Sensorless Direct Torque Controlled Drive of Brushless DC Motor based on Fuzzy Logic

YAN Wei-Sheng, LIN Hai, LI Hong, Yan Wei
Department of Mechanical Engineering and Automatic Control, College of Marine
Northwestern Polytechnical University
Xi'an, 710072, China

***Abstract*—Investigations were carried out on a sensorless fuzzy direct torque control (DTC) which drives brushless DC motors (BLDC). It is deduced that the amplitude of stator flux linkage can not been controlled in BLDC-DTC since it is automatically determined by every 60 electrical degrees commutation. Then, the control of the flux linkage is unused in the proposed system. For the sake of improving the static and dynamic performance of the system, fuzzy logic is introduced into the system, which the torque error and flux linkage angle of BLDC were all properly fuzzified into several subsets to accurately select the voltage space vector in order to smooth the torque and quicken the torque response. A state observer is designed to estimate the back-EMF, the torque and rotor speed can be derived from the estimated back-EMF. Simulations illustrate the operation and performance of the proposed scheme.**

***Index Terms*—Brushless DC motor(BLDC), Direct torque control (DTC), fuzzy Logic control, torque ripple.**

I. Introduction

Permanent magnet brushless DC motor (BLDC) with trapezoidal back-EMF have been widely used in many field of variable-speed drives for their higher power/weight and higher efficiency. However, in practice, torque ripple may exist for the motor itself and feeding system. Particularly, torque ripple during the commutation period is one of the main drawbacks which deteriorate the performance of BLDC drives. To reducing torque ripple effectively, various torque control methods have been proposed for BLDC [1-14].

In [9], a novel torque controller attenuating the undesired torque pulsation for BLDC with non-ideal trapezoidal back-EMF is presented, in which the torque is estimated from the product of the instantaneous back-EMF and current. However, the winding resistance was neglected and the back-EMF shape functions according to the rotor position are tested by off-line, and set up at the look up table. In [10], for achieving instantaneous torque control and reducing the torque ripple, direct torque control (DTC) has been successfully extended to a three-phase BLDC drive operating in the 120 elec. degrees conduction mode. DTC scheme was originally developed for induction machines drives which was first proposed by Takahashi [5] and Depenbrock [6] in the mid 1980s. Control of torque is exercised through control of the amplitude and angular position of the stator flux vector relative to the rotor flux vector. It is claimed that the electromagnetic torque and the amplitude of stator flux linkage can be controlled simultaneously [10]. However, the control effect of the stator flux linkage is not good from the simulated and experimental result.

In this paper, a sensorless fuzzy direct torque controlled BLDC drives is proposed to reducing torque ripple in two-phase conduction mode. The proposed scheme differs from the direct torque controlled BLDC drives in [10] in that the amplitude of stator flux linkage is not controlled since it is automatically determined by every 60 elec. degrees commutation. In the system, the torque error and flux linkage angle of BLDC were all properly fuzzified into several subsets to accurately select the voltage space vector in order to smooth the torque and quicken the torque response. The torque and rotor speed are derived from the back-EMFs, which are estimated from a designed state observer. Its effectiveness is validated by simulations.

II. Drive Model of BLDC

The BLDC is modeled in the stationary reference frame using phase currents, speed, and rotor position as state variables. As the stator winding neutral point is not accessible, which makes it impossible to directly measure phase voltages, it is necessary to define a BLDCM model with line voltages as input variables. On the basis of the BLDCM model with phase voltages, the following model has been derived

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

$$T_e = \frac{e_a i_a + e_b i_b + e_c i_c}{\omega} \quad (2)$$

Where $u_a u_b u_c$, $i_a i_b i_c$ and $e_a e_b e_c$ are phase stator voltages, stator currents and back-EMFs respectively, R and L are the stator phase winding resistance and phase inductance, T_e is the electromagnetic torque, ω is the rotor speed in angular frequency, p is the differential operator (d/dt). With the transformation in (3) and (4), the equations (1) and (2) can be transformed to the stationary frame.

$$\begin{bmatrix} f_\alpha \\ f_\beta \\ f_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -1/2 & -1/2 \\ 0 & \sqrt{3}/2 & -\sqrt{3}/2 \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} \quad (3)$$

The inverse transformation is

$$\begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & 0 & 1/\sqrt{2} \\ -1/2 & \sqrt{3}/2 & 1/\sqrt{2} \\ -1/2 & -\sqrt{3}/2 & 1/\sqrt{2} \end{bmatrix} \begin{bmatrix} f_\alpha \\ f_\beta \\ f_0 \end{bmatrix} \quad (4)$$

Where f represents the voltage, current and back EMF.

