Influence of Transient Current to PM-AC Motor Driven By BLDC Mode

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Abstract- **When BLDC drive mode is used to drive PM-AC motors, the influence of the transient current cannot be neglected, especially during high speed operation. In this paper, this influence to the BLDC drive mode is analyzed, and an analytic model for describing the transient current to the commutation angle and copper loss is presented. A method to determine the optimal commutation angle of the BLDC mode is introduced. Both the simulation and testing results prove the effectiveness of the model and the method.**

I. Introduction

Reducing the power losses of the permanent magnet (PM) AC motor is a very concerned issue in many applications. In PM-AC motor operation, copper loss contributes to one of the major power losses. This loss is not only related with the motor specifications, but also linked with the drive mode of the motor controller. Brushless DC (BLDC) drive mode is an effective drive mode for the PM-AC motors, and has been widely used in the products like hard disk drive (HDD). Many BLDC drive modes have been developed and reported, e.g., constant drive current BLDC mode and constant drive voltage mode [1]. In this paper, for the PM-AC motor driven by BLDC mode, we will call it as PM-BLDC motor for short.

For a given PM-BLDC motor, its performance is related with the commutation angle of the drive mode, and it is expected that, we can find a special angle which can generate the required drive torque, and meantime the copper loss of the motor be minimum [2]-[5]. This angle will be defined as the ***Optimal Commutation Angle*** (***OCA***).

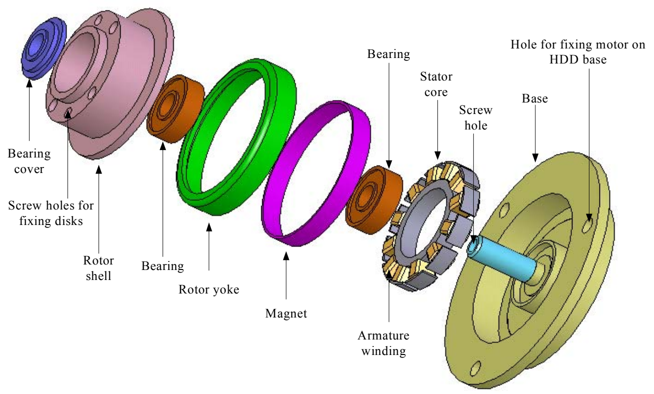

Fig. 1 A spindle motor used in hard disk drive

Many PM-BLDC motors are using surface mounted PM rings rotor. For realization of the compact structure, frictional concentric armature windings are used in the motor. A typical application of this structure is found in HDD spindle motors; see Fig. 1. For this kind of motor, its equivalent airgap is big, and armature reaction is weak. It is clear, such a motor can thus be analyzed accurately with a linear model, i.e., its winding inductances are independent to the rotor position. As frictional concentric windings are used and slot shape is optimized, the back-emfs generated in the windings are quite sinusoidal, i.e., the waveform of back-emf contains very weak harmonics. In the paper, this class of PM-BLDC motor will be used in the analysis. That is, the back-emf of the motor is sinusoidal, inductances of the winding are constant, and voltage constant is independent to the motor speed. As this kind of motor is normally operates at high speed, e.g., 10,000 rpm, or even higher, the influence of transient current caused by the winding inductance is not negligible.

II. The Drive Current In The BLDC Mode Operation

Using BLDC mode to drive the 3-phase PM AC motors, the current is commutated with six steps in one electric cycle, i.e., A_+C_-, C_-B_+, B_+A_-, A_-C_+, C_+B_-, and B_-A_+. In each step, only two phase windings have current. Fig. 2 shows the power bridge circuit of sensorless BLDC drive system, where, the drive circuit is in the step of A_+C_-, and only QA_H and QC_L are switched on.

