Unbalanced Magnetic Pull Induced by Drive Current In PM-BLDC Motor Operation

Chao BI, Nay Lin Htun Aung, Hla Nu Phyu, Quan JIANG, and Song LIN
Data Storage Institute, Singapore
e-mail: Bi_Chao@dsi.a-star.edu.sg

Abstract — In the applications of high performance permanent-magnetic brushless DC (PM-BLDC) motor, the effects of unbalanced–magnetic-pull (UMP) is very concerned. Besides the intrinsic and extrinsic reasons [1], the motor drive current may also be an UMP source if the armature winding design is not reasonable. This paper presents an analytic model for analyzing the UMP induced by electromagnetic (EM) structure and drive current of the PM-BLDC motor, and the model can simplify effectively the analysis procedure. The analysis shows that, the UMP induced by the drive current can be avoided by using the reasonable winding structure, magnetic pole-pairs and stator slot number. For verifying the effectiveness of the analytic method proposed, several PM-BLDC motors are analyzed with the numerical method to confirm the effectiveness of the UMP model presented.

I. I. INTRODUCTION

PM-BLDC motor has been widely used in different areas. As the UMP generated in the motor operation can induce serious acoustic noise and vibration, this kind of force is very concerned in the motor applications [1][2][3][4]. A typical EM structure of the PM-BLDC motor is shown in Fig. 1, and it is a 3-phase PM-BLDC motor with surface mounted magnet on its rotor, like the spindle motor used in hard disk drive. For realizing compact structure, the fractional concentrated armature windings are used in the motor; see Fig. 2. This kind of winding can realize multiple magnetic pole-pair with limited stator slots, which is important for the applications like the spindle motors.

The PM-BLDC motors are driven by BLDC drive mode, i.e., one electric drive cycle is formed by six steps, and every time only two phase of windings are energized with current.

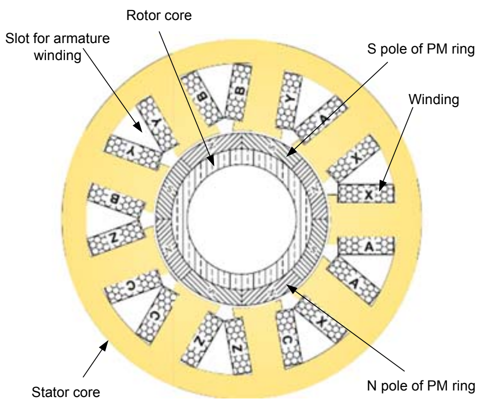

Fig. 1 the PM-BLDC motor with surface mounted magnet on the rotor

Reference [1] points that, the UMP generated in the motor operation can be classified into two parts: extrinsic UMP and intrinsic UMP. The former is induced by the reasons unrelated with motor EM structure, like the problems in the quality of magnetic ring and rotor eccentricity rooted in the motor production. The later is linked directly with the motor EM structure, like the stator slot number and magnetic pole-pairs of the motor.

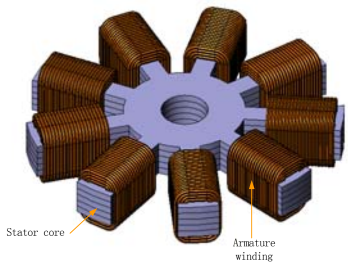

Fig. 2 the fractional concentrated windings in spindle motor

In the analysis introduced in [2], only the magnetic field produced by the permanent magnet is considered. The analysis there gets a deduction that, if the number of the stator slot is even, no intrinsic UMP can be induced in the motor operation.

However, in the motor operation, the motor is driven by currents in the armature windings. Therefore, besides of PM ring on the rotor, the drive current can also generate EM field in the motor operation. When the effects of driven current are considered, whether the deduction of [2] can still be true?

