Improved BLDCM Direct Torque Control Strategy

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Abstract. For conventional BLDCM direct torque control strategy existing many disadvantages, for example, flux ring observation algorithm is complex, electromagnetic torque ripple is too large, the current waveform is not ideal, high switching frequency and large switching losses are also serious, designing an improved BLDCM direct torque control strategy. it used different zero voltage vectors in a need to reduce the torque ripple. Simulation results showed that the improved strategy could suppress the freewheeling in non-conduction phase, and could effectively improve the current waveform, suppress torque ripple, and this strategy could also reduce the inverter's chopping frequency, improve system reliability and reduce the switching losses of the device.

Introduction

The brushless DC motor has simple structure, high reliability and good speed performance, and it can output larger torque than other motors do at the same volume. However, due to the impact of structural features, the smooth performance of the output torque is poor. There are large fluctuations in torque. This shortcoming limits its applications in the situations with high-precision requirements.

Currently, the control methods of BLDCM can be divided into current control strategy and torque control strategy, current control belongs to the open-loop torque control, the torque response is slow. The torque control is closed-loop control of torque, the torque response is relatively fast. A direct torque control method is proposed in literature [1] to improve the brushless DC motor performance which adopts a theory of fuzzy adaptive PID and eliminates flux observer, but the algorithm theory is too complex; Literature [3] refers to the new variable structure anti-saturation Anti-windup PI control device, using fuzzy theory to adjust the control parameters on line , but there are also controller design problems for complex method. In this paper, improvement and optimization are taken into direct torque control system of brushless DC motor to make a new calculation for torque observer, and deriving a reasonable hysteresis broadband for the current formula , using different vector modulation output can not only solve the problem of torque ripple, but also suppress freewheeling.

The Mathematical Model Of Brushless DC Motor

Brushless DC motor (BLDCM) consists of three parts by the motor body, rotor position detecting device and an electronic commutator (inverter and controller). DC power supplies to the motor stator windings through the switching circuit. The position detecting apparatus is ready to detect the position of the rotor, and according to the rotor position signals to control the conduction state of the inverter switches automatically to control various windings' situation in order to achieve automatic electronic commutation.

Equivalent circuit diagram of the motor main body is shown in Fig.1, winding inductance is L_S, mutual inductance is M , resistance value is R .

Fig.1 shows that the brushless DC motor voltage balance equation can be expressed as:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} p \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (1)$$

Where, u_a, u_b and u_c are every winding's phase voltage respectively; R and L are every motor winding's corresponding equivalent resistance and equivalent inductance respectively; e_a, e_b ,e_c and i_a, i_b, i_c are counter electromotive force and the flowing current in three phase windings respectively. p is differentiating factor.

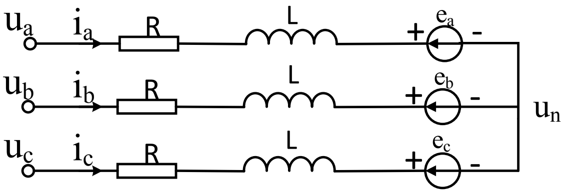


Fig.1 Motor equivalent circuit diagram of the body

Stator winding flux equation generated in each phase is:

$$\begin{cases} \psi_{sa} = \int (u_a - Ri_a) dt \\ \psi_{sb} = \int (u_b - Ri_b) dt \\ \psi_{sc} = \int (u_c - Ri_c) dt \end{cases} \quad (2)$$

After three-two transforming the flux equation in the stator on $\alpha\beta$ axes is:

$$\begin{cases} \psi_{s\alpha} = \int (u_{s\alpha} - Ri_{s\alpha}) dt \\ \psi_{s\beta} = \int (u_{s\beta} - Ri_{s\beta}) dt \end{cases} \quad (3)$$

The flux equation in the rotor on $\alpha\beta$ axes is:

$$\begin{cases} \psi_{r\alpha} = \psi_{s\alpha} - Li_{s\alpha} \\ \psi_{r\beta} = \psi_{s\beta} - Li_{s\beta} \end{cases} \quad (4)$$

The formula of electromagnetic torque is:

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\Omega} \quad (5)$$

Improved BLDCM Direct Torque Control Strategy

The flux rotation space is divided into six sections, and the torque control requirements decide the hysteresis of the torque tolerance. After the system starts, the real-time torque is compared with a given value, then based on the comparison result and the segment of the stator flux, select the appropriate voltage vector to control inverter switching devices being on or off, and corresponding output voltage space vector is used to control the output torque of the motor.