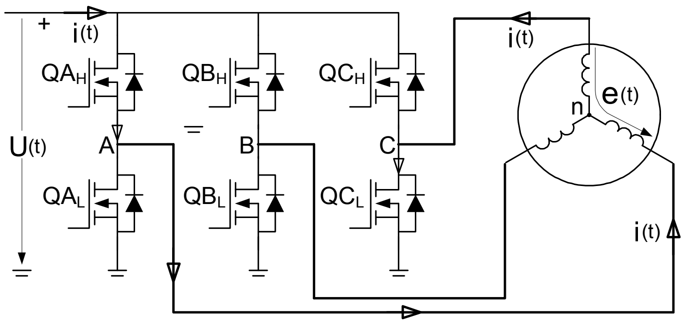

Fig. 2 Bridge circuit for sensorless BLDC drive

The constant voltage BLDC drive mode is popularly used in HDD spindle system. Using this drive mode, the operation of the motor winding can be described with Fig. 3, where $\boldsymbol{\alpha}$ is the commutation angle, which is the distance between the zero crossing point of back-emf, and the point where QA_H and QC_L

are commutated; see Fig. 2. From Fig. 3, it can be known that the line winding operation is formed by two states: silent and energized states. In the sensorless BLDC drive, the former state is used to detect the rotor position, and latter is used to generate the drive torque.

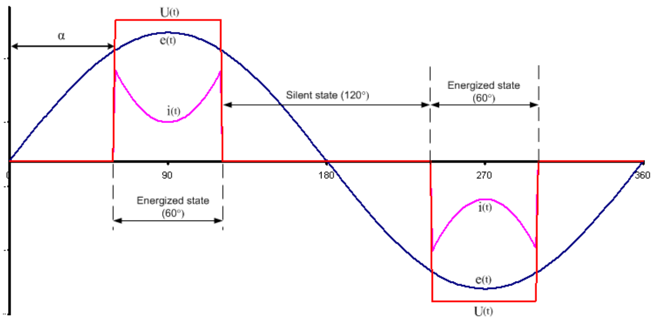

Fig. 3 The relationship in the line voltage, back-emf, and current of BLDC motor

When this drive mode is used, in the energized state, the drive current in the windings is determined by

$$U = e(t) + R_l \cdot i + L_l (di/dt) = E_m \cdot Sin(\omega t) + R_l \cdot i + L_l (di/dt) \cdot \qquad (1)$$

where $\boldsymbol{R_l}$ and $\boldsymbol{L_l}$ are the resistance and inductance of the related motor winding respectively. $\boldsymbol{U}$ is the DC-link voltage, $\boldsymbol{\omega}$ and $\boldsymbol{E_m}$ are the angular frequency and amplitude of the back-emf induced in the winding, respectively.

From Fig. 3, it can be known that, in the energized state, for a given motor operating at required speed with the same drive voltage, the waveform of current $\boldsymbol{i(t)}$ is certainly related with the commutation angle $\boldsymbol{\alpha}$. If the influence of winding inductance is negligible, it can be proven that [1], the optimal commutation angle (OCA) $\boldsymbol{\alpha_{op}}$ is

$$\alpha_{op} = \pi / 3 \cdot \qquad (2)$$

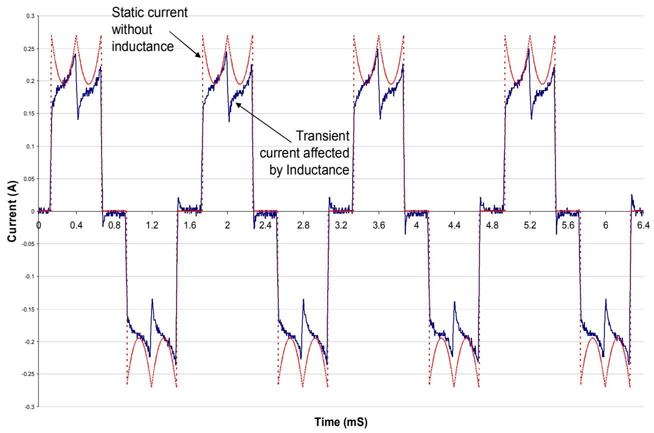

Fig. 4 The drive current of the PM AC motor in using the constant voltage BLDC drive mode

But, in many applications, the influence of the inductances cannot be neglected, especially for the motors operating at high speeds. Fig. 4 shows the current waveforms of a spindle motor driven by the constant voltage BLDC mode. Two currents are provided, one of which is a simulated waveform (dotted) for the motor with inductance set to zero, and the other is the captured experimental current containing the transient component. It can be found that, in such a case, the current is obviously deformed by the winding inductance. Now the question is, in the case where the influence of inductance cannot be neglected, what is the optimal commutation angle of the BLDC drive?

III. The Optimal Commutation Angle of PM-BLDC Motor

As was explained in above section, the operation of BLDC is formed by six drive steps. In each step, the drive circuit sends only current into one line winding. Therefore, in the steady motor operation, the study and analysis of the performance in its one step would exemplify the same insights for the motor performance in whole time domain.