From [1][2], the UMP is caused by the unbalanced magnetic field in the motor. If the field produced by the drive current is asymmetric in the motor space, the drive current can certainly engender UMP in the motor operation. As this kind of UMP is linked with the motor winding structure, and according to the definition in [1], this UMP belongs to the category of intrinsic UMP. However, as this UMP is different from the intrinsic UMP introduced in [1], where the intrinsic UMP is induced by the unbalanced field of the permanent magnet, and is not related with drive current. In this paper, the intrinsic UMP induced by the magnet is defined as M-I-UMP, and the one related with drive current is C-I-UMP. We will concentrate to analyze the conditions inducing the C-I-UMP in this paper.

II. MMF PRODUCED BY THE DRIVE CURRENT OF SPINDLE MOTOR

It was mentioned that, the fractional concentrated windings are used in the spindle motors for realizing compact structure and multiple magnetic pole-pairs. When a motor uses this kind of windings, in normally, the relationship between the magnetic pole-pair and stator slot number can be described by

$$Z_s = 3p, \tag{1}$$

or

$$Z_s = 1.5p, \tag{2}$$

where, p is the magnetic pole-pairs, and Z_s is the stator slot number of the motor.

The typical structures of the motor with the winding described by (1) include the motor with 6 slots and 2 magnetic pole-pairs. The motors described by (2) include the motor with 6 slots and 4 magnetic pole-pairs. These two kinds of motors will be discussed further in the Section-V.

When the fractional concentrated winding is used, the relationship between the lowest order of the MMF produced by the drive current, $\boldsymbol{q}$, and the magnetic pole-pairs of the motor, $\boldsymbol{p}$, can normally be categorized as

$$q = p, \tag{3}$$

$$q = p/2, \tag{4}$$

$$q = 1. \tag{5}$$

In Section-V, several examples will be used to show the structures of these motors. In the following analysis, q will be called as "fundamental order" of the drive current MMF.

Therefore, the MMF of the drive current can be described by

$$F_C = \sum_{n=1} f_{cn} Sin[nq(\theta - \beta_n)], \tag{6}$$

where, f_{cn} is the amplitude of the nq's order of harmonic.

III. Intrinsic UMP Induced In The Motor Operation

In the airgap of the motor, the MMF generated by the PM ring on the rotor can be described by,

$$F_R(\theta, t) = \sum_{m=1} f_{rm} Sin[(2m-1)p(\theta - \alpha)], \tag{7}$$

where, f_{rn} is the amplitude of the harmonic with the order of (2m-1)p.

For making the influence of the drive current to the UMP be clear, in this paper, the eccentricity of the rotor is not considered. In this case, the unit permeance of the motor airgap can be described by

$$\Lambda(\theta) = \Lambda_0 \{1 + \sum_{n=1}^{\infty} [\lambda_n Cos(nZ_s \cdot \theta)]\}, \tag{8}$$

where, Λ_0 is the average value of the unit permeance of the airgap, and it is determined by the effective airgap length. Z_s is the slot number of stator core, and λ_n is the coefficients of the n^{th} order unit permeance.

When the drive current exists, the magnetic flux density in the airgap, B_a, can be expressed as

$$B_a(\theta, \alpha, \beta) = \Lambda(\theta) \cdot [F_R(\theta, \alpha) + F_C(\theta, \beta)], \tag{9}$$

where, β is the phase angle of f_{cn}

In the airgap of the motor, the local radial force density at position θ can be calculated by

$$p_r(\theta, \alpha, \beta) = \frac{v_0}{2} B_a^{\,2}(\theta, \alpha, \beta), \tag{10}$$

where, v_0 is the reluctivity of vacuum.

Using Cartesian coordinate system to do the analysis, the components of $p_r(\theta, \alpha, \beta)$ in x and y directions can be described separately by

$$\begin{cases} p_x(\theta, \alpha, \beta) = p_r(\theta, \alpha, \beta) \cdot Cos(\theta) \\ p_y(\theta, \alpha, \beta) = p_r(\theta, \alpha, \beta) \cdot Sin(\theta) \end{cases} \tag{11}$$