The mathematical model of a BLDC drive can be described by the following equations in a stationary frame as[13]

$$\begin{bmatrix} u_\alpha \\ u_\beta \end{bmatrix} = \begin{bmatrix} R+pL & 0 \\ 0 & R+pL \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \begin{bmatrix} e_\alpha \\ e_\beta \end{bmatrix} \quad (5)$$

$$T_e = \frac{e_\alpha i_\alpha + e_\beta i_\beta}{\omega} \quad (6)$$

Where $u_\alpha u_\beta$, $i_\alpha i_\beta$ and $e_\alpha e_\beta$ are the $\alpha\beta$-axis rotor flux linkages, rotor stator voltages, rotor stator currents and back-EMFs respectively.

III. BLDC-DTC System Based on Fuzzy Logic

A standard 6-switch 3-phase inverter fed BLDC drive system in two-phase conduction mode, as show in Fig. 1.

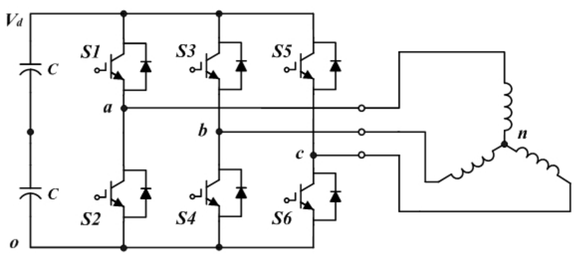


Fig. 1. A inverter-fed BLDC

The primary voltage v_{an}, v_{bn}, v_{cn} are determined by the status of the six switches, $S1$, $S2$, $\cdots$ and $S6$. There are six nonzero voltage vectors: $v_1(100001)$, $v_2(001001)$, $v_3(011000)$, $v_4(010010)$, $v_5(000110)$, $v_6(100100)$ and one zero voltage vector $v_0(000000)$. The six nonzero voltage vectors are 60^o apart from each other as in Fig. 2, but 30 elec. degrees shifted from the corresponding voltages vectors which are used in PMSM-DTC[7] systems[11].

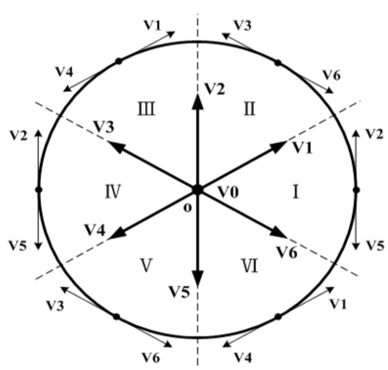


Fig. 2. The control of the stator flux linkage

It is well known that the change of the torque can be controlled by keeping the amplitude of the stator flux linkage and changing the rotating speed of the stator flux linkage[7]. For a BLAC motor with sinusoidal back-EMF waveform and sinusoidal stator current, the amplitude of stator flux linkage is a constant. However, for brushless machines with a non-sinusoidal back-EMF waveform and quasi-square stator current, under conventional two-phase conduction, every commutation will cause the stator flux linkage decreasing dramatically and the locus of the stator flux linkage is unintentionally kept in hexagonal sharp. The amplitude of stator flux linkage varies around the reference stator flux linkage and could be regarded as a constant approximately.

The stator flux linkage of a BLDC that can be expressed in the stationary reference frame is

$$\psi_s = \int (u - Ri)dt \quad (7)$$

During the short switching interval, each voltage vector is constant, and (7) is rewritten as

$$\psi_s = ut + \int (Ri)dt + \psi_s(0) \quad (8)$$

Neglecting the stator resistance, the amplitude of the flux linkage can be controlled by selecting proper space voltage vector in (8). For example, in the region **I** of Fig. 2, vector v1 (v3) is selected to increase (decrease) the amplitude of stator flux linkage rotating in counter-clockwise direction. However, for BLDC, there are only two fixed phases (phase B and phase C) operating in the region **I** under 120 elec. degrees conduction (i.e. two phases conducting), which causes the locus of the stator flux linkage increasing gradually. The vector v1 (v3) will change the operating state of two fixed phases. Because every commutation will cause the stator flux linkage decreasing dramatically and sharp dip appears on the locus of the stator flux linkage every 60 elec. degrees, the best way to control the amplitude of the stator flux linkage is to know the exact shape of it. But it is difficult to predict the size of sharp dips accurately. Therefore, control of the amplitude of stator flux linkage should be abandoned in the system of BLDC-DTC and the amplitude of stator flux linkage can be regarded as a constant approximately for its little variation.