For the motor operates at steady speed Ω, its average EM torque in one step can be calculated with

$$T_{av}(\alpha) = \frac{3}{\pi\Omega}\int_0^{\pi/3} i(t,\alpha)\cdot e(t,\alpha)dt \, . \qquad (3)$$

When constant voltage drive mode is used and the motor back-emf is sinusoidal, in the drive period, the drive current is determined by (1).

It is clear, the average copper loss of the motor can be calculated by

$$p_{av}(\alpha) = \frac{3R_l}{\pi}\int_0^{\pi/3} i^2(t,\alpha)dt \, . \qquad (4)$$

When the EM torque generated by the motor is set at a requested value $\boldsymbol{T_{re}}$,, its OCA means the angle which can minimize $\boldsymbol{p_{av}}$ of (4). Therefore, the copper loss defined by (4) can be used as the objective function for the determination of OCA at speed $\boldsymbol{\Omega}$ and load $\boldsymbol{T_{re}}$. Consequently, the following objective function is defined,

$$O(\alpha) = \int_0^{\pi/3} i^2(t,\alpha)dt \, , \qquad (5)$$

and the calculation of OCA, $\boldsymbol{\alpha_{op}}$, can be described as solving the following constrained optimization problem

$$\begin{cases} O(\alpha_{op}) = Min[O(\alpha)] = Min[\int_0^{\pi/3} i^2(t,\alpha)dt] \\ \dfrac{3}{\pi\Omega}\int_0^{\pi/3} i(t,\alpha)\cdot e(t,\alpha)dt = T_{re} \end{cases} . \qquad (6)$$

In order to illustrate the validity of the constrained optimization problem defined in (6), we consider a simple case where the influence of the inductances is neglected. In this case, from (1), the drive current in the energized state is

$$i(t) = [U - E_m Sin(\omega t + \alpha)]/R \cdot \qquad (7)$$

From (3) and (7), we can know that the relationship between the drive voltage and EM torque through the constrained condition related with $\boldsymbol{T_{re}}$,

$$U = \frac{2E_m^2\pi + 4\pi\Omega T_{re} + 3E_m^2[Sin(2\alpha) - Sin(2\alpha + 2\pi/3)]}{6E_m[Cos(\alpha) - \sqrt{3}Sin(\alpha)]} \quad (8)$$

Therefore, the OCA can be obtained by solving the following optimization equation with constrained condition linked to the drive voltage ***U***,

$$\begin{cases} \min[O(\alpha)] = \min\{\int_0^{\pi/(3\omega)} [\frac{U - E_m Sin(\omega t + \alpha)}{R_l}]^2 dt\} \\ U = \frac{2E_m^2\pi + 4\pi\Omega T_{re} + 3E_m^2[Sin(2\alpha) - Sin(2\alpha + 2\pi/3)]}{[\![6E_m[Cos(\alpha) - \sqrt{3}Sin(\alpha)]]\!]} \end{cases}, \quad (9)$$

and the final expression of ***O(α)*** is,

$$\begin{aligned} O(\alpha) = [\![& E_m^4(8\pi^3 - 54\sqrt{3} - 45\pi) + 32\pi E_m^2(\pi^2 - 9)\Omega T_{re} + 32\pi^3\Omega^2 T_{re}{}^2 - 6E_m^2 \\ & [E_m^2(2\sqrt{3}\pi^2 - 9\sqrt{3} - 6\pi) + 4\pi(\sqrt{3}\pi - 6)\Omega T_{re}]Cos(2\alpha) + 27E_m^4(\sqrt{3} - \pi/2) \cdot \\ & Cos(4\alpha) - 18E_m^2[E_m^2(9 + 2\sqrt{3} - 2\pi^2) + 4(2\sqrt{3} - \pi)\pi\Omega T_{re}]\omega Sin(2\alpha) \\ & - 27E_m^4(\sqrt{3}\pi/2 - 3)Sin(4\alpha)]\!] / [\![216E_m^2\omega[Cos(\alpha) + \sqrt{3}Sin(\alpha)]^2]\!] \end{aligned} \quad (10)$$

The optimal commutation angle α_{op} can be obtained by solving the following equation,

$$O'(\alpha) = 0, \quad (11)$$

and the solution is

$$\alpha_{op} = \pi/3. \quad (12)$$

which is the same as the one obtained in [1]. This proves, at a certain level, the effectiveness in using the constrained optimization problem defined by (6) to find the OCA.

