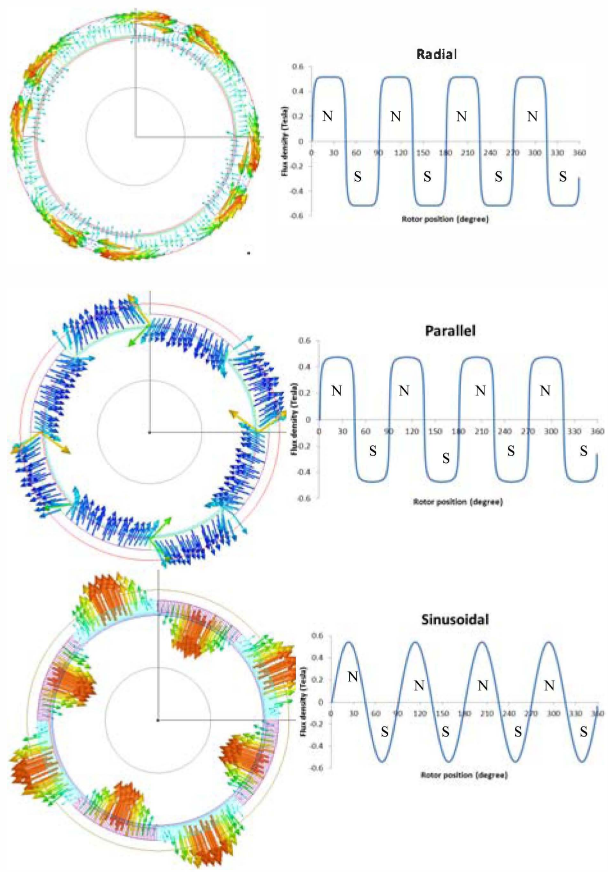

Fig.2 PM radial, parallel and sinusoidal magnetization field patterns

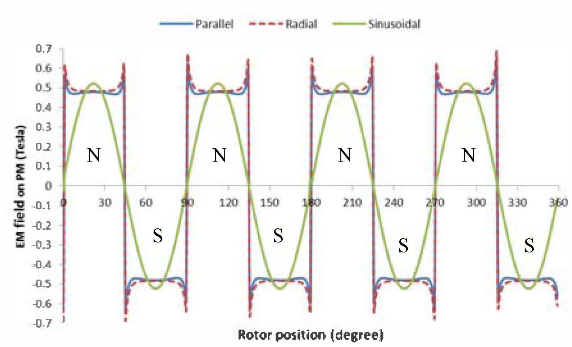

Fig.3 PM Surface field with radial, parallel and sinusoidal magnetization

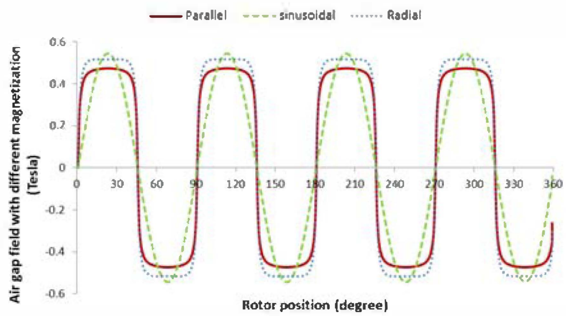

Fig.4 Comparison of air gap field with different magnetizations

B. *Effect of PM magnetization to motor Back-emf*

For a high efficiency, good quality high speed PMSMs, back-emf waveform induced by rotor motion must be well estimated because it is closely related to the producing of EM torque and torque ripple for the motor [8]. Motor designers want to get purely sinusoidal or trapezoidal back-emf waveform based on motor types and control schemes. However, back-emf waveform depends on PM excitation, winding arrangement, motor structure and pole/slot combinations. Fig.5 shows simulated back-emf waveforms with different pole/slot combinations. Even though it is theoretically possible to produce smooth torque for any back-emf waveform by controlling the current waveform with a chopping scheme, this requires a relatively complex and precise control procedure and expensive electronic circuits. In this work, 8pole-9slot and 6pole-9slot PM motor are used to analyze the effect of PM magnetizations on back-emf waveform. Results show that different magnetizations gives different air gap field distribution in both 8pole-9slot and 6pole-9slot PM motor as shown Fig.6 and Fig.8. However, Sinusoidal magnetization gives sinusoidal air gap field and sinusoidal back-emf waveform regardless of pole/slot combinations and winding arrangement as shown in Fig. 7 and Fig.9. It can conclude that PM magnetization is one of the key factors to shape the back-emf waveform. Preliminary investigation of the effect of PM excitation on motor back-emf is necessary to identify proper driver circuit and control scheme.

