An improved double loop control method for brushless DC motors

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Abstract. The stator flux-linkage and torque double loop control strategy has been used in the traditional two-phase conducting brushless DC (BLDC) motor direct torque control (DTC) system. Based on the study of the control system, this paper presents a new space voltage vector switching table and new methods for the stator flux-linkage amplitude given and estimation. The improved control scheme obtained by the application of the methods and switching table to the double loop control system, can effectively control the stable operation of BLDC motors, and the scheme is verified by the experimental results.

Introduction

BLDC motors are widely used in aerospace, industrial control, automation, and other aspects [1, 3]. With the development of technology, the market demand for the performance of BLDC motors is becoming higher and higher. Researchers in the process of research found that direct torque control technology has the advantages of simple structure, fast torque response, and therefore be promoted in BLDC motor control [4, 5]. Among them, the stator flux-linkage and torque double loop direct torque control strategy was first proposed and successfully applied [6, 8]. Based on the analysis of the two-phase conducting BLDC motor direct torque control system, this paper presents an improved control scheme for BLDC motors. The difference between the improved and traditional control scheme are the space voltage vector switching table and the methods of the stator flux-linkage amplitude given and estimation. Further, the methods in improved control scheme do not contain stator resistance and integrator. The experimental results show that the improved scheme can effectively control the stable operation of BLDC motors.

Theoretical analysis of double loop control method for BLDC motors

Under ideal conditions, the voltage equation of BLDC motors is:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & R_s \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L-M & 0 & 0 \\ 0 & L-M & 0 \\ 0 & 0 & L-M \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

Where u_a, u_b and u_c are the phase voltage of phase a, b and c, respectively. i_a, i_b and i_c are the phase current of phase a, b and c, respectively. e_a, e_b and e_c are the back-emf of phase a, b and c, respectively. R_s and L are the each phase of the stator resistance and the self inductance, and M is the mutual inductance between two phases.

The common used electromagnetic torque equation based on the three phases back-emf can be expressed as：

$$T_e = K(e_a i_a + e_b i_b + e_c i_c) \tag{2}$$

Under the two-phase conducting control mode, the upper and lower switches of each bridge arm in the inverter may be shut down at the same time. Therefore, six digits are required to represent the conduction state of the six power switches, where 1 means on, 0 means off. The six effective states of the inverter, the corresponding voltage vector and six sectors are obtained by listing all the possible, as shown in Fig.1 [9, 10].

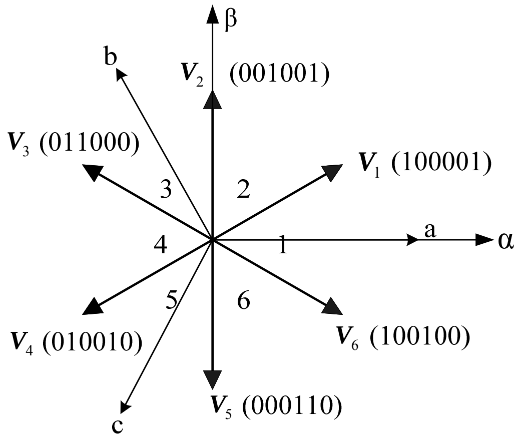


Fig. 1 Space voltage vector distribution and sector division

For example, when the rotor is located in the first sector, $\boldsymbol{V}_1$ is used to increase the torque and stator flux-linkage, $\boldsymbol{V}_2$ is used to increase the torque and keep the stator flux-linkage unchanged, $\boldsymbol{V}_3$ is used to increase the torque and decrease the stator flux-linkage, $\boldsymbol{V}_4$ is used to decrease the torque and stator flux-linkage, $\boldsymbol{V}_5$ is used to decrease the torque and keep the stator flux-linkage unchanged, $\boldsymbol{V}_6$ is used to increase the stator flux-linkage and decrease the torque, other sectors and so on. According to this principle and specific requirements, the space voltage vector switching table can be obtained, as shown in Table 1.

