On Control of Brushless Torque Motors with High Phase Inductance in Direct Drives of Gyro Devices

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Abstract. The paper studies how the phase inductance of brushless DC torque motors affects their performance within high precision electric direct drives. Modified control laws for torque motors with high phase inductance are described, which optimize their performance by various criteria. The modified laws are based on continuous regulation of mutual attitude of current and voltage vectors in the motor windings. Parameters of torque motors are compared with the described control laws applied, and advantages of their use are covered.

1. Introduction
In modern navigation systems, object rotation is controlled by precision electric direct drives based on brushless DC torque motors (BDCM) with permanent magnets. They feature a high specific torque, broad control range, and high reliability [1-4]. To control a BDCM within an electric drive, m-phase system of sine voltages with preset amplitude and phase angle of space voltage vector in the rotor rotation angle function is generated in its stator windings [2, 3, 5, 6]. Inductance in BDCM winding phases during the rotor rotation changes the mutual attitude of current and voltage vectors in the stator windings, which decreases the torque and degrades the motor performance within the electric drive [7, 8]. Therefore, reaching the utmost performance of BDCM with high phase inductance requires that not only the amplitudes but also mutual attitude of current and voltage vectors in the stator windings be controlled. This is particularly important for high torque BDCM with increased density of magnetic flux and its concentration in magnetic cores, and hence phase inductance of windings [9-11].

One of the solutions to the problem is the continuous control of phase angle of voltage vector by the laws determining its relation to the mutual attitude of vectors in the rotor rotation frequency function.

This paper modifies the control algorithm for a high inductance BDCM with by synthesizing the laws to control the voltage vector phase angle optimal by the criterion of obtaining the maximum torque throughout the rotor rotation frequency range or its relation to the power consumption.

2. Modified control algorithm for an BDCM with high phase inductance
2.1. Torque and its connection with the phase angle of voltage vector
The vector diagram of BDCM is shown in Fig. 1, where the following notations are used: U, E and I are the space vectors of stator windings’ voltage, counter EMF, and current; Φ is the space vector of rotor magnetic flux; R is the dc resistance of stator windings; X = 2·π/60·np·L is the inductive resistance of stator windings; L is the inductance of stator windings; n is the rotor rotation frequency; p is the number of rotor pole pairs; Ψ is the angle between space vectors of rotor magnetic flux Φ and...
stator winding current $I$; $\Theta$ is the angle between space vectors of rotor magnetic flux $\Phi$ and stator winding voltage $U$.

In general case the motor torque can be presented as [6, 8]:

$$T = K_T \cdot I \sin(\Psi),$$

where $K_T$ – torque coefficient; $I$ – module of current space vector.

The inverter generating the voltages in BDCM stator windings directly controls the module of voltage vector and angle $\Theta$ by feedback signals from the rotor angular position sensor. As a rule, the value $\Theta=\pi/2$ is commanded and maintained by BDCM.

With the rotor rotating at low frequencies, the inductive resistance of stator windings is low and the current vector almost coincides with the vector of voltage generated in the windings, i.e., $\Psi=\Theta=\pi/2$, which provides the maximum torque. As the rotation frequency increases the inductive component of winding resistance $X$ grows, which displaces the current vector and violates the equality $\Psi=\Theta=\pi/2$, then angle $\Theta$ should be corrected to reach the maximum torque.

To find the optimal $\Theta$ control law, dependency of angle $\Psi$ (directly affecting the torque) on angle $\Theta$ should be determined.

According to the vector diagram given in Fig. 1, the voltage losses in the stator windings due to their effective and inductive resistance can be described by the following expressions:

$$I^2 = U^2 + E^2 - 2 \cdot U \cdot E \cdot \sin \Theta,$$

$$R \cdot I = U \cdot \cos \Theta \cdot \cos \Psi + (U \cdot \sin \Theta - E) \cdot \sin \Psi,$$

$$X \cdot I = (U \cdot \sin \Theta - E) \cdot \cos \Psi - U \cdot \cos \Theta \cdot \sin \Psi,$$

where $U$ and $E$ – modules of space voltage and counter EMF vectors, respectively.

Based on (2), (3), and (4), $\Psi(\Theta)$ dependency can be written as:

$$\sin \Psi = \frac{U \cdot (R \cdot \sin \Theta - X \cdot \cos \Theta) - R \cdot E}{I \cdot (R^2 + X^2)}.$$  \hspace{1cm} (5)

With account for (5) the expression for the BDCM torque (1) will take the form:

$$T = K_T \cdot \frac{U}{R} \left( \sin \Theta - 2 \cdot \frac{\pi}{60} \cdot \tau_e \cdot p \cdot n \cdot \cos \Theta \right) - \frac{K_E \cdot n}{1 + \left(2 \cdot \frac{\pi}{60} \cdot \tau_e \cdot p \cdot n \cdot R\right)^2},$$

where $n$ – rotor rotation frequency; $p$ – number of pole pairs; $\tau_e = X / (2 \cdot \frac{\pi}{60} \cdot p \cdot n \cdot R)$ – electromagnetic time constant of stator winding; $K_E = E / n$ – counter EMF coefficient.
2.2. Controlling the phase angle of voltage vector and optimality criteria