Flux rotating space is divided as shown in Table 1.

Tab.1 Partition of 6 spaces

Electrical angle θe(rad)	$\frac{11\pi}{6} \le \theta e < 2\pi$ $0 \le \theta e < \frac{\pi}{6}$	$\frac{\pi}{6} \le \theta e < \frac{\pi}{2}$	$\frac{\pi}{2} \le \theta e < \frac{5\pi}{6}$	$\frac{5\pi}{6} \le \theta e < \frac{7\pi}{6}$	$\frac{7\pi}{6} \le \theta e < \frac{9\pi}{6}$	$\frac{9\pi}{6} \le \theta e < \frac{11\pi}{6}$
Sector S	I	II	III	Ⅳ	V	Ⅵ

This study eliminates the flux hysteresis. When the electromagnetic torque needs to increase, use non-zero voltage space vector, and when the electromagnetic torque needs to reduce, the zero voltage vector is used. And being different from the traditional zero voltage vector, there are six different zero voltage vectors, then each zero voltage vector represents that there is one switch in the inverter being turned on. Non-zero voltage vector and zero voltage vector selection are shown in Table 2 and Table 3 respectively.

Tab.2 Non-zero voltage vector selection table

Sector S	I	II	III	IV	V	VI
Non-zero voltage vector	u_1 (100001)	u_2(001001)	u_3 (011000)	u_4 (010010)	u_5 (000110)	u_6 (100100)

Tab.3 Zero voltage vector selection table

Electrical angle θe(rad)	$0 \le \theta e < \frac{\pi}{3}$	$\frac{\pi}{3} \le \theta e < \frac{2\pi}{3}$	$\frac{2\pi}{3} \le \theta e < \pi$	$\pi \le \theta e < \frac{4\pi}{3}$	$\frac{4\pi}{3} \le \theta e < \frac{5\pi}{3}$	$\frac{5\pi}{3} \le \theta e < 2\pi$
Zero voltage vector	(000001)	(001000)	(010000)	(000010)	(000100)	(100000)

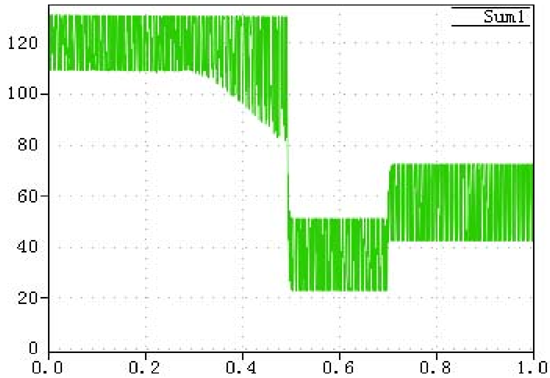
The traditional direct torque control system generally uses H_PWM_L_PWM modulation, which means that the upper and lower switches will be turned off when torque hysteresis output zero. Switch loss is large in this mode, and in some hysteresis band, frequency will be very high.

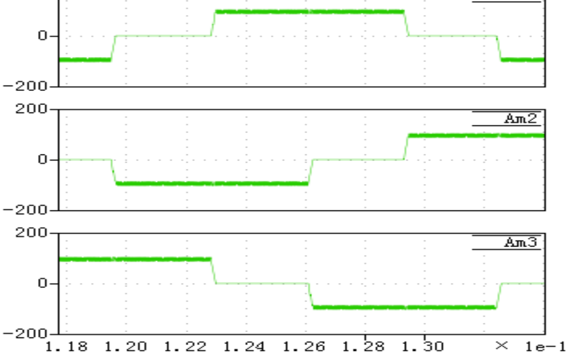
The selection of voltage vector in the improved control strategy can achieve PWM_ON_PWM modulation. In this modulation, the former 30° selects PWM modulation, intermediate 60° selects ON modulation, and the last 30° selects PWM modulation, acting on each switch.This control mode can not only reduce switching loss, it can also inhibit the freewheeling in the non-conduction phase.

