Advances in Intelligent Systems Research, volume 154
6th International Conference on Measurement, Instrumentation and Automation (ICMIA 2017)

Research on Control Method of Brushless DC Motor Based on Continuous Three-Phase Current

Li Ding [1],Mingliang Hu [2] , Jun Zhao [2] and Weiyun Mao[3]

[1] Xi'an Modern Control Technology Research Institute, Xi'an 710065, China

[2]AVIC Computing Technique Research Institute, Xi'an 710068, China

[3]Northwestern Polytechnical University, Xi'an 710068, China

[a]493098006@qq.com, [b]minglhu@163.com, [c]huangmi008@163.com, [d]xjtumtds@aliyun.com

Keywords: continuous three-phase current; current limit solution; torque pulsation suppression; power density.

Abstract. With regard to non-conduction phase and non-commutation current pulsation in brushless DC motor for aviation in conventional two-two conduction based drive mode which are not only to restrict range of speed regulation of motor but also lead to larger torque pulsation, a continuous three-phase current based drive mode is presented to solve limit value of current to minimize copper loss in three phase winding by taking motor torque equation and counter potential equation as restrictive condition. The method is to divide motor rotor position into 12 sectors and then allocate the limit value to three phase current based on the sector. According to the principle that the sum of currents from three phases of star winding is equal to zero, it is advisable to adopt two phase current close loop control to achieve continuous output of three phase current to suppress commutation torque pulsation, improve motor power density and expand range of speed regulation. The mentioned continuous three phase current based drive method has its feasibility and efficiency verified by Matlab simulation.

Introduction

Brushless DC motor is about 15% higher than permanent magnet synchronous motor in power density on the premise that they have same casing size and characterized by simple structure, large output and having wide application prospect in the field of compressor for aviation. However, BLDCM in two-two conduction based drive mode is large in torque pulsation and difficult in weak magnetic speed up operation, with non-conduction phase having no current to decrease power output and having restricted its application in operation environment with high requirement of torque precision, power density and range of speed regulation, especially in the airborne equipment with strict power density requirement. It is important to solve the above mentioned problem so as to promote its wide application to aviation field.

Regarding torque pulsation of brushless DC motor, non commutation current hysteresis control adopted in literature [2] is able to achieve square wave control at low speed of motor but its effect at high speed of motor is to be improved. It is advisable to add boost and buck circuit to front-stage of inverter to decrease commutation torque pulsation of motor [3][4]. The control method presented in literature [5] is to add voltage source to neutral point to decrease commutation torque pulsation. The current prediction control method based on model put forward in literature [6] is similar to the method to lag commutation of turn-off phase current. Research of high power density may be divided into research of motor body loss and research of drive circuit. The research object of motor body includes eddy-current loss, copper loss, stray loss and heat dissipation etc. Research method is based on electromagnetic analysis, mechanical technology, and cooling and heat dissipation [7]. In order to improve power density of air compressor, a type of high speed brushless dc motor with a speed of 500,000r/min designed in literature, however, there are problems such as complex system and lower efficiency due to bearing life and BUCK circuit added to front stage for power conversion. At present, a majority of researches on brushless dc motor control are based on “two-two conduction” based drive mode, in which there is only two-phase winding to output electromagnetic power, being adverse to improvement in power density and expansion in range of speed regulation; there is larger non-commutation current pulsation in commutation process, generating commutation torque pulsation. In case that control mode based on three-phase continuous conduction is adopted to make three-phase winding of motor output continuous and effective electromagnetic power at the same time so as not only to increase power density but also expand range of speed regulation and decrease commutation torque pulsation.

The paper presents a “continuous three-phase current based drive method to make three-phase winding of motor output continuous and effective electromagnetic power at the same time. The method takes motor torque equation, counter potential equation, sum of currents from three phases equal to zero as restrictive condition to solve current limit able to minimize copper loss in three-phase winding and allocate current limit to three-phase current based on rotor position, since sum of currents from three phases is equal to zero, it is advisable to achieve continuous output of three-phase current and suppress commutation torque pulsation and improve motor power density by closed loop control of two-phase current.