On the other hand, rotating speed of the stator flux linkage can be controlled easily by selecting proper voltage vector. For instance, in the region **I** of Fig. 2, in the direction of counter-clockwise operation, if the actual torque is bigger than the reference, voltage vector v5 is selected to keep flux linkage rotating in the reverse direction. The torque angle decrease as fast as it can, and the actual torque decrease as well. Once the actual torque is smaller than the reference, voltage vector v2 is selected to increase torque angle and the actual torque. Once the region of the stator flux linkage is known, selecting proper voltage vector can reach fast torque control.

The switching table for controlling rotating direction of the stator flux linkage is as follows:

TABLE I
THE SWITCHING TABLE FOR INVERTER

e_T	I	II	III	IV	V	VI
1	V_2	V_3	V_4	V_5	V_6	V_1
0	V_5	V_6	V_1	V_2	V_3	V_4

In table I, $'e_T'$ represents the error between reference torque and estimated torque, and the value $'0'$ or $'1'$ stands for that the estimated value is smaller or bigger than the reference value, respectively. $'\mathbf{I}, \mathbf{II}, \cdots \mathbf{VI}'$ denotes the region number for the present stator flux linkage vector position in Fig. 2.

A. Fuzzy Logic Based on BLDC-DTC System

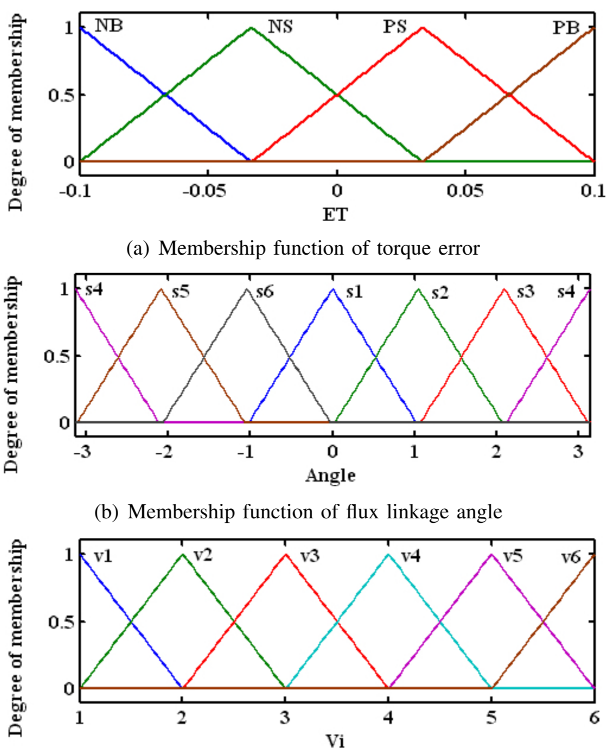
1) Fuzzification: The fuzzification is the process of a mapping from input to the corresponding fuzzy set in the input universe of discourse. There are two inputs to the fuzzy logic controller.

$$ET = T_e^* - \hat{T}_e \tag{9}$$

$$Angle = \hat{\theta}_e \tag{10}$$

Where ET is the error between reference torque and estimated torque, $Angle$ is the estimated angle. Output of the fuzzy logic controller is space voltage vector (V_i).

Torque error (ET) is divided into four fuzzy subsets with the linguistic value $\{PB, PS, NS, NB\}$ and its universe of discourse is [-0.1 0.1]. Flux linkage angle $(Angle)$ is divided into six fuzzy subsets $\{s1, s2, s3, s4, s5, s6\}$ and its universe of discourse is [-π π]. Space voltage vector (V_i) is divided into six singleton fuzzy subsets $\{v1, v2, v3, v4, v5, v6\}$. Membership functions of two fuzzy input variables (ET and $Angle$) and one fuzzy output variables (V_i) are triangle type as shown in Fig.3.



(a) Membership function of torque error

(b) Membership function of flux linkage angle

(c) Membership function of space voltage vector

Fig. 3. Membership functions of the fuzzy controller

2) Rules and Fuzzy Reasoning: Fuzzy control rules are expressed in the IF-THEN format. The ith rule Ri can be written as

$$Ri : IF\ ET\ is\ Ai\ and\ Angle\ is\ Bi, THEN\ v\ is\ Vi,$$

Where Ai,Bi,Vi denote fuzzy sets. The control rules can be expressed form Fig. 1 in the Table II.