From the analysis shown from (5) to (12), it can be known that, if the inductance of the motor is neglected, its OCA is constant, i.e., OCA is independent to the motor load and speed. However, in the high speed operation of the PM-AC motor, the influence of the inductance must be considered. In this case, how can the OCA be obtained? Is the OCA still independent to the load and speed of the motor?

IV. The Influence of Winding Inductance to Optimal Commutation Angle

From (1), it can be known that, in the energized state, the transient current in the related winding is determined by the following differential equation with the initial current $\boldsymbol{i_0}$,

$$\begin{cases} L_l(di/dt) + R_l \cdot i = U - E_m \cdot Sin(\omega t) \\ i|_{t=0} = i_0 \end{cases}. \quad (13)$$

Solving above equation, we have

$$i(t,\alpha) = K_1 e^{-\frac{R_l t}{L}} + \frac{U}{R_l} + \frac{L_l\omega Cos(\omega t + \alpha) - R_l Sin(\omega t + \alpha)}{Z^2} E_m. \quad (14)$$

In the equation, ***Z*** is the impedance of the winding, and $\boldsymbol{K_1}$ is a constant related with the initial current value of the energized state. The expressions of these two values are

$$\begin{cases} K_1 = i_0 - \frac{UZ^2 + E_m L R_l \omega Cos(\alpha) - E_m R_l{}^2 Sin(\alpha)}{R_l Z^2} \\ Z = \sqrt{R_l{}^2 + (\omega L_l)^2} \end{cases}. \quad (15)$$

In high speed BLDC operation, within each step, the current from the beginning of the energized state to the end of the state is transient. At the end of the energized state, the current is stepped down to zero, which in turn is followed by another line winding entering into energized state. Many simulation and testing results have shown that, in comparison to the energized period, the time used in current step-down is comparatively very short. This phenomenon can also be found in Fig. 5 , where a testing result is provided. Setting the voltage ***U*** in (14) and (15) to zero, these equations can also be used to describe the step-down current. Considering the influence of the transient step-down current will make the analysis be very difficult. As the step-down time is very short, its influences to the average EM torque and copper loss are very limited. In order to make the analysis effective yet manageable, in this paper, the influence of the step-down current will be neglected, i.e., in the BLDC motor operation, the torque and copper loss are induced only in the energized state.

For the initial current of the energized state, setting it to zero is reasonable; see Fig. 5.

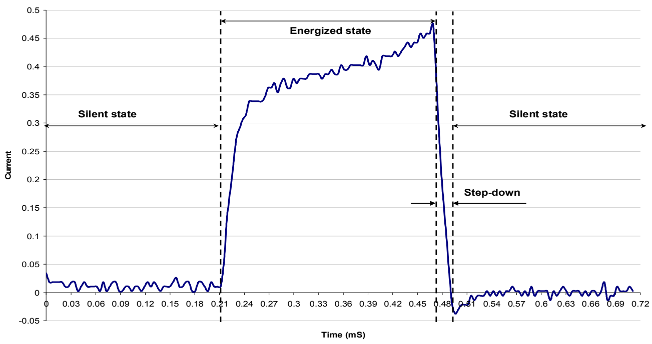

Fig. 5 Transient line current in the BLDC operation

From (3) and (14), it can be known that the relationship between the drive voltage and the requested drive torque $\boldsymbol{T_{re}}$ is linear, and the following result can be obtained from these equations,

$$U(T_{re}, \alpha) = [T_{re} - H_2(\alpha)] / H_1(\alpha), \quad (16)$$

where,

$$\begin{aligned} H_1(\alpha) = \frac{3E_m\omega}{\pi R_l\Omega} \{ & [Cos(\alpha) + \sqrt{3}Sin(\alpha)]/(2\omega) - L_l[\![L_l\omega Cos(\alpha) + \\ & R_l Sin(\alpha) - \beta[R_l Cos(\alpha - \pi/6) + L_l\omega Sin(\pi/6 - \alpha)]]\!]/Z^2\} \end{aligned}, \quad (17)$$

and

$$\begin{aligned} H_2(\alpha) = \frac{3\omega E_m}{\pi Z^2\Omega} \int_0^{\pi/(3\omega)} & [\![[R_l Sin(\alpha) - L_l\omega Cos(\alpha)]e^{-\frac{R_l t}{L_l}} \\ & + L_l\omega Cos(\omega t + \alpha) - R_l Sin(\omega t + \alpha)]\!] dt \end{aligned}, \quad (18)$$