Table 1 Space voltage vector switching table

τ	ϕ	Sector（S）					
		1	2	3	4	5	6
1	1	$\boldsymbol{V}_1$	$\boldsymbol{V}_2$	$\boldsymbol{V}_3$	$\boldsymbol{V}_4$	$\boldsymbol{V}_5$	$\boldsymbol{V}_6$
	0	$\boldsymbol{V}_2$	$\boldsymbol{V}_3$	$\boldsymbol{V}_4$	$\boldsymbol{V}_5$	$\boldsymbol{V}_6$	$\boldsymbol{V}_1$
	-1	$\boldsymbol{V}_3$	$\boldsymbol{V}_4$	$\boldsymbol{V}_5$	$\boldsymbol{V}_6$	$\boldsymbol{V}_1$	$\boldsymbol{V}_2$
0	1	$\boldsymbol{V}_6$	$\boldsymbol{V}_1$	$\boldsymbol{V}_2$	$\boldsymbol{V}_3$	$\boldsymbol{V}_4$	$\boldsymbol{V}_5$
	0	$\boldsymbol{V}_5$	$\boldsymbol{V}_6$	$\boldsymbol{V}_1$	$\boldsymbol{V}_2$	$\boldsymbol{V}_3$	$\boldsymbol{V}_4$
	-1	$\boldsymbol{V}_4$	$\boldsymbol{V}_5$	$\boldsymbol{V}_6$	$\boldsymbol{V}_1$	$\boldsymbol{V}_2$	$\boldsymbol{V}_3$

In Table 1, τ and ϕ are the state parameters, and used to represent adjustments to the stator flux-linkage and electromagnetic torque, respectively. In each sector, if the actual torque is smaller than the commanded value ($\tau = 1$), it indicates a requirement to increase the torque. If the actual torque is greater than the commanded value ($\tau = 0$), it indicates a requirement to decrease the torque. In addition, when the actual stator flux-linkage is smaller than the commanded value ($\phi = 1$), it indicates a requirement to increase the stator flux-linkage. When the actual stator flux-linkage is the same as the commanded value ($\phi = 0$), it indicates a requirement to keep the stator flux-linkage unchanged. When the actual stator flux-linkage is greater than the commanded value ($\phi = -1$), it indicates a requirement to decrease the stator flux-linkage.

For a BLDC motor operating in the two-phase conducting mode, the components of the stator flux-linkage amplitude in the stationary αβ reference frame can be expressed as:

$$\begin{aligned} \psi_{\mathrm{s\alpha}} &= L_{\mathrm{s}} i_{\mathrm{s\alpha}} + \psi_{\mathrm{r\alpha}} = L_{\mathrm{s}} \left| \boldsymbol{I}_{\mathrm{s}} \right| \cos\theta + \psi_{\mathrm{r}} \cos\theta_{\mathrm{r}} \\ \psi_{\mathrm{s\beta}} &= L_{\mathrm{s}} i_{\mathrm{s\beta}} + \psi_{\mathrm{r\beta}} = L_{\mathrm{s}} \left| \boldsymbol{I}_{\mathrm{s}} \right| \sin\theta + \psi_{\mathrm{r}} \sin\theta_{\mathrm{r}} \end{aligned} \tag{3}$$

Where ψ_{r} is the rotor flux-linkage amplitude and it is usually constant, θ_{r} is the rotor position angle,

θ is the angle between the α axis and phase synthesis current vector.

In addition, for the amplitude of the two conduction phase synthesis current vector, it is proportional to the value of the electromagnetic torque, as:

$$\left|\boldsymbol{I}_{\mathrm{s}}\right| = \frac{1}{\sqrt{3}\mathrm{K}}\left|T_{\mathrm{e}}\right| \tag{4}$$

Where K is the ratio between the motor back-emf and the mechanical velocity. Substituting equation (4) into equation (3) gives:

$$\begin{aligned} \psi_{\mathrm{s\alpha}} &= L_{\mathrm{s}}\left|\boldsymbol{I}_{\mathrm{s}}\right|\cos\theta + \psi_{\mathrm{r\alpha}} = \frac{1}{2\mathrm{K_T}}L_{\mathrm{s}}\left|T_{\mathrm{e}}\right|\cos\theta + \psi_{\mathrm{r}}\cos\theta_{\mathrm{r}} \\ \psi_{\mathrm{s\beta}} &= L_{\mathrm{s}}\left|\boldsymbol{I}_{\mathrm{s}}\right|\sin\theta + \psi_{\mathrm{r\beta}} = \frac{1}{2\mathrm{K_T}}L_{\mathrm{s}}\left|T_{\mathrm{e}}\right|\sin\theta + \psi_{\mathrm{r}}\sin\theta_{\mathrm{r}} \end{aligned} \tag{5}$$

Then the amplitude of the stator flux-linkage can be calculated as:

$$|\boldsymbol{\psi}_{\mathrm{s}}| = \sqrt{\psi_{\mathrm{s\alpha}}^2 + \psi_{\mathrm{s\beta}}^2} \tag{6}$$

Therefore, equation (3) and (6) can be used to calculate the actual amplitude of the stator flux-linkage, so as to perform estimation of it. Substituting the given torque into equation (5) and (6) to calculate can obtain the corresponding given stator flux-linkage amplitude. While the torque given can be obtained through the PI regulator.