TABLE II
FUZZY REASONING RULES FOR BLDC- DTC

	Angle	S_1	S_2	S_3	S_4	S_5	S_6
ET	PB	V_2	V_3	V_4	V_5	V_6	V_1
	PS	V_2	V_3	V_4	V_5	V_6	V_1
	NB	V_5	V_6	V_1	V_2	V_3	V_4
	NS	V_5	V_6	V_1	V_2	V_3	V_4

Mamdani's Min-Max method is employed in the reasoning. The firing strength of the ith rule α_i is decided with min operator.

$$\alpha_i = \min(\mu_{A_i}(ET), \mu_{B_i}(Angle)) \tag{11}$$

By fuzzy reasoning, the membership function value for each fuzzy rule is

$$\mu_{V_i'}(v) = \min(\alpha_i \mu_{V_i}(v)) \tag{12}$$

Where μ_{A_i}, μ_{B_i} and $\mu_{V_i'}$ are fuzzy subset's membership function sets, whose corresponding fuzzy subset are A, B and V respectively. Therefore, membership function for output's fuzzy variable of the fuzzy controller is

$$\mu_V(v) = \max_{i=1}^{24}(\mu_{V_i'}(v)) \tag{13}$$

Since the output of the fuzzy controller is just six singleton fuzzy subsets which is the actual PWM voltage vector sequence composed of only seven different states, the defuzzification is not required in the controller and these states could be directly used as the successor of the fuzzy rules.

B. Back-EMF estimation

According to the equation (6), for a brushless machine with a non-sinusoidal back-EMF waveform and quasi-square stator current, the electromagnetic torque can be obtained by estimating the back-EMF waveform and the rotor speed. An observer is designed to estimate the back-EMF waveform.

Considering the equation (5), the state equations of a BLDC can be described as follows:

$$\begin{cases} \dot{i}_\alpha = -(Ri_\alpha - e_\alpha + u_\alpha)/L \\ \dot{i}_\beta = -(Ri_\beta - e_\beta + u_\beta)/L \end{cases} \tag{14}$$

By choosing α-axis and β-axis stator currents and back-EMFs as the state-variables, the following state-variable equations can be obtained

$$\begin{cases} \dot{\mathbf{x}} = \mathbf{Ax} + \mathbf{Bu} \\ \mathbf{y} = \mathbf{Cx} \end{cases} \tag{15}$$

Where $\mathbf{x} = [i_\alpha, i_\beta, e_\alpha, e_\beta]^T$ is the state vector, $\mathbf{u} = [u_\alpha, u_\beta]^T$ is the input vector, $\mathbf{y} = [i_\alpha, i_\beta]^T$ is the output vector, and

$$\mathbf{A} = \begin{bmatrix} -R/L & 0 & -1/L & 0 \\ 0 & -R/L & 0 & -1/L \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix},$$

$$\mathbf{B} = \begin{bmatrix} -1/L & 0 & 0 & 0 \\ 0 & -1/L & 0 & 0 \end{bmatrix}^T, \mathbf{C} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}.$$

Because the system (15) can be observed, it is possible to obtain the following observer

$$\dot{\hat{\mathbf{x}}} = \mathbf{A}\hat{\mathbf{x}} + \mathbf{B}\mathbf{u} + \mathbf{K}(\mathbf{y} - \hat{\mathbf{y}}) \tag{16}$$

Where $\mathbf{K}$ is a gain matrix of the observer, and choose the proper constant to make the designed observer stable and estimate back-EMF exactly, and

$$\mathbf{K} = \begin{bmatrix} k_1 & 0 & k_3 & 0 \\ 0 & k_2 & 0 & k_4 \end{bmatrix}^T$$

Where k_1, k_2, k_3 and k_4 are positive constants.

The equations of back-EMF in (16) are described as

$$\dot{\hat{\mathbf{e}}} = \mathbf{K}_i(\mathbf{y} - \hat{\mathbf{y}}) \tag{17}$$

Where $\hat{\mathbf{e}} = [e_\alpha, e_\beta]^T$ is the back-EMF vector, $\mathbf{K}_i = diag(k_3, k_4)$ is the gain matrix.