UMP is a global force acting on the rotor, or stator, of the motor, and its components in x and y directions can be calculated by using the local radial forces expressed by (11), i.e., P_x and P_y can be calculated separately by using the following equations,

$$\begin{aligned} P_x(\alpha, \beta) &= hR\int_0^{2\pi} p_x(\theta, \alpha, \beta) d\theta \\ &= \frac{v_0 R \cdot h}{2} \int_0^{2\pi} \{[F_R(\theta, \alpha) + F_C(\theta, \alpha, \beta)] \cdot \Lambda(\theta)\}^2 \, Cos(\theta) d\theta \end{aligned}, \tag{12}$$

and

$$\begin{aligned} P_y(\alpha, \beta) &= hR\int_0^{2\pi} p_y(\theta, \alpha, \beta) d\theta \\ &= \frac{v_0 R \cdot h}{2} \int_0^{2\pi} \{[F_R(\theta, \alpha) + F_C(\theta, \alpha, \beta)] \cdot \Lambda(\theta)\}^2 \, Sin(\theta) d\theta \end{aligned}, \tag{13}$$

where, h is the thickness of the motor core, and R is the average radius of the motor airgap.

Let us analyze $P_x(\alpha, \beta)$ first. Its force density, i.e., the local force in x direction, can be expressed as

$$\begin{aligned} p_x(\theta, \alpha, \beta) &= \frac{v_0 R \cdot h}{2} \{[F_R(\theta, \alpha) + F_C(\theta, \alpha)] \cdot \Lambda(\theta)\}^2 \, Cos(\theta) \\ &= \frac{v_0 R \cdot h}{2} [F_R^2(\theta, \alpha) + 2F_R(\theta, \alpha) F_C(\theta, \beta) + F_C^2(\theta, \beta)] \Lambda^2(\theta) Cos(\theta) \\ &= p_{imx}(\theta, \alpha) + p_{ihx}(\theta, \alpha, \beta) + p_{icx}(\theta, \alpha, \beta) \end{aligned}, \tag{14}$$

where, $p_{imx}(\theta, \alpha)$ is the M-I-UMP density which has been described amply in [2]. From the analytic model introduced by [2], this kind of UMP is related only with the magnetic field of the permanent magnet, and stator slot structure. But this UMP not related with the drive current. As the existence of the drive current, two more components are added in the UMP, i.e., $p_{ihx}(\theta, \alpha, \beta)$ and $p_{icx}(\theta, \alpha, \beta)$. The former is related with the field produced by the permanent magnet, slot structure and drive current. The later is not related with the field produced by the magnet, but only related with the slot structure and drive current.

IV. Effects of Drive Current on The UMP

Let us analyze the effects of $p_{ihx}(\theta, \alpha, \beta)$ first. Integrate the $p_{ihx}(\theta, \alpha, \beta)$ in (14), we can get

$$\begin{aligned} P_{ihx}(\alpha, \beta) &= \frac{v_0 R \cdot h}{2} \int_0^{2\pi} p_{ihx}(\theta, \alpha, \beta) d\theta = v_0 R \cdot h \\ &\times \int_0^{2\pi} \left\{ \sum_{m=1} f_{Rm} Sin[(2m-1)(\theta - \alpha)p] \right\} \left\{ \sum_{n=1} f_{cn} Sin[(2n-1)(\theta - \beta_n)q] \right\} \Lambda(\theta) d\theta \\ &= v_0 R \cdot h \int_0^{2\pi} \left\{ \sum_{m=1} f_{Rm} Sin[(2m-1)(\theta - \alpha)p] \right\} \left\{ \sum_{n=1} f_{cn} Sin[(2n-1)(\theta - \beta_n)q] \right\} \\ &\times \sum_{k=0} l_k Cos(kZ_s \theta) \cdot Cos(\theta) d\theta \end{aligned}, \tag{15}$$

where, l_k is related with the unit permeance of the airgap, which is determined by the stator slot number, slot structure, and airgap length of the motor. The expression of l_k can be found in [2], and the l_0 and l_1 are the dominant parts of l_k.