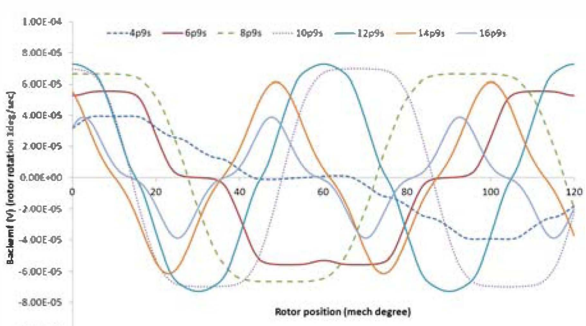

Fig.5 Comparison of back-emf with different pole/slot combinations

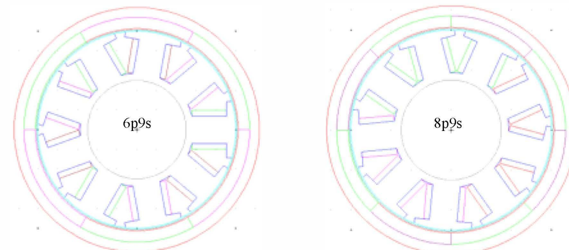

Fig.6 Motor structure: 6pole-9slot and 8pole-9slot

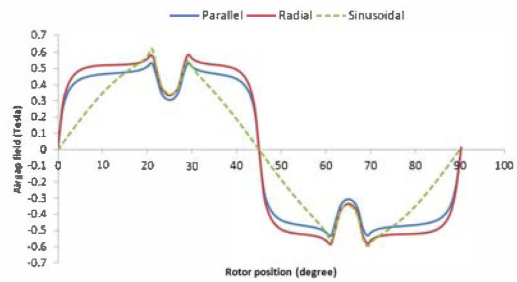

Fig.6 Air gap field distribution for 8pole-9slot motor with different magnetizations

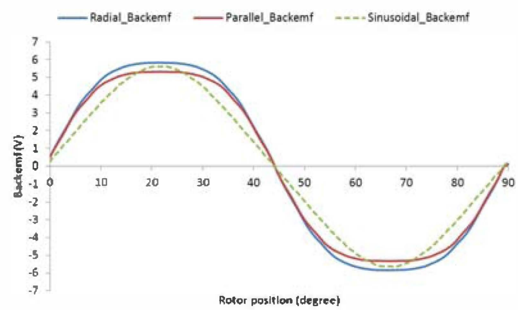

Fig.7 Back-emf waveforms for 8pole-9slot motor with different magnetizations

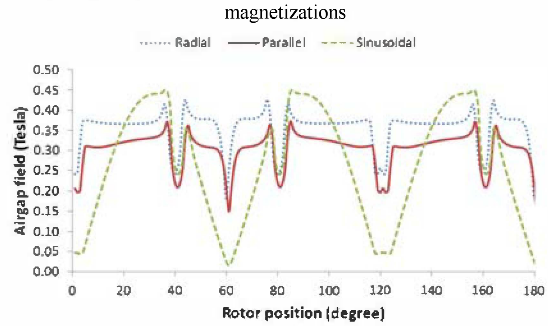

Fig.8 Air gap field distribution for 6pole-9slot motor with different magnetizations