Integrating (17) and the estimated back-EMF is converted to:

$$\hat{\mathbf{e}} = \int \mathbf{K}_i(\mathbf{y} - \hat{\mathbf{y}})dt \tag{18}$$

Adding the proportional term to the estimated back-EMF, the equation (18) can be rewritten as:

$$\hat{\mathbf{e}} = \mathbf{K}_p(\mathbf{y} - \hat{\mathbf{y}}) \int \mathbf{K}_i(\mathbf{y} - \hat{\mathbf{y}})dt \tag{19}$$

Where $\mathbf{K}_p = diag(k_5, k_6)$ is the gain matrix, k_5 and k_6 are positive constants. .

C. Speed, rotor position and torque estimation

For a brushless machine with a trapezoidal back-EMF waveform and quasi-square stator current, the rotor position information is included in the waveform of back-EMF, and the speed can be easily obtained from the derivation of the position. The relation between the rotor speed and the amplitude of the back-EMF is:

$$E = PK_e\omega \tag{20}$$

Where P is the number of pole pairs, K_e is the back-EMF constant of the motor, E is the amplitude of every phase back-EMF.

The amplitude of the back-EMF can be obtained by calculating the maximum of the three phase back-EMF absolute value. Then, the estimated speed is given by

$$\hat{\omega} = \hat{E}/(PK_e) \tag{21}$$

As integrating (21), the estimated rotor position is obtained by

$$\hat{\theta} = \int \hat{\omega}dt + \hat{\theta}_0 \tag{22}$$

Where $\hat{\theta}_0$ is initial position of rotor.

According to the equation (6), the estimated torque can be obtained by

$$\hat{T}_e = \frac{\hat{e}_\alpha i_\alpha + \hat{e}_\beta i_\beta}{\hat{\omega}} \tag{23}$$

IV. Implementation of Fuzzy BLDC-DTC System

The block diagram of a sensorless BLDC drive with fuzzy DTC may be as shown in Fig, 4. In the proposed system, there are the inner torque loop and outer speed loop. The main parts of the system are speed PI controller, fuzzy logic controller, clark translation, back-EMF observer and torque estimator etc.. The reference torque is obtained from the speed controller and is limited at a certain value. Stator currents(i_a, i_b, i_c) and voltages(V_a, V_b, V_c) are measured and then transformed into the stationary reference frame alpha and beta components in the system.

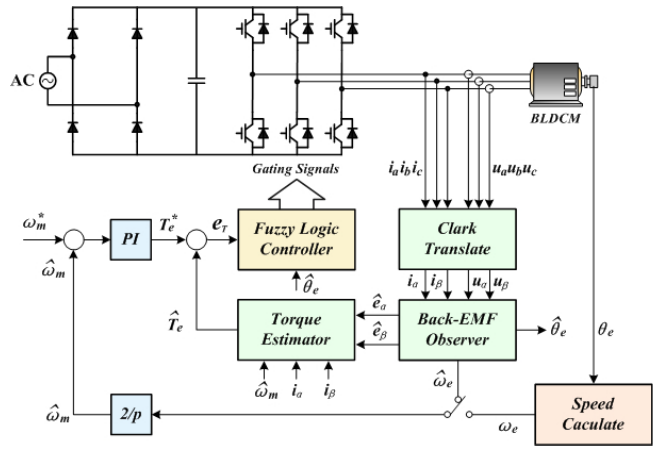


Fig. 4. Block diagram of the proposed control system

As described above, a back-EMF observer provides the estimated back-EMF. The rotor position, rotor speed and the torque are calculated from estimates of the back-EMF. A fuzzy logic controller generates the commutation signals based on the error between the reference and estimated torque. It is also seen that the DTC scheme for BLDC is independent of motor parameters except for the stator resistance and inductance, which affects only the low-speed performance of the drive and can be compensated.

TABLE III
THE PARAMETERS OF BLDC

parameter		value
DC link voltage	V_{dc}	300V
Base speed	ω_b	1000rpm
Armature resistance	R_s	2.875Ω
d-axis inductance	L_d	8.5mH
q-axis inductance	L_q	8.5mH
Magnet flux linkage	ϕ	0.175Wb
Number of poles	P	4

V. Simulation Results

To verify the proposed scheme, MATLAB model was developed for fuzzy BLDC DTC system. The parameters of the BLDC used in the system are listed in the table 3.