Analysis shows that, for the result of the integration of (15), the contributions of all the harmonics are zero, except the harmonics which can meet the following relationships:

$$\begin{cases} nq = (2m-1)p + kZ_s - 1 \\ nq = (2m-1)p + kZ_s + 1 \\ nq = -(2m-1)p + kZ_s - 1 \\ nq = (2m-1)p - kZ_s + 1 \\ nq = (2m-1)p - kZ_s - 1 \\ nq = (2m-1)p + kZ_s + 1 \\ nq = -(2m-1)p - kZ_s + 1 \\ nq = -(2m-1)p - kZ_s - 1 \end{cases} \tag{16}$$

Based on relationships described by (16), the following six special cases should be paid attention to. Actually, for the motors mentioned in these six cases are the ones met frequently in the applications.

Case-1: p, q and Z_S are even

It is clear, (16) cannot come into existence in this case as its left side is even and right side is odd. Therefore, no P_{ihx} can be induced for this kind of motor.

Case-2: Z_S =3p and q=p

In this case, the following sufficient equation can be deduced from (16),

$$[n \pm (2m-1) \pm 3k]p = \pm 1 . \tag{17}$$

It is clear, if the magnetic pole-pair is bigger than 1, (17) cannot stand, i.e., no P_{icx} can be induced in this kind of motor.

Case-3: Z_S =3p and q=p/2

In this case, p must be even. Let p=2a, t the following sufficient equation can be deduced from (16),

$$[n \pm 2(2m-1) \pm 6k]a = \pm 1 . \tag{18}$$

It is clear, if a is bigger than 1, (18) cannot stand, i.e., no P_{icx} can be induced in the operation of kind of motor.

Case-4: Z_S =1.5p and q=p

In this case, p must be even. Let p=2b, the following sufficient equation can be deduced from (16),

$$[2n \pm 2(2m-1) \pm 3k]b = \pm 1 . \tag{19}$$

It is clear, if b is bigger than 1, (19) cannot stand, i.e., no P_{icx} can be induced in the operation of kind of motor.

Case-5: Z_S =1.5p and q=p/2

In this case, p must be even. Let p=2c, the following sufficient equation can be deduced from (16),

$$[n \pm 2(2m-1) \pm 3k]c = \pm 1 . \tag{20}$$

It is clear, if c is bigger than 1, (20) cannot stand, i.e., no P_{icx} can be induced in the operation of kind of motor.

Now we consider effects of $p_{icx}(\theta,\alpha,\beta)$,

$$\begin{aligned} P_{icx}(\alpha,\beta) &= \frac{\nu_0 R \cdot h}{2} \int_0^{2\pi} p_{icx}(\theta,\alpha,\beta) d\theta = \frac{\nu_0 R \cdot h}{2} \\ &\times \int_0^{2\pi} \left\{ \sum_{n=1} f_{cn} Sin[(2n-1)(\theta - \beta_n)q] \right\}^2 \Lambda(\theta) d\theta \\ &= \frac{\nu_0 R \cdot h}{2} \int_0^{2\pi} \left\{ \sum_{n=1} f_{cn} Sin[(2n-1)(\theta - \beta_n)q] \right\}^2 \\ &\times \sum_{k=0} l_k Cos(kZ_s\theta) Cos(\theta) d\theta \end{aligned} \tag{21}$$

Analysis shows that, for theintegration result of (21), the contributions of all the items are zero, except the harmonics which can meet the following relationships:

$$nq = kZ_s \pm 1 \tag{22}$$

and

$$nq = -kZ_s \pm 1 . \tag{23}$$

It is clear, the items related with (23) has no meaning to PM-BLDC motor. We should consider only the items related with (22) in calculating P_{icx}.

Consider above Case-1 to Case-5, we can use the similar method to do the analysis and know that, P_{icx} is also zero in all these cases.

Though these results are got from the analysis to the X-component of the UMP, it can be proven that, the analysis to the Y-component of UMP can also generate the same results.

From above analysis, we can know that, if the magnetic pole-pair and the fundamental order of drive current MMF are high, the drive current cannot induce the UMP in the PM-BLDC motor operation.

V. VERIFYING UMP OF SPINDLE MOTOR WITH FEM

It is well known that the finite element method (FEM) can be used to calculate the magnetic field in the motor accurately. Therefore, FEM is an effective tool in analyzing the UMP generated in the motor operation, and the authors have used this tool to analyze many PM-BLDC motors. In this section, the FEM results will be used to verify the analytic ones obtained in Section-IV. As the limitation in the paper length, only two kinds of motors will be introduced here.