Analysis of conventional “Three-phase and six-state” based drive mode

Current closed loop control for BLDCM contains current calculation, current closed loop, PWM module, logic synthesis and power drive, in which power drive is based on three-phase full-bridge. Current calculation is to carry out closed loop calculation of feedback current due to two-phase current and rotor position and given current, resulting in PWM so as to achieve current closed loop control for BLDCM based on logic synthesis and power drive. In case that BLDCM is at low speed, phase current waveform is approximate to the preferred square wave, with slight fluctuation of non-commutation current, however, in case that motor is at high speed, non-commutation current fluctuation is on the increase, in which one-phase current as non commutation current is taken as an example, it is advisable to deduce pulsation values of torque before and after commutation according to equivalent circuit model of winding.

$$T_{e\Delta} = -2\Psi_m \frac{3RI_{a0}^2 + 4EI_{a0} - UI_{a0}}{U + 2E + 3RI_{a0}} \tag{1}$$

Where, U —inverter voltage, Ψ_m —magnetic flux linkage of permanent magnet of every phase winding linkage, I_{a0} —current of A phase before commutation, R—phase resistance, $T_{e\Delta}$ —torque pulsation value before and after commutation, E —flat-topped wave amplitude value of counter potential of motor

If motor resistance is ignored and that counter potential $E < U/4$, commutation torque pulsation is positive, only if counter potential $E = U/4$, pulsation is zero. If counter potential $E > U/4$, pulsation is negative. If motor is at low speed, $E \le U/4$, it is advisable to carry out real-time regulation of the voltage applied to both terminals of winding based on current closed-loop control to maintain constant non-commutation current, if motor torque is higher, $E < U/4$, current closed-loop control effect is on the decline. Although it is advisable to decrease pulsation of non-commutation current by delaying turn-off and overlapping commutation on the premise that motor is in operation at high speed, however, the above mentioned researches are carried out in “three-phase and six-state” based drive mode, failing to solve the problem on current pulsation in such drive mode. It is observed from mark A and mark B on two diagrams that phase current is equal to zero. The phase winding in the interval is not to output electromagnetic torque, with low utilization rate of counter potential having prevented power density from increasing. Conventional “Three-phase and six-state” based drive mode is adverse to increase in motor power density; in addition, non-commutation current pulsation is likely to result in torque pulsation.

Principle of "Continuous three-phase current" based drive mode

The difference between continuous three-phase current based drive mode and three-phase six-state based drive mode in terms of current closed-loop control architecture lies in solution to given current and current loop. First, it is advisable to carry out calculation of given three-phase current by solution method for current to minimize copper loss to obtain 9 sets of current state, and then carry on real time allocation of the state based on sector of motor to obtain per-unit value and of given current by phase A and phase B. and are multiplied by given torque to generate actual current and and then generate and by closed loop calculation of current, since three-phase winding symmetry may be obtained by subtracting and from bus voltage, finally, three – path PWM module shall generate complementary 3 sets of PWM drive signals subjected to power drive and amplification so as to rotate motor.

Solution to current to minimize copper loss

The reason why voltage utilization rate of brushless dc motor is low is that motor winding is only subject to two-phase conduction at any moment, in addition, the preferred phase current of motor and counter potential in relevant phase are identical so as to obtain electromagnetic torque [7].

$$T_{em} = \frac{2E_f I_{dc}}{\Omega} = \frac{P_{em}}{\Omega} \tag{2}$$

Where, T_{em}—electromagnetic torque of motor; E_φ—counter potential flat topped wave (bottom) amplitude value; I_{dc} —electrified winding current; Ω —angular speed of motor rotation; P_{em}—electromagnetic power of motor;

Electromagnetic torque and electromagnetic power of motor shown in Eq.are only related to two-phase counter potential and its current, without taking their phase into consideration. In principle, for three-phase motor, as long as current is injected into three-phase winding at any moment, electromagnetic torque shall be outputted. In order to maximize motor power density and minimize torque fluctuation, the injected current shall satisfy two principles: counter potential utilization rate maximization and three-phase winding copper loss minimization.

To change Eq.2 to:

$$T_{em} = \frac{e_a i_a + e_b i_b + e_c i_c}{\Omega} = \frac{P_{em}}{\Omega} \tag{3}$$

Where, i_a , i_b and i_c—winding current of phase A, phase B and phase C of motor;

e_a , e_b and e_c—counter potential of phase A, phase B and phase C of motor.