The constrained optimization problem is thus changed to

$$\begin{cases} \min[O(\alpha)] = \min\{\int_0^{\pi/3}\{[\frac{R_l Sin(\alpha) - L_l\omega Cos(\alpha)}{Z^2}E_m - \frac{U(T_{re},\alpha)}{R_l}]e^{-\frac{R_l t}{L_l}} \\ \quad + \frac{L_l\omega Cos(\omega t+\alpha) - R_l Sin(\omega t+\alpha)}{Z^2}E_m + \frac{U(T_{re},\alpha)}{R_l}\}^2 dt \\ U(T_{re},\alpha) = \frac{T_{re} - H_2(\alpha)}{H_1(\alpha)} \end{cases} \quad (19)$$

From (3) to (19), it can be known that, the final expression of the objective function, $\boldsymbol{O}(\alpha)$, is very complicated when the inductance is considered,. For such an $\boldsymbol{O}(\alpha)$, it is not easy to find its OCA to make $\boldsymbol{O}(\alpha)$ be minimum. The special method must be developed to solve the equation effectively.

V. An Effective Algorithm for Calculating *OCA*

From the analysis in Section-II, it was shown that if the inductance of the winding is neglected, $\alpha_{op}=\pi/3$. We know that the influence of the inductance makes the waveform of the drive current be changed, and the value of α_{op} should also be changed. Such change makes α_{op} be deviated from π/3, but should not be far away from π/3.

From (5), it can be derived that,

$$O'(\alpha) = 2\int_0^{\pi/3} i(t,\alpha,T_{re})\cdot i'(t,\alpha,T_{re})dt . \quad (20)$$

The final expression of (20) is still quite complicated, and this makes the further analysis of OCA be difficult.

O'(α) in (20) can be expressed approximately by using Taylor series with degree two at π/3,

$$\bar{O}'(\alpha) = 2[C_0 + C_1(\alpha-\pi/3) + C_2(\alpha-\pi/3)^2], \quad (21)$$

where, $\boldsymbol{C_0}$, $\boldsymbol{C_1}$ and $\boldsymbol{C_2}$ are the constants related with $\boldsymbol{L_l}$, $\boldsymbol{R_l}$, $\boldsymbol{E_m}$, motor speed **Ω** and load torque $\boldsymbol{T_{re}}$., and they are not difficult to be derived by using the following equations,

$$C_0 = \frac{O'(\pi/3)}{2} = \int_0^{\pi/3} i(t,\alpha,T_{re})\cdot i'_\alpha(t,\alpha,T_{re})dt\Big|_{\alpha=\pi/3}, \quad (22)$$

$$C_1 = \frac{1}{2}\frac{d[O'(\alpha)]}{d\alpha}\Big|_{\alpha=\pi/3} = \int_0^{\pi/3}\{[i'_\alpha(t,\alpha,T_{re})]^2 + i(t,\alpha,T_{re})i''_\alpha(t,\alpha,T_{re})\}dt\Big|_{\alpha=\pi/3}, \quad (23)$$

and

$$C_2 = \frac{1}{4}\frac{d^2[O'(\alpha)]}{d\alpha^2}\Big|_{\alpha=\pi/3} = \frac{1}{2}\int_0^{\pi/3}\{2i'_\alpha(t,\alpha,T_{re})i''_\alpha(t,\alpha,T_{re}) + i'_\alpha(t,\alpha,T_{re})i''_\alpha(t,\alpha,T_{re}) + i(t,\alpha,T_{re})i'''_\alpha(t,\alpha,T_{re})\}dt\Big|_{\alpha=\pi/3}. \quad (24)$$