Motor-1: ***Spindle motor with 6 slots and 4 pole-pairs***

For this motor, both the winding shown in Fig. 3 and Fig. 4 can be used for realizing the 4 pole-pair.

From [2], if the current is zero, no UMP can be generated in the operation of this kind of motor. But, when the drive currents are applied, whether the UMP can be generated?

The MMFs produced by these two drawings are different; see Fig. 5 and Fig. 6. The spectrums of these waveforms are shown in Fig. 7 and Fig. 8 respectively.

From the spectrum shown in Fig. 7 , it can be known that, the fundamental order of the MMF produced by the 1st kind of winding is 1. For this kind of motor, we can find the items which can match the relationships described by (16) and (22), and their major parts are listed in Table 1. The table shows it clearly that, the drive current can induce UMP in the motor operation. Fig. 9 shows the UMP calculated by using FEM.

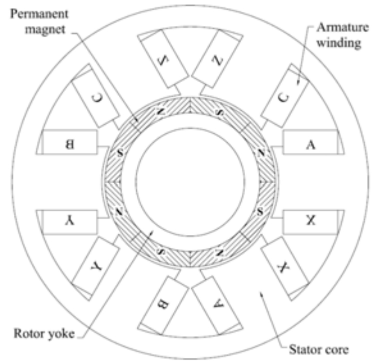

Fig. 3 The 1st winding in the spindle motor with 6-slot and 4 pole-pairs

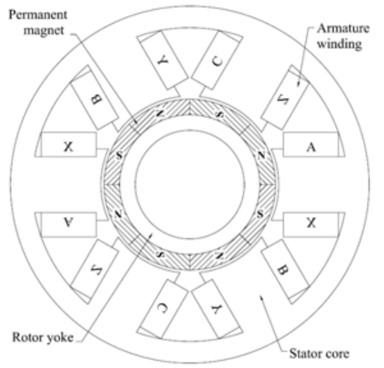

Fig. 4 The 2nd winding in the spindle motor with 6-slot and 4 pole-pairs

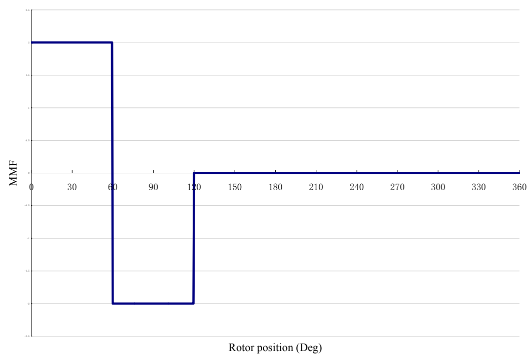

Fig. 5 The MMF generated by one phase current of the 1st kind of winding

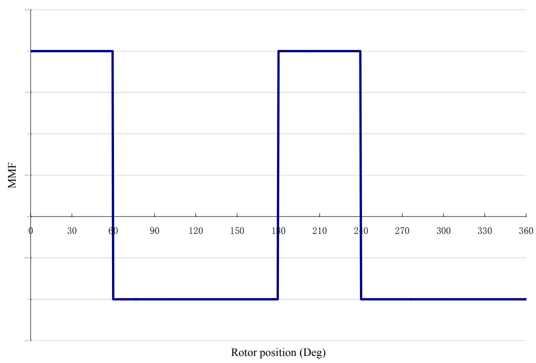

Fig. 6 The MMF generated by the one phase current of the 2nd winding

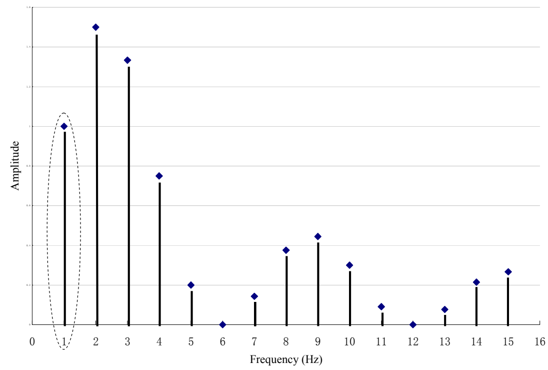

Fig. 7 The spectrum of the MMF generated by one phase current of the 1st kind of winding