Supposing that three-phase counter potential is preferred, in case that counter potential is from 150° to 180° for analysis, counter potential of phase A is in change stage with positive pole, phase B and phase C are on negative flat top and positive flat top of flat topped wave respectively. In addition, $e_a = E_\varphi(\theta_r) = E_\varphi \theta_r / 60$, $e_b = E_\varphi$, $e_c = -E_\varphi$, θ_r is electrical angle of rotor. To substitute $i_a + i_b + i_c = 0$ into Eq.3, then

$$T_{em} = \frac{P}{\Omega} = \frac{E_f(q_r)i_a + E_f i_b + E_f(i_a + i_b)}{\Omega} \tag{4}$$

Namely $C_T(q_r) = \frac{E_f(q_r)}{\Omega} = \frac{C_e f(q_r) n}{2p\,n/60} = \frac{C_e f(q_r)60}{2p}$, $C_T = \frac{E_f}{\Omega} = \frac{C_e f\,n}{2p\,n/60} = \frac{C_e f\,60}{2p}$. Then

$$T_{em} = (C_T(q_r) + C_T)i_a + 2C_T i_b \tag{5}$$

Where, C_e— potential coefficient; C_T—torque coefficient; φ— magnetic flux per stage

Supposing that three-phase winding resistance is r , then copper loss equation:

$$p_{Cu} = r[i_a^2 + i_b^2 + (i_a + i_b)^2] \tag{6}$$

Simultaneous Eq.5 and 6, to solve limit value based on copper loss equation:

$$\begin{cases} i_{\text{aset}} = T_{em} \dfrac{C_T(q_r)}{C_T{}^2 + C_T(q_r)^2} = T_{em} \times i_a^* \\ i_{bset} = T_{em} \dfrac{C_T - C_T(q_r)}{2(C_T{}^2 + C_T(q_r)^2)} = T_{em} \times i_b^* \\ i_{cset} = -T_{em} \dfrac{C_T + C_T(q_r)}{2(C_T{}^2 + C_T(q_r)^2)} = T_{em} \times i_c^* \end{cases} \quad (7)$$

Given that air-gap field of brushless dc motor is subject to saturated design, it is permitted to ignore influence of armature field and eddy current loss. After motor design, C_T is fixed value, it is observed from Eq.7 that every given phase current is only associated with electromagnetic torque T_{em} and electrical angle of rotor θ_r and is unrelated to motor speed. Namely per-unit value of given current of phase A, phase B and phase C:

$$\begin{cases} i_a^* = \dfrac{C_T(q_r)}{C_T{}^2 + C_T(q_r)^2} \\ i_b^* = \dfrac{C_T - C_T(q_r)}{2(C_T{}^2 + C_T(q_r)^2)} \\ i_c^* = -\dfrac{C_T + C_T(q_r)}{2(C_T{}^2 + C_T(q_r)^2)} \end{cases} \quad (8)$$

In case that that counter potential is from 330° to 360° , counter potential of phase A is in change stage with negative pole, phase B and phase C are on negative flat top and positive flat top of flat topped wave respectively. The per-unit value of given current of phase A, phase B and phase C:

$$\begin{cases} i_a^* = \dfrac{C_T(q_r)}{C_T{}^2 + C_T(q_r)^2} \\ i_b^* = \dfrac{-C_T - C_T(q_r)}{2(C_T{}^2 + C_T(q_r)^2)} \\ i_c^* = -\dfrac{-C_T + C_T(q_r)}{2(C_T{}^2 + C_T(q_r)^2)} \end{cases} \quad (9)$$

In case that counter potential is from 30° to 60° , counter potential of phase C is in change stage with positive pole, phase A and phase B are on positive flat top and negative flat top of flat topped wave respectively. The per-unit value of phase A, phase B and phase C:

$$\begin{cases} i_a^* = \dfrac{C_T - C_T(q_r)}{2(C_T{}^2 + C_T(q_r)^2)} \\ i_b^* = -\dfrac{C_T + C_T(q_r)}{2(C_T{}^2 + C_T(q_r)^2)} \\ i_c^* = \dfrac{C_T(q_r)}{C_T{}^2 + C_T(q_r)^2} \end{cases} \quad (10)$$

Other conditions shall be subject to analogy in order; there are calculated values of 18 given currents in 9 sets.

Selection of given current

It is observed from Fig.5 that 360°of electrical angle is divided into 12 sectors according to the principle that winds in three phases output effective electromagnetic power at the same time. In case that electrical angle of motor rotor is from 30° to 90°, with e_c changing from E_φ to $-E_\varphi$ in succession, when its electrical angle is at 90°, its polarity is changed, on the premise that positive electromagnetic power is outputted, i_c is expected to be positive and consistent with positive polarity of e_c from 30° to 60° and i_c is expected to be negative and consistent with negative polarity of e_c from 60° to 90°, various given three-phase current equation shall be selected according to determination of rotor angle sector.

Current loop design

The calculated per-unit value of current is multiplied by given torque to generate actual current, with feedback current collected by current sensor and its error subjected to determination and calculation so as to achieve current closed loop.

