Torque Ripple Improvement by Injecting High Voltage Pulses

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Abstract: This paper presents a new method of injection of high voltage pulses (IHVP) during commutation in order to shorten current's rising-edge time and reduce the torque ripple. A quantitative method for choosing the voltage magnitude and the pulse width is put forward with trapezoidal back EMF under square voltage wave condition. Its optimal discrete solutions and the principle of choosing the discrete pulse coefficient under PWM control are derived. Finally, the effect of the method is verified by experiments.

Introduction

With BLDC motor, a large leakage inductance is often caused by a full power output and numbers of winding turns, which lead to a severely abnormal current waveform and a serious torque ripple. Similar consequences can also be brought about by a much smaller leakage inductance when the motor speed is high enough, which signifies a shorter lead time. Moreover, different magnetization patterns lead to various odd harmonics of radial flux density on the rotor surface, which results in a great obstacle for the suppression of torque ripple.

Based on PWM-on modulation method, Bu [1] proposed a new method that duty cycle of the each phase is calculated by analyzing the current flow in commutation to suppress the commutation torque ripple. Zhang et al. [2] presented a new method for reducing the torque ripple in BLDC motors with a single current sensor by adding the step-down BUCK converter. Although the two methods are quite effective for commutation torque ripple reducing, they cost great amount of computation and lots of control resource. Li et al. [3] proposed a novel improved bipolar PWM scheme on the basis of the traditional bipolar PWM method, in which four power transistors are controlled simultaneously and the on-off states of two power transistors in one phase leg are opposite. This method is quite concise, but the effect is not obvious.

In this paper, a new method of injection of high voltage pulses (IHVP) is proposed, which is not only with properties of conciseness and accuracy but also much effective on the suppression of torque ripple.

Theory of IHVP method

Basic equations of IHVP method. For BLDC motors, the analytical solution of commutation currents meets the following equations ^[4]

$$\begin{cases} i_a(t) = -\frac{U+2E}{3R} + \left(I_s + \frac{U+2E}{3R} \right) e^{-\frac{t}{\tau}} \\ i_b(t) = \frac{2U-2E}{3R} + \frac{2E-2U}{3R} e^{-\frac{t}{\tau}} \\ i_c(t) = \frac{4E-U}{3R} + \left(I_s + \frac{4E-U}{3R} \right) e^{-\frac{t}{\tau}} \end{cases} \quad (1)$$

where, U is the phase voltage, E is the back EMF of phase winding, $i(t)$ is the current in phase winding, R is the phase resistance, I_s is the phase current under voltage U before commutation, $\tau=L_\sigma/R$ is the electromagnetic time constant.

When current $i_a(t)$ in Eq.1 decrease to 0, the commutation process is considered to an end, the current falling-edge time t_u is derived as

$$t_u = -\tau \ln \left(\frac{U+2E}{3RI_s + U+2E} \right) \quad (2)$$

During commutation, the current rising-edge time is equal to the falling-edge time, thus t_u is also the current rising-edge time. The shorter the current rising-edge time is, the more similar the current waveform is to a square wave, the smaller torque ripple is, and vice versa. From formula(2), both deducing the electromagnetic time constant τ and raising the commutation voltage U are advantageous to shorten current rising-edge time t_u . If pulses of high voltage were injected into the commutation circuit, which makes the conduction phase under a high voltage at initial time, the torque ripple could be effectively suppressed.

Parameters selection strategy of IHVP method. A BLDC motor with 2 poles and 24 slots is taken as an example. The motor parameters are shown in Table 1.

Table 1 Parameters of BLDC motor with 2P24S	
<i>Parameters</i>	<i>Magnitude</i>
Speed (r/min)	100,000
Power (kW)	10
length (mm)	65
Stator outer diameter(mm)	80
Rotor outer diameter(mm)	27
Rated current (A)	48
Time constant (s)	2.17e-003

Voltage coefficient K_0 and pulse coefficient K are defined as

$$K_0 = U / 2E \quad (3)$$

$$K = U' / U \quad (4)$$

For a certain back EMF, a bigger K_0 and K mean a higher voltage U and U' , respectively. Substituting Eq.3 and 4 into Eq.2, the rising-edge time is derived as

$$t_u' = -\tau \ln \left(\frac{U'+2E}{3RI_s + U'+2E} \right) = -\tau \ln \left(\frac{KU+2E}{3RI_s + KU+2E} \right) \quad (5)$$

and

$$I_s = \frac{U - 2E}{2R} \left(\frac{2e^{\frac{10}{pnt}} - 2}{2e^{\frac{10}{pnt}} - 1} \right) \quad (6)$$