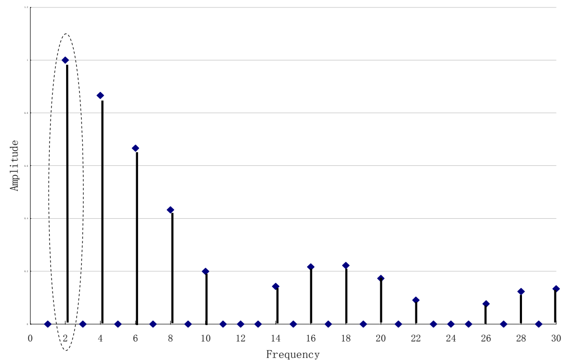

Fig. 8 The spectrum of the MMF generated by one phase current of the 2nd kind of winding

Table 1 The 1st winding: The harmonics inducing the C-I-UMP

Harmonic order of rotor magnet	Harmonic order of drive current	Harmonic order of slot permeance
1	3	0
1	5	0
1	1	1
1	3	1
0	5	1
0	7	1

From the spectrum shown from Fig. 8, it can be known that, for the motor with the 2nd kind of drawing, its fundamental order is 2, therefore, it belongs to the motors categorized into Case-1 and 2 which were mentioned in Section-IV. According to the analysis in Section-IV, no C-I-UMP can be produced by this kind of motor; therefore, no intrinsic UMP can be induced in the motor operation. For verifying the result, FEM is still used to calculate the UMP, and the result is shown in Fig. 10. Comparing with the UMP shown in Fig. 9, the peak value of the UMP produced by the second kind of winding is only about 0.2% of the one generated by the first kind of winding. As its value is so small, and waveform is irregular, the UMP shown in Fig. 10 can be considered as the result of the errors being from the numerical mode and numerical calculation. Therefore, the intrinsic UMP of this kind of motor can be neglected in the motor design.

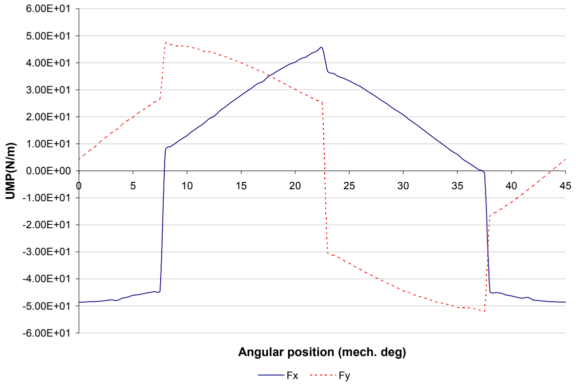

Fig. 9 FEM result: UMP of the motor shown in **Fig. 3**

Let us consider the magnetic field produced by the drive current. Fig. 11 and Fig. 12 show these fields in the motors with the first and second kind of windings separately. From the figures, the field produced by the first kind of winding is unbalanced in the space, and the second one is balanced. It is clear, though the slot structure and magnetic pole-pair of the motors are same, the first kind of field can induce the UMP, but the second cannot.