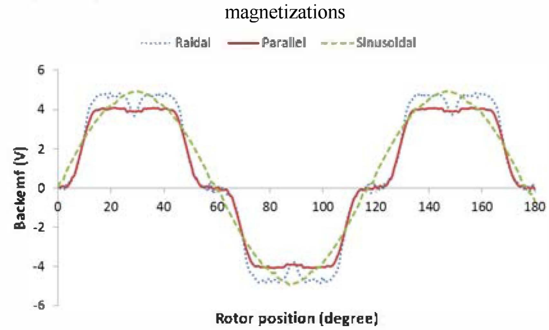

Fig.9 Back-emf waveform for 6pole-9slot motor with different magnetizations

C. Effect of PM magnetization on UMP

The interaction between the magnetic field and the salient poles produce tangential and radial EM forces [9]. Tangential force produces EM torque in the rotor and radial EM force creates UMP which effects to motor stability. In 8pole-9slot structure as shown in figure, the magnetic field on the left side and right side of the motor is unbalanced. When the rotor rotates, this unbalanced magnetic field produces unbalanced magnetic pull (UMP) even there is no eccentricity in the rotor mechanical parts [10]-[11]. When different PM magnetization excites to motor magnetic structure, different UMP induces as show in Fig.10. Even for the same structure, different magnetization resulting different amount of UMP. In this 8pole-9slot structure, sinusoidal magnetization gives the lowest UMP where radial magnetization produces the highest. UMP is unwanted forces and one of the major sources of vibration and acoustic noise. To reduce UMP even without the rotor eccentricity, it is needed to analyze the effect of PM magnetization to UMP in preliminary design stage to avoid unwanted noise and vibration.

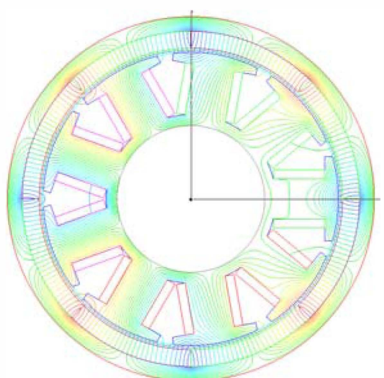

Fig. 10 Unbalance magnetic field in the 8pole-9slot PM motor

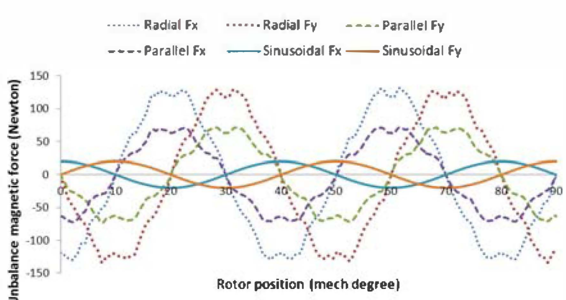

Fig. 11 UMP produced in motor operation

D. Effect of PM magnetization on Cogging Torque

In any type of PM motors, due to the slotted stator structure, the air gap reluctance between the permanent magnet and the stator varies while the magnet rotates with the rotor yoke. The tangential attraction forces will also vary with the rotor positions. Therefore, the cogging torque is generated. The cogging torque can cause start-up problem and greatly effect to the running torque fluctuation. Hence, it is desirable to minimize it at the design stage.

In this work, effect PM magnetization to the producing of cogging torque is analyzed. Cogging torques developed by 8pole-9slot structure and 6ploe 9slot structure are calculated where same stator structure and same magnet strength (10MGOe) are used. Results show that different magnetizations give different cogging torque profiles both in magnitudes and wave forms as shown in Fig.12 and Fig.13. Cogging torque developed by 8pole-9slot is relatively very low compares with 6pole-9slot. Pole/slot combination plays a key role in producing cogging torque. Furthermore, sinusoidal magnetization offers the lowest cogging torque regardless of pole/slot combination and stator structure.