Results Of Simulation

Brushless DC motor simulation model is built in PLECS environment according to the mathematical model of permanent magnet brushless DC motor. Parameters of the motor model are as follows: the DC bus voltage $U = 540\text{V}$, the stator winding equivalent resistance R=0.0685Ω, the equivalent inductance of the stator winding L=0.38mH, the motor rated speed $n = 3000\text{r/min}$, damping coefficient $B = 0.0002\text{N}\cdot\text{m}\cdot\text{s/rad}$, number of pole pairs $P = 4$ and moment of inertia $J = 0.1244\text{kg}\cdot\text{m}^2$.

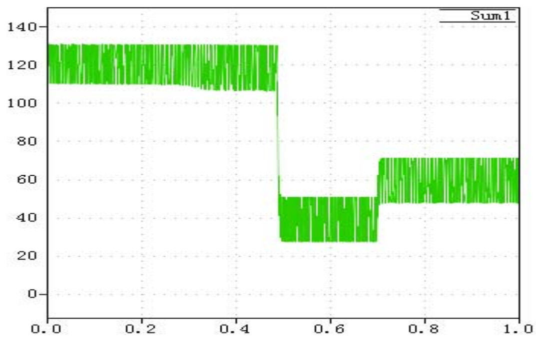
Start the brushless DC motor system. The initial value of load torque is 40N · m, the load torque is mutated to 60N · m at time t = 0.7s, and the simulation time is 1s. The torque and current simulation results of traditional direct torque control strategy and improved one are shown in Fig. 2 and 3 respectively.



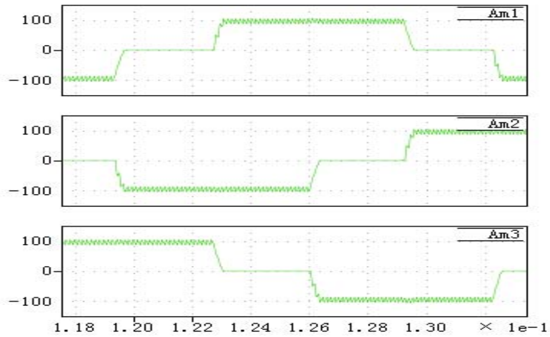


(a) Torque simulation waveform under the traditional control strategy (b) Current simulation waveform under the traditional control strategy

Fig.2 Simulation waveforms under the traditional control strate



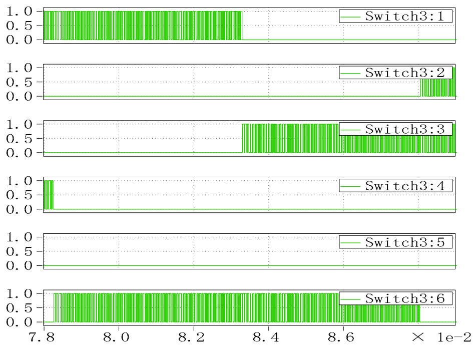
(a) Torque waveform under the improved strategy



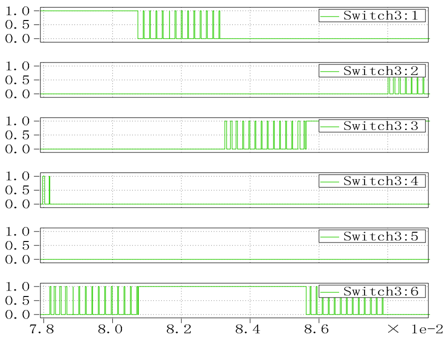
(b) Current waveform under the improved strategy

Fig.3 Simulation waveform under improved control strategy

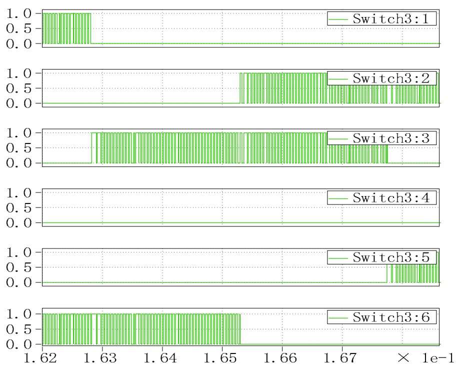
The driving waveforms of the traditional control strategy and improved control strategy are shown in Fig 4. Comparison shows that improved control strategy can reduce the inverter's chopping frequency.