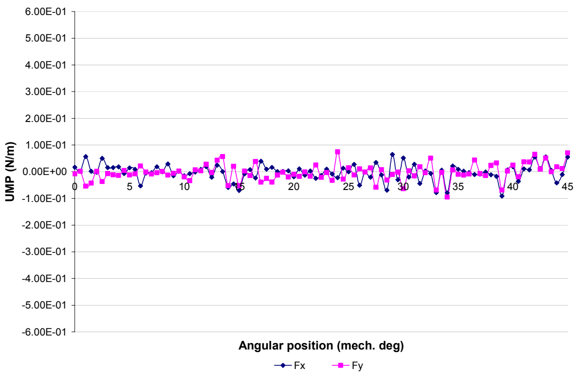

Fig. 10 FEM result: UMP of the motor shown in **Fig. 4**

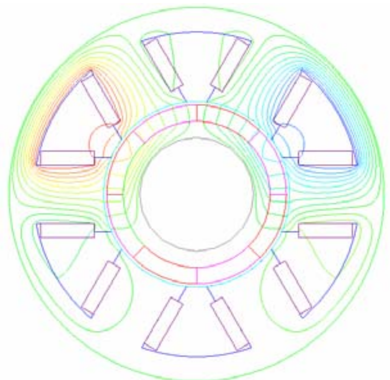

Fig. 11 FEM result: The magnetic field produced by the drive current in the motor shown in Fig. 3

From [1], both the slot number and magnetic pole-pair of Motor-1 are even, therefore the M-I-Intrinsic UMP cannot be induced in the operation of Motor-1. But the results here show that, for the same motor, when different windings are used, the UMP can be very different as the effects of the C-I component.

From the results of Motor-1 obtained by FEM, we can know that the analytic results mentioned in the Section-IV are tenable.

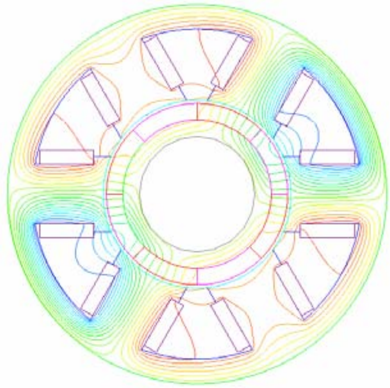

Fig. 12 FEM result: The magnetic field produced by the drive current in the motor shown in Fig. 4

Motor-2:* *Spindle motor with 9 slots and 4 pole-pairs

The structure of this kind of motor is shown in Fig. 1 For this kind of motor, the intrinsic UMP can be generated even the drive current is zero [2][1], i.e., M-I-UMP can be induced in the operation of the motor, and its waveform is shown in Fig. 13. But, what are the effects of the C-I-UMP induced by the drive current?

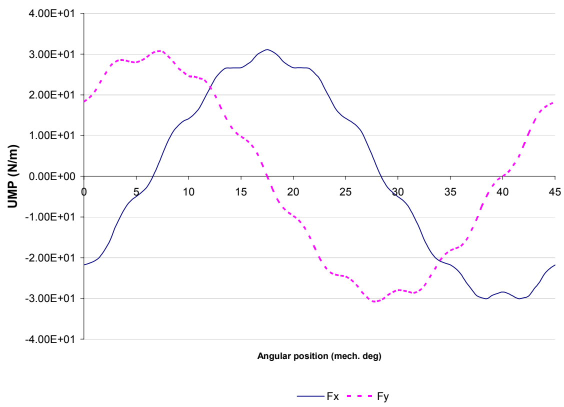

Fig. 13 The UMP generated in the 9-slot/4-pp spindle motor without drive current

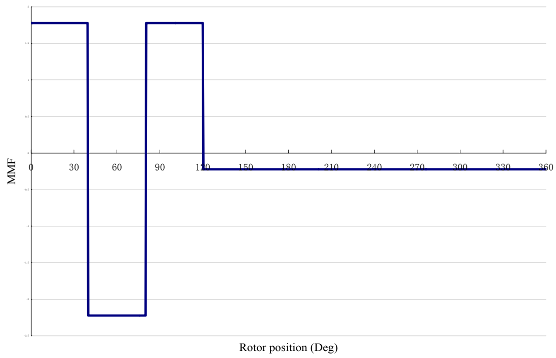

Fig. 14 The MMF generated by the one phase current of the 2nd kind of winding

The drive current MMF of the motor is shown in Fig. 14, and the spectrum of the MMF is shown in Fig. 15. From the spectrum, it can be known that the fundamental order of the MMF is 1. For this kind of motor, the relationships described by (16) and (22) can be easily matched, and their major parts are listed in Table 2. Therefore, the intrinsic UMP is unavoidable in operation of Motor-2. Fig. 16 shows the UMP calculated by using FEM. Comparing with the M-I-UMP shown in Fig. 13, the drive currents deform the UMP waveform obviously.