From (15), it can be known that the derivatives in equations (22) to (24) can be expressed as

$$i'(\alpha) = \frac{E_m e^{-\frac{Rt}{L}}[R_l Cos(\alpha) + L_l Sin(\alpha)]}{Z^2} - \frac{R_l Cos(\alpha+\omega t) + L_l Sin(\alpha+\omega t)}{Z^2}E_m + \frac{U'(\alpha)(1-e^{-\frac{Rt}{L}})}{R}, \quad (25)$$

$$i''(\alpha) = \frac{E_m e^{-\frac{Rt}{L}}[-R_l Sin(\alpha) + L_l Cos(\alpha)]}{Z^2} - \frac{L_l Cos(\alpha+\omega t) - R_l Sin(\alpha+\omega t)}{Z^2}E_m + \frac{U''(\alpha)(1-e^{-\frac{Rt}{L}})}{R}, \quad (26)$$

and

$$i'''(\alpha) = -\frac{E_m e^{-\frac{Rt}{L}}[R_l Cos(\alpha) + L_l Sin(\alpha)]}{Z^2} + \frac{R_l Cos(\alpha+\omega t) + L_l Sin(\alpha+\omega t)}{Z^2}E_m + \frac{U'''(\alpha)(1-e^{-\frac{Rt}{L}})}{R}. \quad (27)$$

Let ***Ō'(α)*** defined by (21) be zero, i.e.,

$$C_0 + C_1(\alpha-\pi/3) + C_2(\alpha-\pi/3)^2 = 0, \quad (28)$$

OCA can be obtained by solving (28),

$$\alpha_{op} = \frac{-3C_1 + 2\pi C_2 \pm 3\sqrt{C_1^2 - 4C_0C_2}}{6C_2}. \quad (29)$$

From (19) to (24), it can be known that the coefficients of $\boldsymbol{C_0}$, $\boldsymbol{C_1}$ and $\boldsymbol{C_2}$ in (29) are the functions of the motor parameters $\boldsymbol{L_l}$, $\boldsymbol{R_l}$, $\boldsymbol{E_m}$, motor speed **Ω** and load torque $\boldsymbol{T_{re}}$. Based on simulation results of many motor's parameters, it was found that, comparing the values of $\boldsymbol{C_0}$ and $\boldsymbol{C_1}$ against $\boldsymbol{C_2}$, the value of $\boldsymbol{C_2}$ is normally quite small. Therefore, for the two solutions shown in (29), only the following one is effective,

$$\alpha_{op} = \frac{-3C_1 + 2\pi C_2 + 3\sqrt{C_1^2 - 4C_0C_2}}{6C_2}. \quad (30)$$

Using (30), the OCA can be obtained conveniently. As the coefficients $\boldsymbol{C_0}$, $\boldsymbol{C_1}$ and $\boldsymbol{C_2}$ contain the parameters $\boldsymbol{L_l}$, $\boldsymbol{R_l}$, $\boldsymbol{E_m}$, **Ω** and $\boldsymbol{T_{re}}$, the influence of these parameters to the OCA can also be known through (30).

VI. Calculating OCA of The Spindle Motor Drive

The method for determination of OCA derived in above section have been applied it in the analysis of several spindle motor drive systems used in HDDs. In this section, its application in one of the motor drives will be introduced, and the motor used is named as Motor-A.

TABLE 1
THE PARAMETERS OF MOTOR-A

R (Ω)	L (mH)	Pole-pair	Voltage constant (V/krpm)
2.56	0.6	4	1.049

The parameters of the Motor-A are listed in TABLE 1. This is a spindle motor used in a 3.5” enterprise drive.

In the HDD operation, the HDD is predominantly in the idle state. In this state, the speed of the motor is constant, and the motor load is formed by the windage loss and the bearing friction loss of the motor. Therefore, in the idle state, the relationship between the load and speed is monotonic. Such a relationship can be known accurately through a set of motor test, and Fig. 6 shows the one of Motor-A through testing. When the curve shown in Fig. 6 has been obtained, knowing motor speed is equivalent to knowing the load of the motor.

It is clear, the reduction of the power consumption in idle state is critical to HDDs as this operation consumes the most of energy in its application.