where the p and n are the number of pole-pairs and the motor speed, respectively. Simultaneously solving Eqs. 3 to 6 yields

$$t_u - t_u' = -t \ln \left\{ \frac{(K_0 + 1) \left[\frac{3}{2}(K_0 - 1) \left(\frac{2e^{\frac{10}{pnt}} - 2}{2e^{\frac{10}{pnt}} - 1} \right) + KK_0 + 1 \right]}{\left[\frac{3}{2}(K_0 - 1) \left(\frac{2e^{\frac{10}{pnt}} - 2}{2e^{\frac{10}{pnt}} - 1} \right) + K_0 + 1 \right] (KK_0 + 1)} \right\} \quad (7)$$

Equation 7 indicates that the saved rising-edge time is only relevant with parameter K and K_0 , when number of pole-pairs, motor speed and electromagnetic time constant are determined. The curve series of the saved rising-edge time vs various K and K_0 is shown in Fig.1. From the figure, the larger K_0 or K is, the more rising-edge time can be saved, which also means a greater improvement on torque ripple. However, both K and K_0 are limited by the largest available voltage U_{max} . Furthermore, the ratio of the saved rising-edge time to its pulse coefficient K represents the economy of pulse coefficient. On each curve that has a same K_0 , there is a point represents the maximum value of the ratio. Connecting the points into a line, the recommended line of pulse coefficient is depicted in the figure. Therefore, the economy of pulse coefficient K would be better if the pulse coefficient selected was closer to the recommended line.

Fig.1 The curves series of saved rising-edge time versus various K_0 and K

After the parameters selection, the voltage magnitude U' and the rising-edge time tu' can be quantitatively calculated by Eq.3 to 5. However, the rising-edge time tu' usually can't be chosen arbitrarily because it must be an integer times of the chopping period. If the chopping frequency is determined, the parameters in Eq.5 will be limited to some discrete values. Therefore, the continuous curves in Fig.1 will be turned into discrete points. The chopping frequency of 100 kHz is taken as an example. After the discretization of the curves, several discrete lines are obtained, as

shown in Fig.2. The lines represent how many chopping periods the pulse width is equal to. Similarly, a pulse coefficient K can be economically chosen referencing the recommended line. Moreover, the rising-edge time will not be fully reduced if the pulse coefficient is smaller than calculation. On the other hand, if the pulse coefficient is bigger, spikes will appear in the current waveform, which is not conducive to the suppression of the commutation torque ripple. Considering the chopping limitation, a smaller pulse coefficient K is more appropriate if the two pulse coefficients have a similar saved rising-edge time.

Fig.2 The discrete saved rising-edge time versus various K_0 and K

Simulation and experimental verification

A simulation model of exciting IHVP into the three-phase bridge circuit was established with the motor mentioned in Table 1. The simulation results are shown in Fig. 3. The rising-edge time and the torque ripple are significantly decreased, which makes the current waveform much closer to a square wave.

Fig.3 Theoretical currents and torque waveforms with and without IHVP method

A small power BLDC motor is used in experimental verification. Figure 4 shows the currents and torque ripple with and without IHVP method. With the IHVP method, the rising-edge time is evidently shortened and the current become stable. Since the voltage dead time has less effect on the current, torque ripple is effectively decreased, which contribute to the smoothness of motor running.

Fig.4 Experimental currents and torque waveforms with and without IHVP method

Conclusions

In this paper, we proposed a new method for solving BLDC motor's current distortion and commutation torque ripple, by which the current delay can be effectively shortened and its waveform is much closer to a square wave. The improvement of the current waveform and commutation torque ripple with the IHVP method is verified by both simulation and experiment. The main conclusions can be summarized as follows:

- (1) A higher voltage in current rising-edge state results in a shorter current rising-edge time. The parameters K_0 and K present the magnitude of original voltage and pulse voltage respectively, but both they are limited by the largest available voltage U_{max} . The larger K is, the more current rising-edge time can be saved.
- (2) Limited by the chopping frequency, the rising-edge time tu' usually can't be chosen arbitrarily because it must be an integer times of the chopping period. Therefore, K is turned into discrete instead of a continuous value.
- (3) The ratio of the saved rising-edge time to its pulse coefficient K represents the economy of pulse coefficient. The closer a pulse coefficient is to the line connected by the points of the maximum value of the ratio on each curve, the better the economy of pulse coefficient is.
- (4) To prevent the current spike, a small pulse coefficient is appropriate for the similar control effect.

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