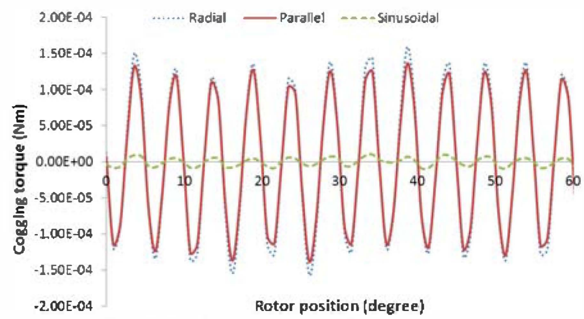

Fig. 12 Cogging torque for 8pole-9slot structure

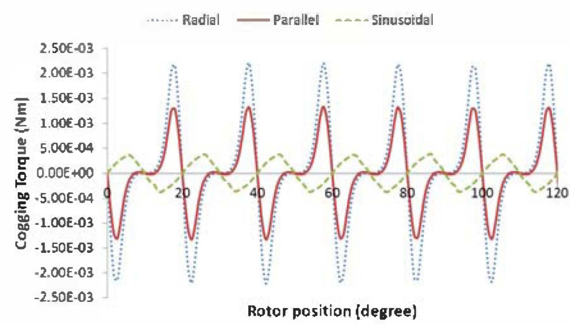

Fig. 13 Cogging torque for 6pole-9slot structure

E. Effect of PM magnetization on EM torque, Torque Ripple and Motor Drive

In ideal case, PMSM requires alternating phase current that may be sine waves or square waves depending on whether the motor is designed with sinusoidal or trapezoidal back-emf [12]. In both sine drive and square wave drive (or BLDC drive), the power electronics controllers are identical as shown in Fig. 1 and only the control strategy is different. The control strategy is arranged to give smooth, accurate control of torque and speed while limiting the current [12].

Motor EM torque is produced by the interaction of the stator current and the PM rotor field. EM torque depends on the shape of the flux density distribution in the air gap which in turn relies on PM magnetization. In this work, motor EM torque is calculated with different PM magnetizations and analyzed the motor EM torque and torque ripple with both sine drive mode and BLDC drive mode.

1) BLDC drive mode

In BLDC drive mode, six steps operation is used where fixed supply voltage is applied to the motor. Supply voltage to the driver circuit is shown in Fig.14. Two phase windings out of three are conducting at every commutation period and they are switched in a logical sequence by electronic controller. Stator phase currents and EM torques are calculated with different magnetizations in BLDC drive mode. In 8pole-9slot structure, sinusoidal magnetization gives the highest stator current and EM torque, Fig.15 and Fig.16. In 6pole-9slot structure, parallel magnetization develops the highest stator current and EM torque, Fig.17 and Fig18. However, torque ripple for sinusoidal magnetization is the lowest in 6pol-9slot (Fig.18). Sinusoidal magnetization generates purely sinusoidal back-emf wave form in 8pole-9slot structure (Fig.7) and parallel magnetization offers nearly perfect trapezoidal wave shape in 6pole-9slot structure (Fig.9). Results prove that pure sinusoidal or trapezoidal back-emf offers the most optimal motor torque. In addition, detail analysis of PM magnetization is essential to get the high torque.

2) Sine drive mode

In sine drive mode, the three line currents are sinusoidal and conducting at any time with 120 electrical degree out of phase each other. Since 8pole-9slot structure holds sine wave shape back-emf, sine drive is implied in this work to reduce the motor torque ripple. Back-emf with different magnetizations and stator phase current are shown in Fig. 19. For comparison, same stator phase current (0.6A) is allowed to flow in the drive circuit then EM torques with different magnetizations are calculated. As shown in Fig.20, sinusoidal magnetization generates ripple free torque. Fig. 21 shows comparison of torque ripple where motor is operated with sine drive mode and BLDC drive mode. Result shows that sine drive reduces up to 90% compare with BLDC drive mode in 8pole-9slot structure. This analysis shows that motor and driver performance should match each other in order to get motor optimal performance especially to get a smooth torque and the lowest speed variation.

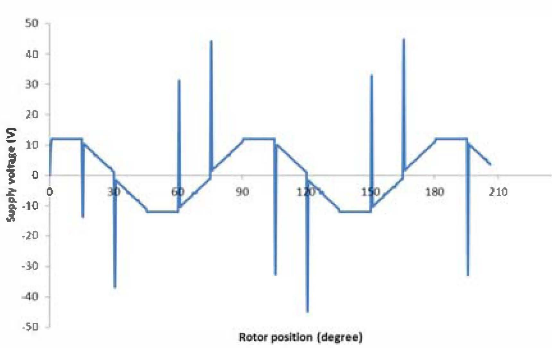

Fig. 14 Supply voltage for BLDC drive mode

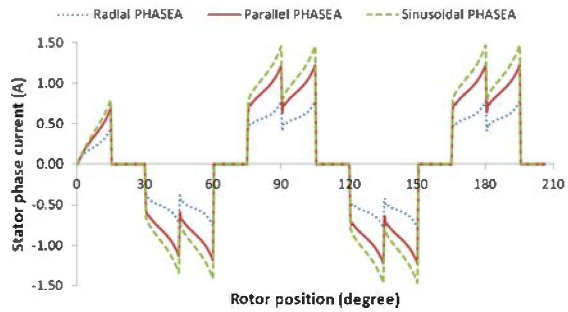

Fig. 15 Stator currents with different magnetization for 8pole-9slot operated in BLDC drive mode