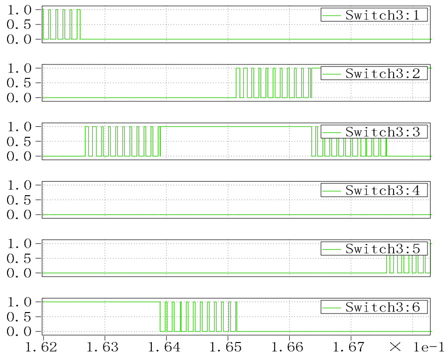
(a) Drive waveform under traditional control Strategy when n = 500r / min



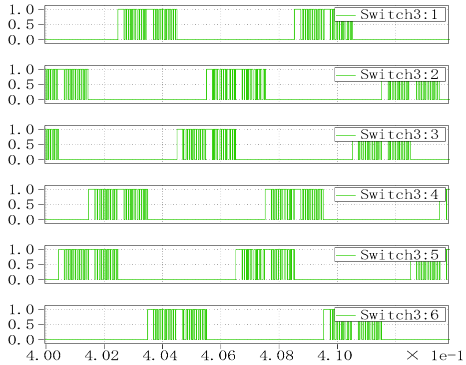
(b) Drive waveform under improved control strategy when n = 500r / min



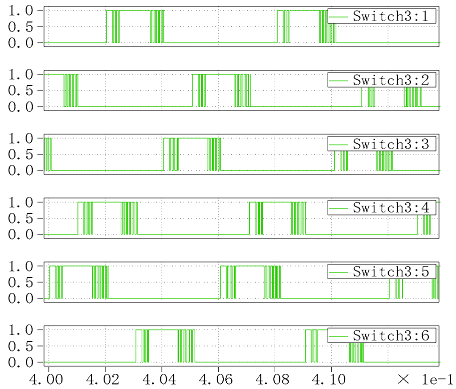
(c) Drive waveform under traditional control strategy when n = 1000r / min



(d) Drive waveform under improved control strategy when n =1000r / min



(e) Drive waveform under traditional control strategy when n = 2500r / min



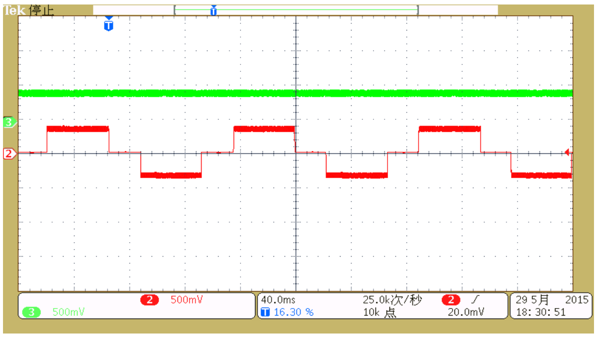
(f) Drive waveform under improved control strategy when n =2500r / min

Fig.4 Drive waveforms under traditional control strategy and improved control strategy

As it can be seen from the simulation results, the improved brushless DC motor direct torque control strategy can effectively suppress the motor torque ripple, improve the current waveform and reduce the switching frequency of the devices, at the same time it can also reduce switching losses and improve the stability of the motor .

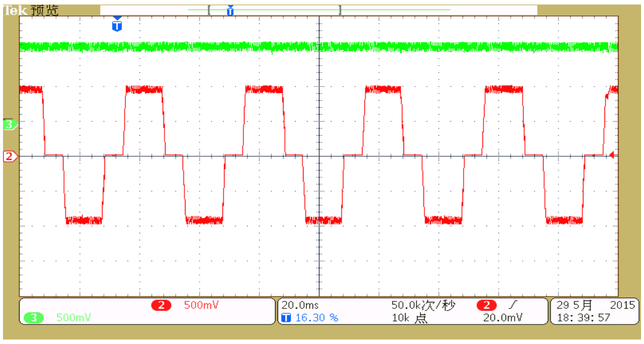
Results Of Experiment

A permanent magnet brushless DC motor is used in experiment, the motor parameters are the same with the parameters used in the simulation. The experimental waveforms are shown in Fig.5.



Current waveform at low speed

(b) Current waveform at medium speed



(c) Current waveform at high speed

Fig.5 Experimental waveforms

Conclusions

This paper presents an improved brushless DC motor direct torque control strategy, eliminating the need for flux observer link and flux hysteresis adjustment link. It not only makes controller algorithm easier, but also effectively suppresses current freewheeling through the PWM_ON_PWM control strategy. In addition, it reduces the switching frequency of the switches and switching losses so that it can improve the stability and reliability of the system.

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