Control law for the phase angle of voltage vector $\Theta$ providing maximum BDCM torque under any rotor rotation frequency can be obtained by examining (6) to find an extremum for argument $\Theta$ and recorded as follows:

$$\Theta = \arccos\left(-\tau_e \cdot 2 \cdot \pi / 60 \cdot p \cdot n\right).$$

(7)

According to (5), with (7) substituted to it the sine of angle $\Psi$ is different from 1, and angle $\Psi$ is not equal to $\pi/2$. Hence, with account for (1), the control algorithm providing the maximum torque throughout the frequency range will not be optimal in terms of torque/current consumption ratio, i.e., power consumption.

To obtain a control law for the phase angle of voltage vector $\Theta$ providing maximum torque/power consumption ratio, write an expression for $\Psi$ cosine based on (2), (3), (4) similarly to (5), equate it to zero, and express the angle $\Theta$. The obtained expression takes the form:

$$\Theta = \arccos\left(\frac{\tau_e \cdot 2 \cdot \pi / 60 \cdot p \cdot n^2 \cdot K_e}{U \cdot \sqrt{1 + \left(\tau_e \cdot 2 \cdot \pi / 60 \cdot p \cdot n\right)^2}}\right) + \frac{\pi}{2} - \arccos\left(\tau_e \cdot 2 \cdot \pi / 60 \cdot p \cdot n\right).$$

(8)

2.3. BDCM characteristics with different control laws

To estimate the efficiency of the obtained control laws, BDCM performance was simulated with the following conditions: without $\Theta$ control with the preset fixed value $\Theta=\pi/2$, with $\Theta$ control by the law (7) and by the law (8).

The following BDCM parameters were used in the simulation: power supply voltage $U=24$ V; torque coefficient $K_T=3.44$ N·m/A; counter EMF coefficient $K_E=0.24$ V/(rpm); number of rotor pole pairs $p=32$; winding dc resistance $R=0.825$ Ohm; electromagnetic time constant $\tau_e=5$ ms, which corresponds to the winding inductance $L=4.125$ mH.

BDCM speed-torque characteristics obtained by simulation are presented in Fig. 2. As seen from the plots, without $\Theta$ control with its preset value $\pi/2$ the BDCM speed-torque characteristic is deflected: the torque decreases as the rotation frequency increases. $\Theta$ control by the law (8) provides the torque increase by lowering its loss with the growing rotation frequency. With $\Theta$ control by the law (7) along with the torque increase no-load speed is increased, and therefore rotation frequency control range is widened.

![Fig. 2. BDCM speed-torque characteristics: 1 – with $\Theta=\pi/2$; 2 – with $\Theta$ controlled by (8); 3 – with $\Theta$ controlled by (7).](image)

BDCM operation was simulated with different electromagnetic time constants $\tau_e=1$; $\tau_e=2$, $\tau_e=5$, and $\tau_e=10$ ms, corresponding to the stator winding inductance $L=0.825$; $L=1.65$; $L=4.125$, and $L=8.25$ mH to estimate how the stator winding inductance influences the efficiency of the described $\Theta$ control laws in terms of torque increase.
Figure 3 presents the simulation plots showing the torque increase $\Delta T$ due to $\Theta$ control as compared to the torque observed with the fixed $\Theta=\pi/2$ expressed in per cent of the starting torque $T_1$.

![Figure 3. Increase in BDCM torque by $\Theta$ control: a) by law (8), b) by law (7).](image)

It follows from the plots that the described laws are the most effective for the control of BDCM with high phase inductance of stator windings. $\Theta$ control by the law (7) provides the largest torque over a broader rotation frequency range.

Figure 4 presents the torque/power consumption ratio with $\Theta$ control reduced to the similar ratio with the fixed $\Theta=\pi/2$. The presented plots demonstrate that application of $\Theta$ control law (7) providing the maximum torque degrades the energy efficiency under higher rotation frequencies. As to control law (8), it improves the energy efficiency of the motor.

![Figure 4. Reduced torque/power consumption ratio with $\Theta$ control: 1 – by law (8); 2 – by law (7).](image)

### 3. Conclusions

The proposed control laws for the phase angle of voltage vector modifying the algorithm for high inductance BDCM are able to increase the torque, broaden the rotation frequency control range, and improve the motor energy efficiency.

The presented method to synthesize the control laws for the phase angle of voltage vector according to the BDCM vector diagram optimizes its performance within an electric direct drive with account for the features and needs of a specific gyro device.

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