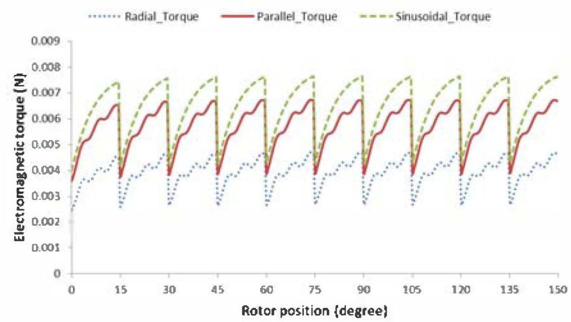

Fig. 16 EM torques with different magnetizations for 8pole-9slot operated in BLDC drive mode

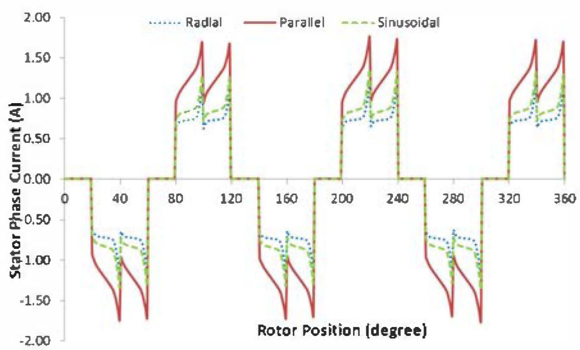

Fig. 17 Stator phase current with different magnetizations for 6pole-9slot operated in BLDC drive mode

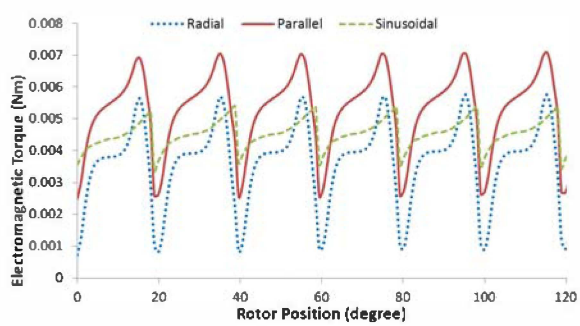

Fig. 18 EM torque with different magnetizations for 6pole-9slot operated in BLDC drive mode

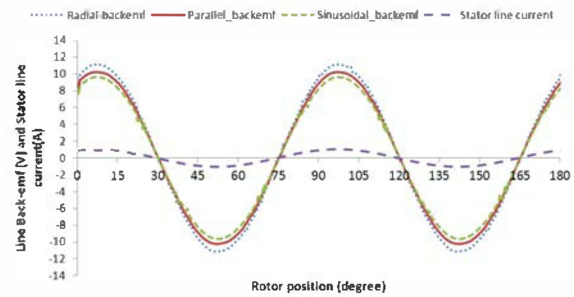

Fig. 19 Back-emf and stator current for 8pole-9slot operated in Sine drive mode

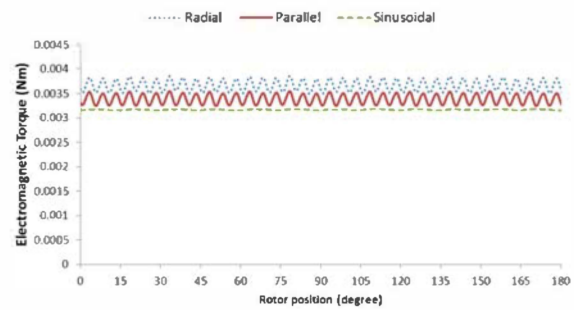

Fig. 20 EM torques with different magnetizations for 8pole-9slot operated in Sine drive mode

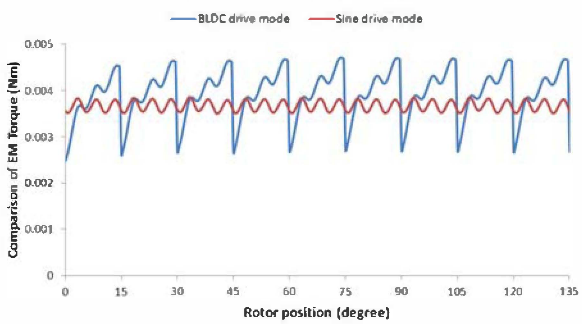

Fig. 21 Comparison of EM torque ripple of sine drive mode and BLDC drive mode with radial magnetization