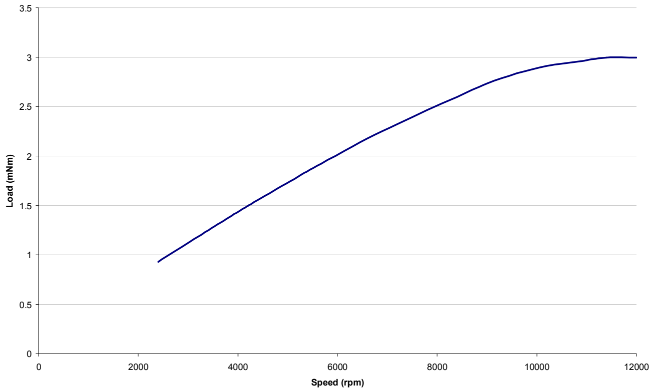

Fig. 6 The relationship between the load and speed of the spindle motor

When the relationship between the load and speed of the spindle motor is clear, we can determine the relationship between the OCA and the spindle motor speed by using (30), and the result of Motor-A is shown in Fig. 7. From this curve, it can be known that, when the speed is increased to higher than 10,000 rpm, the optimal angle approaches a constant.

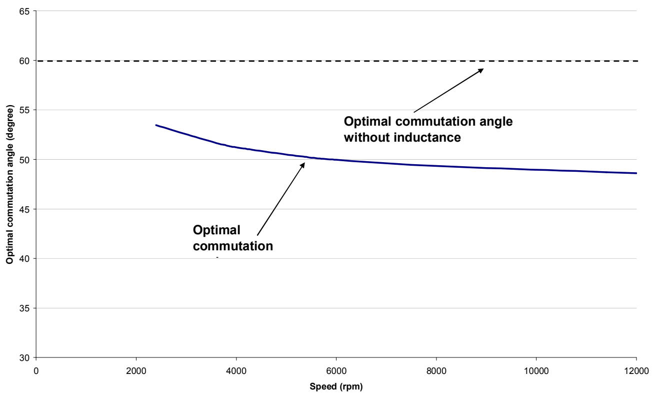

Fig. 7 The relationship between the optimal commutation angle and the spindle motor speed

When the relationships between OCA and speed, and between load and speed, are clear, we can also know the relationship between drive voltage and motor speed by using (16), and the result of Motor-A is shown in Fig. 8. From the figure, it can be known that, the relationship between the drive voltage and the speed is almost linear when the OCA is used. This phenomenon can simplify the motor control procedure.

After getting the data of the curves shown in Fig. 7 and Fig. 8, the data can be saved first in the memory of the drive system, and then used in driving the motor. However, in the idle operation of HDD, due to a change in the environment factors, e.g., atmospheric pressure, temperature and humidity, even in the same speed, the motor load could vary a little. This creates problem in the HDD operation. For example, in the motor starting, when the motor is started from zero to rated speed, we can use the use the voltage and the OCA at the rated speed, which are predetermined through the curves of Fig. 8 and Fig. 7, respectively. But, when these drive voltage and commutation angle are used, it could be found that the speed of the motor is not the intended value. As the relationship between the EM torque $\boldsymbol{T}_{re}$ and drive voltage $\boldsymbol{U}$ is linear when $\boldsymbol{\alpha}$ is fixed (see (16)), one recommendation for working around this problem is that, we can keep the same commutation angle, and change the drive voltage to adjust the motor speed into the rated one. This can make the commutation angle be quite close to the optimal one, and meantime let the motor operate at the required speed. This solution can simplify the speed control. We can use this method to process the motor operation in the idle and sleeping states.

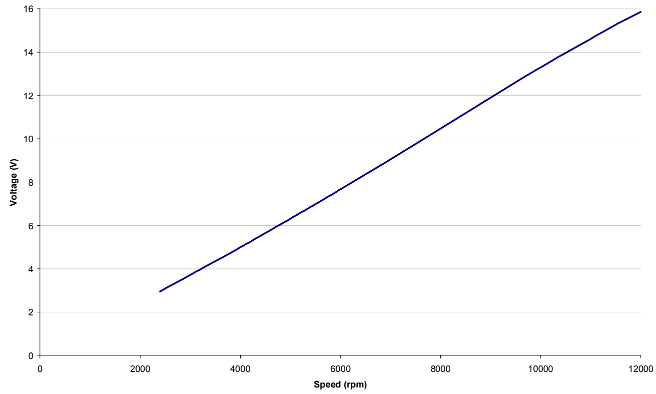

Fig. 8 The relationship between the drive voltage and the speed with optimal commutation angle