From equation (3) and (5) can be seen, the mathematical models of the stator flux-linkage estimation and given do not contain stator resistance and integrator. On the one hand, it can effectively control the impact of the stator resistance pressure drop and resistance change on flux-linkage calculation accuracy under the condition of low speed and temperature raise. On the other hand, it can avoid the integrator saturation problem caused by the DC offset.

The improved double loop control scheme implementation

Fig.2 shows the block diagram for the two-phase conducting BLDC motor DTC double loop control system. As will be seen, the calculation accuracy of the rotor position angle directly affects the control effect of the whole system. Therefore, this system adopts photoelectric position sensor which can distinguish finer angle to accurately calculate the rotor position.

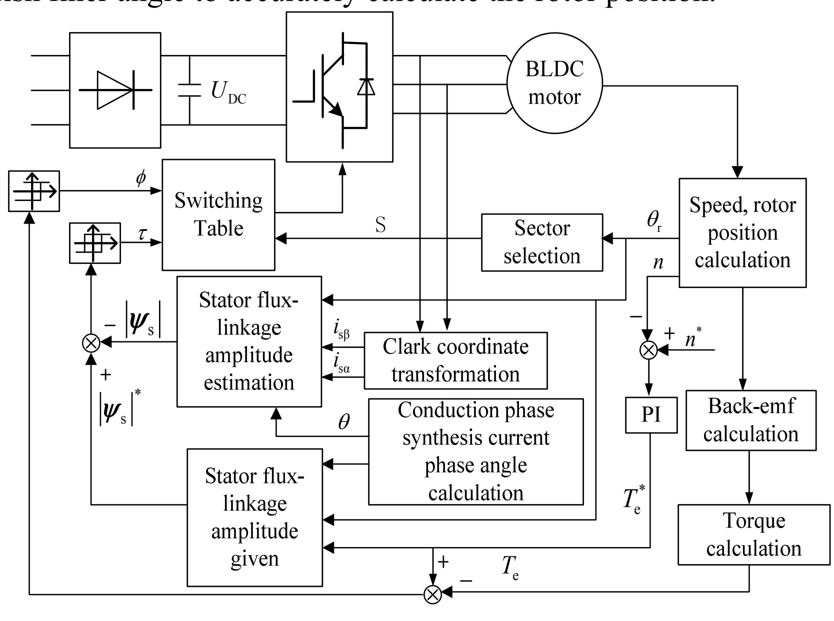


Fig. 2 The block diagram for DTC of BLDC motor

For the torque calculation of the improved control scheme, this paper adopts the above most common torque equation of BLDC motors to calculate the actual torque. Further, the torque calculation is based on the back-emf shape function. Therefore, for different BLDC motors with different non-ideal back-emf, substituting the corresponding actual back-emf shape function into the calculation can obtain the actual torque. For the stator flux-linkage amplitude given and estimation, this paper adopts the above equation (5) and (6) to calculate the given amplitude of the stator flux-linkage, and uses the equation (3) and (6) to realize the estimation of the stator flux-linkage.

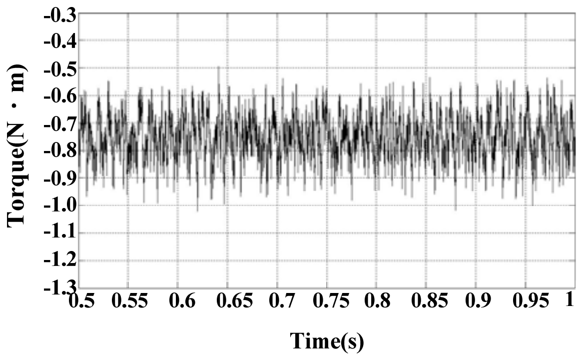
The state parameters can be obtained by comparing the actual value of the torque and stator flux-linkage with the given value of that through the hysteresis comparator. Then combining with the sector and voltage vector switching table, the control system will select the correct voltage vector to act on BLDC motors, so as to realize the stable operation control of BLDC motors.