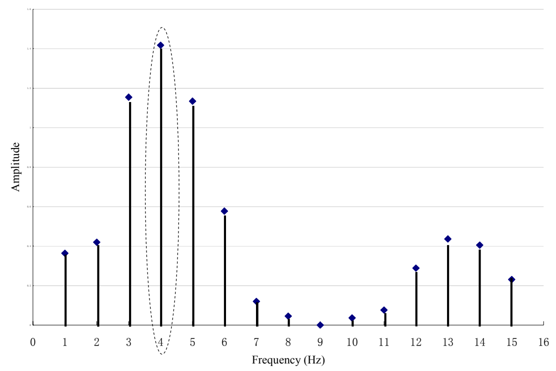

Fig. 15 The spectrum of the MMF generated by one phase winding of the 9-slot/4-pp spindle motor

Table 2 The harmonics inducing the C-I-UMP in the spindle motor with 9-slots/4-pp

Harmonic order of rotor magnet	Harmonic order of drive current	Harmonic order of slot permeance
1	3	0
1	5	0
1	1	1
1	3	1
0	5	1
0	7	1

The C-I-UMP can also be explained by magnetic field distribution. The field produced by one step winding current is shown in Fig. 17. It can be known that, the winding used in the 9-slot/4-pp spindle motor can let the drive current produce unbalance field in the motor operation, and this unbalance can certainly induce the additional UMP in the motor operation. These results confirm again the analysis in Section-IV.

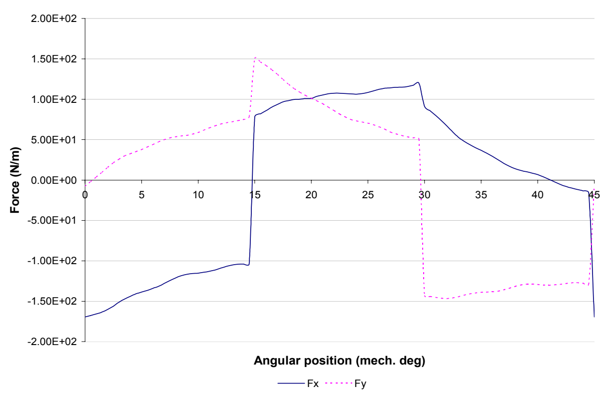

Fig. 16 The UMP generated in the 9-slot/4-pp spindle motor

driven by rated current

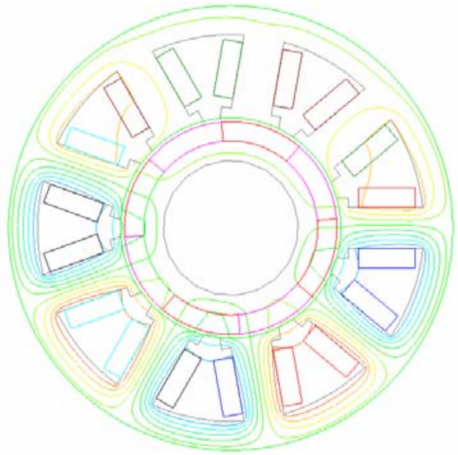

Fig. 17 The magnetic field produced by the drive current of the 9-slot/4-pp spindle motor

VI. CONCLUSIONS

Besides of the EM structure and component quality issues, when the BLDC drive mode is used, the drive current may also induce UMP in the PM-BLDC motor operation. Utilize the UMP model presented in the paper, it can be known that, if the fundamental order of the drive current MMF and magnetic pole-pair are multiple, the drive current is difficult to induce UMP. If the fundamental order of the drive current MMF is one, the UMP is easy to be induced in the motor operation. This has been proven by both the analytic the numerical analysis in the paper. Therefore, in the design of the PM-BLDC motors like the spindle motor used in hard disk drive, it should be careful in using the armature windings whose fundamental order is one. Some armature winding structures could be effective in reducing the cogging torque, but could also induce serious acoustic noise and vibration as they can induce C-I-UMP in the motor operation.

VI. REFERENCES

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