Since the sum of currents from three phases is zero, which is not only to simplify calculation of given value of three-phase current into that of two-phase current but also reduce closed loop of three-phase current to that of two-phase, with the output of third phase obtained by subtracting sum of output of two-phase closed loop from dc bus voltage.

PWM module

Other than conventional “three-phase six-state” based drive mode, since upper tube and down tube of every bridge arm unit are working in complementary state, in order to prevent upper tube and down tube from direct connection, it is necessary to prepare dead zone between upper tube and down tube, in addition, in order to decrease current pulsation, triangular carrier phase of three-path PWM module lagged by 120°of electrical angle of chopping.

Simulation result

In order to verify the effectiveness of “continuous three-phase current” based drive mode, it is necessary to build 15kW motor model with preferred counter potential waveform, the motor is 7400r/min in rated torque and 20Nm in rated torque, 0.2mH in phase inductance, 0.02Ω in phase resistance and 2 in pole pairs. In simulation(see Fig.1), the given speed is 6000r/min, load torque is 20Nm, and switch frequency is 10 kHz. Fig.2 shows torque of outer speed ring, phase current inner ring, simulation waveform of per-unit value of phase current and phase voltage in two-two conduction based drive method. Fig.3 shows correlation waveform in “continuous three-phase current” based drive mode. In order to compare characteristics of two drive modes in an objective way, the two drive modes are identical in terms of control loop architecture and speed loop and current loop parameters.

In case that counter potential of phase A is in transition interval as shown in positions of ellipse 1 and 2 in Fig 2 and Fig 3. In Fig.2, in case that inductive current tail is ignored, A phase current is zero, without electromagnetic torque outputted. It is observed from Fig.3 that A phase current and counter potential change in terms of like polarity to output positive electromagnetic power. The phenomenon has increased utilization rate of motor winding in “continuous three-phase current” based drive mode, being the key to output larger electromagnetic torque.

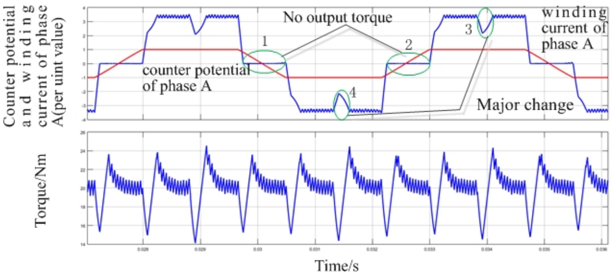

Fig.1 Simulation waveform in “two-two conduction” based drive mode with a given speed of 6000r/min

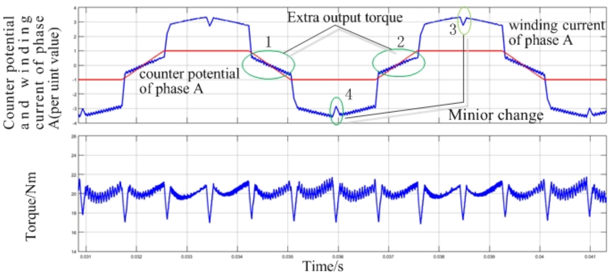

Fig.2 Simulation waveform in “continuous three-phase current” based” drive mode with a given speed of 6000r/min

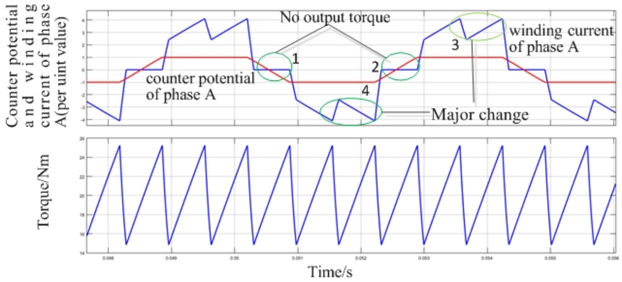

Fig.3 Simulation waveform in “two-two conduction” based drive mode with a given speed of 10000r/min

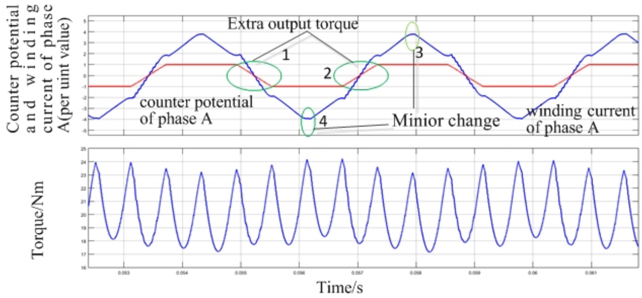

Fig.4 Simulation waveform in “continuous three-phase current” based” drive mode with a given speed of 10000r/min