IV. Conclusions

This paper has presented the effect of three different PM magnetization: Radial, Parallel and Sinusoidal to the electromagnetic field system of the high speed PMSM and analyzed the motor performances such as back-emf, UMP, cogging torque, EM torque and torque ripple. Based on the detailed analysis, the following conclusions have been drawn:

1. PM magnetization is directly related to the air gap field distribution of the non-linear electromagnetic field system of the motor. Different PM magnetization can give different magnetic field distribution in the system which in turn different motor performances.
2. Sinusoidal magnetization can generate the lowest UMP and cogging torque regardless of pole/slot combination and stator slot structure.
3. PM magnetization is one of the key factors to shape the back-emf waveform which is closely related to the producing of EM torque and torque ripple for the motor. In this study, results show that ***parallel magnetization*** generates trapezoidal shape back-emf and offers the highest EM torque when motor is operated in BLDC mode in 6pole-9slot structure. However, in 8pole-9slot structure, ***sinusoidal magnetization*** generates sinusoidal back-emf and offers the highest motor torque. Hence, preliminary investigation of the effect of PM excitation on motor back-emf is vital to get motor optimal performance especially to get a smooth torque and the lowest speed variation.

To improve the motor design, efficiency and reliability, apply the correct magnetization pattern is important. Investigation of the PM magnetization field to the electromagnetic system of the motor is essential to get the motor's optimal performances and to identify proper driver circuit and control scheme.

References

[1] H. N. Phyu, C. Bi and C.S. Soh, "Study of a Spindle Motor Starting Using Circuit-Field Direct Coupled System", Proc. of Int. Conf. on Electrical Machines and Systems (ICEMS 2007), Seoul, Korea, Oct. 8~11, 2007, pp.456-461.

[2] M. A. Jabbar, H. N. Phyu, Z. J. Liu and C. Bi, "Modeling and Numerical Simulation of a Brushless Permanent-Magnet DC Motor in Dynamic Conditions by Time-Stepping Technique", IEEE Trans. Industrial. App., vol. 40, No. 3, Mau/June 2004.

[3] C. M. Stephens, System and method for magnetization of permanent magnet rotors in electrical machines, US patent No. US7228616B2, June 12, 2007.

[4] M.A. Tavakkoli and S. M. Madani, "Material and magnetization effect on permanent magnet motor design", Asian J. Applied Sci., vol 2, No.2, pp.128-138, 2009.

[5] Z. Q. Zhu, "Recent development of halbach permanent magnet machines and applications," IEEE, vol. A247, pp. 529-551, April 2007.

[6] Z. Q. Zhu and D. Howe, "Halbach permanent magnet machines and applications: a review", IEE Proc.-Electrical Power Application, Vol.148, No.4, pp. 299-308, July 2001.

[7] Joseph J. Stupak Jr., "Methods of magnetizing permanent magnets", EMCW coil winding show, Ohio, US, 1 Oct-2 Nov 2000.

[8] J. H. Lee, D. H. Kim and IL.H. Park, "Minimization of higher back-emf harmonics in permanent magnet motor using shape design sensitivity with B-spline parameterization," IEEE Trans.,on Magn., vol39, No.3, pp. 1269-1272, May 2003.

[9] D. Zarko, S. Ban, I. Vazdar and V. Jaric, "calculation of unbalanced magnetic pull in a salient pole synchronous generator," 14th Unt. Power Ele. And Motion Control Conf.,EPE-PEMC 2010.

[10] Z.Q. Zhu, M. L/ Mohd Jamil and L.J. Wu, "Influence of slot and pole number combinatios on unbalanced magnetic force in permanent magnet machines",

[11] C. Bi, Z. J. Liu and T. S. Low, "Effect of unbalanced magnetic pull in spindle motors." IEEE Trans. On Magn., Vol.33, No.5, pp.4080-4082, Sept 1997.

[12] J. R. Hendershot Jr. and TJE Miller, Design of brushless permanent magnet motors, magna Physis publishing and Clarendon Press, Oxford, 1994.