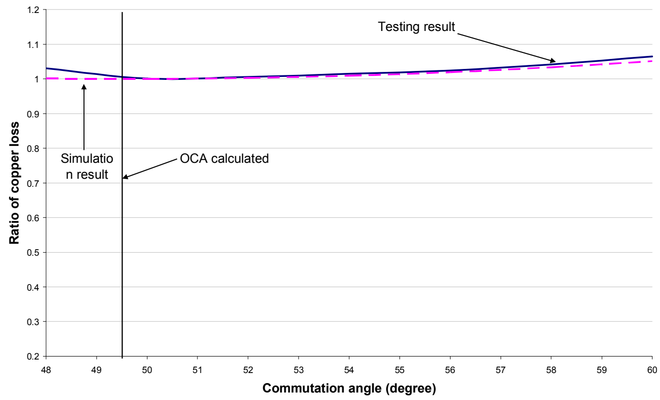

Fig. 9 Motor-A The relationship between the copper loss and commutation angle (Speed: 7,300 rpm)

Fig. 9 shows the simulation and testing results of Motor-A operating at 7,300 rpm. Based on the parameters listed in TABLE 1 and the load shown in Fig. 6 , we can know that the optimal commutation angle at this speed is 49.5°. The copper loss at the OCA is used as the reference to compare the losses on other commutation angles, and the curves shown in Fig. 9 is thus obtained. In the motor testing, the motor speed is kept at 7,300 rpm, and the commutation angle of the BLDC drive system is adjusted from 48° to 60°, and this is a range which was estimated that it can cover OCA.

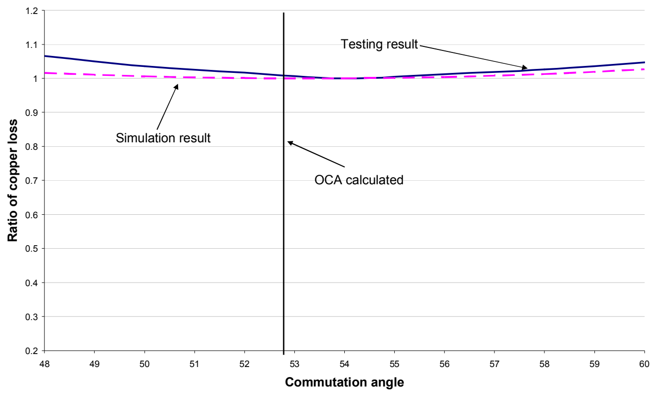

Fig. 10 Motor-A The relationship between the copper loss and commutation angle (Speed: 2,450 rpm)

Fig. 10 shows the results of Motor-A operating at 2,450 rpm. This speed is much lower that the one of Fig. 9, and we want to use these two sets of results to investigate the effectiveness of the OCA model in a wide speed range. At this speed, the optimal commutation angle calculated is 52.7°.

From results shown in Fig. 9 and Fig. 10, it can be found that

(1) when the inductance is considered, the algorithms presented in the paper are good in accuracy to determine the optimal commutation angle over a wide speed range;

(2) when the inductance is neglected, the OCA is a constant, $\pi/3$. This commutation angle has been used in many applications. However, analysis shows, when the winding inductance is considered, OCA is smaller than $\pi/3$, and higher motor speed can make OCA angle be further away from $\pi/3$;

(3) Comparing with the normal BLDC drive mode with $\pi/3$ commutation angle, using the optimal commutation angle can reduced copper loss, which is the major objective in using the OCA.

VII. CONCLUSION

When the influence of inductance is considered, the optimal commutation angle of BLDC drive system is not a constant. From the analysis presented in the paper, if the motor load has been given, the copper loss of the motor can be used directly as the objective function for getting the optimal commutation angle. The paper presents an analytic model for describing the affects of motor parameters and operation state to the optimal commutation angle. As the model is non-linear, a special method based on Taylor series analysis has to be used to solve the equation. The spindle motor in hard disk drive is used to explain the application of the method presented. Analysis shows, when the inductance of the motor is neglected, the optimal commutation angle is consistent at $\pi/3$. But, when the inductance is included, the optimal commutation angle is reduced, and the reduction becomes obvious in high speed operation. In this case, the value of the optimal commutation angle is related with motor parameters and operation state. Both the testing and simulation results show that, using the optimal commutation angle in the BLDC drive, the copper loss of the motor can be reduced. The analysis shows also, when the speed is increased to a certain level, the optimal commutation angle trends to a value smaller than $\pi/3$. This will allow us to use a constant commutation angle in some applications to simplify the control and reduce the copper loss, though the reduction is not maximum. The testing results have proven the effectiveness of the analysis models presented in the paper.

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