In commutation stage, Fig.1 and Fig.2 show positions of ellipse 3 and ellipse 4. It is observed from Fig 1 that A phase current per-unit value ranges from 2.2 to 3.2 in terms of fluctuation and that torque ranges from 14 to 24.5Nm in terms of fluctuation and that pulsating quantity is10.5Nm；it is observed from Fig 2 that A phase current per-unit value ranges from 2.8 to 3.2 in terms of fluctuation and that torque ranges from 15 to 21.4Nm in terms of fluctuation and that pulsating quantity is 6.4Nm.In case that counter potential is in flat-topped wave stage: It is observed from Fig.1 that the preferred value of A phase current is associated with rotor angle, with maximum value up to 3.2, however, the preferred value at start (commutation) point of flat topped wave so as to decrease commutation torque pulsation. After calculation, it is observed from Fig 1 that the effective value of A phase current is 53.1A and that it is observed from Fig 2 that the effective value of A phase current is 51.6A. To maintain constant load, the given speed is set to be 10000r/min to make motor work at speed open loop and current closed loop so as to compare maximum speed in two different drive modes, with their simulation waveform shown in Fig.3 and Fig.4 respectively. It is observed from Fig 3 that since given speed exceeds rated speed in conventional two-phase conduction, motor speed is 7430r/min, output electromagnetic power is 15.6kW, with fluctuation range of phase current in commutation stage from 2.5 to 4.1 and fluctuation range of torque from 15 Nm to 25Nm.

Table.1 Comparison between results in two control methods

Control method		Two-two conduction	Three-phase conduction	Comp
6000r/min Given	Torque fluctuation Nm	14～24.5	15～21.4	Decrease by 39%
	Per-unit value of phase current	2.2～3.2	2.8～3.2	Decrease by 60%
	Effective value A of phase current	53.1	51.6	Copper loss decrease by 5.6%
10000r/min Given	Max speedr/min	7430	8290	Speed increase by 11.6%
	Output power kW	15.6	17.4	Power increase by 11.6%
	Torque fluctuation Nm	15～25	18～24.2	Decrease by 30%
	Effective value A of phase current	53.1	50.3	Copper loss decrease by 10.3%

It is observed from Fig.4 that in “continuous three-phase current” based” drive mode, motor speed is 8290r/min, output electromagnetic power is 17.4kW, with fluctuation range of torque from 17.2 Nm to 24.2Nm preliminary result of comparison between two control methods is as shown in Table.1, on the premise that iron loss and eddy current loss of motor are ignored, compared with “two-two conduction” based drive mode, “continuous three-phase current” based” drive mode is able to increase output power of brushless dc motor by 11.6% and decrease copper loss by 10.3% and expand speed range by 11.6% and decrease torque fluctuation by 39%.

Conclusion

BLDCM in conventional “two-two conduction” based drive mode is not only to increase non-commutation current pulsation but also to decrease utilization rate of three-phase winding of motor and to increase torque pulsation of motor and to decrease motor torque pulsation, decrease power density, narrow range of speed regulation, restrict its application to operation environment with high requirement of torque precision, power density and range of speed regulation. The paper presents “continuous three-phase current” based” drive mode for brushless dc motor and makes a study of calculation of given current by such drive method, takes motor torque equation, counter potential equation as restrictive condition to solve limit value of current to minimize copper loss of three-phase winding and works over architecture approach for solution to current limit and divides position of motor rotor into 12 sectors based on operating characteristics and counter potential waveform of motor and observes the principle that counter potential and phase current are consistent in terms of per-unit value and polarity and makes solution to

References

[1] R.Krishnan, S.Y.Lee:IEEE Transaction on Industry Application Vol. 33(1997), p. 973

[2] T.Shi, Y.Guo, P.Song, et al:IEEE Transactions on Industrial Electronics, Vol. 57(2010), p. 3483

[3] V. Viswanathan, and S. Jeevananthan: IET Power Electronics, vol. 8,(2015), p. 47

[4] J.Gao, Y.Hu: IEEE Transactions on Industrial Electronics, Vol. 57(2010), p.2836

[5] C.Xia, Y.Wang, T.Shi: IEEE Transactions on Industrial Electronics, Vol. 63(2013), p. 896

[6] J.J.Lee, Y.K. Kim, H.Nam,et al: IEEE Transactions on Magnetics, Vol. 40(2004), p. 762

[7] Y.T .Luo, D.Tan: IEEE Transactions on Vehicular Technology, Vol. 99(2012), p. 1