Experimental results

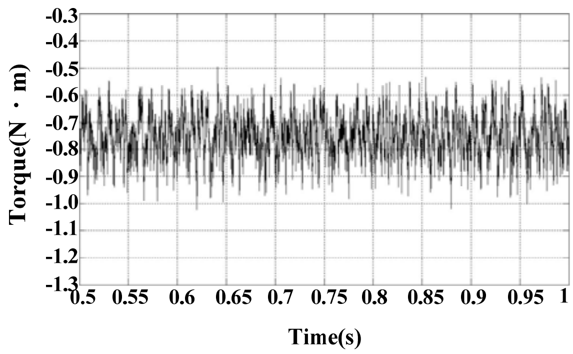
The improved double loop control scheme is validated by experiment for the BLDC motor, whose parameters are given in Table 2. The given speed is 100r/min, and the load is 0.65N.m. Under this condition, the experimental results are shown in Fig.3.

Table 2 Parameters of the BLDC motor

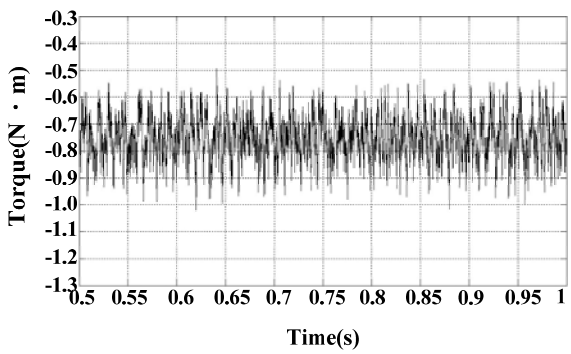
Parameter	Value
Rated Voltage(V)	36
Rs(Ω)	0.25
Stator Inductance(mH)	0.3
Rotor Flux(Wb)	0.0225
Pole Pairs	8



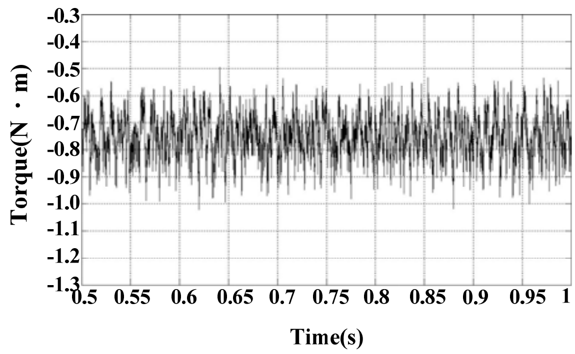
(a) Phase current



(b) Electromagnetic torque



(c) Given stator flux-linkage amplitude



(d) Locus of stator flux-linkage

Fig. 3 Experimental results

As will be seen, the steady-state phase current waveform is shown in Fig.3(a). The current is 120°conduction, and it shows that the BLDC motor operates in two-phase conducting mode. Fig.3(b) for the actual electromagnetic torque waveform, it fluctuates around 0.65 N.m. The torque ripple is bigger but it is stably controlled within a certain range. In addition, the ripple frequency of the electromagnetic torque is the same as that of the phase current. It indicates that the current is proportional to the torque in the two-phase conducting mode, which is consistent with the theoretical analysis. The given and estimated value of the stator flux-linkage are shown in Figs.3(c) and 3(d).

Within a magnetic state, the given value of the stator flux-linkage increases from 0.022 Wb to 0.0232 Wb. The change rule of the estimated value is consistent with the given value. It indicates that the actual flux-linkage strictly tracks the given flux-linkage. Based on the analysis of the above given method for the stator flux-linkage estimation, the actual stator flux-linkage locus should tend to a hexagon, as shown in Fig.3(d).

Summary

In this paper, the new space voltage vector switching table and the new methods of the stator flux-linkage amplitude given and estimation have been applied to the two-phase conduction BLDC motor direct torque control system. This is the main difference between the improved and the traditional control scheme. It has been shown that the improved scheme can effectively control the stable operation of BLDC motors. The correctness of theoretical analysis and the feasibility of the scheme have been validated by the experimental results.

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