Fig. 5 shows the locus of the estimated stator flux linkage of the proposed method at the 1/2 rated load and based speed. When the load torque level increases, more deep sharp changes are observed which increase the difficulty of the flux control

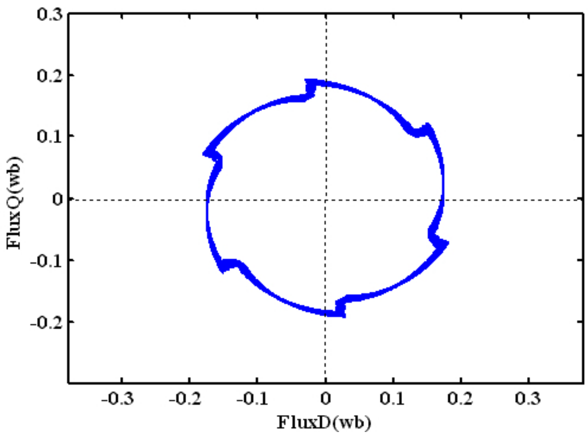
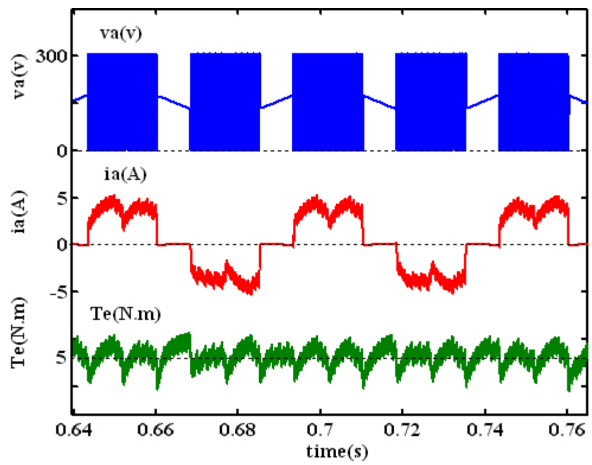
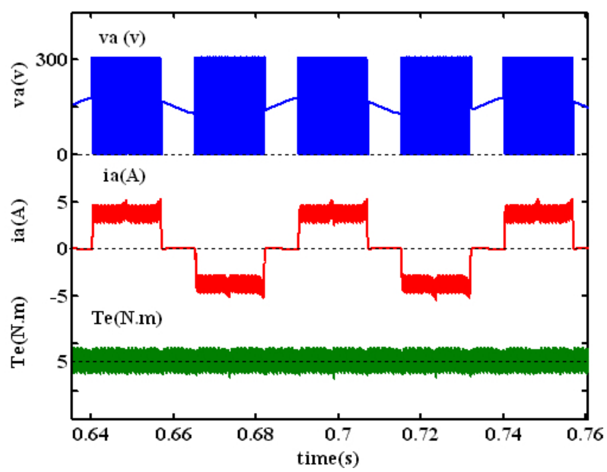


Fig. 5. The stator flux linkage trajectory



(a) PWM scheme

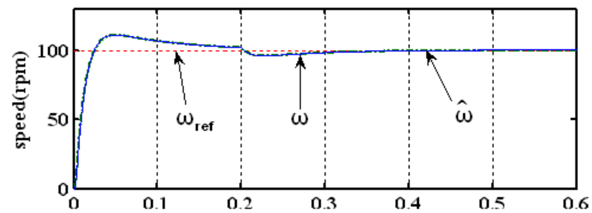


(b) The proposed fuzzy DTC scheme

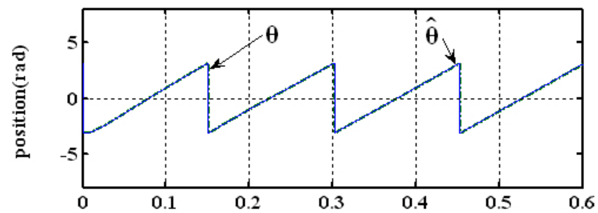
Fig. 6. Comparisons of the conventional and proposed DTC scheme(phase voltage, stator phase current and torque)

in [11]. Fig. 6 shows the performance comparison between the conventional PWM method using the sensor and the proposed method. The torque ripple and the current ripple are much less, compared with the PWM scheme.

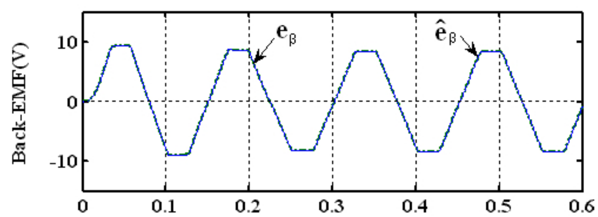
Fig. 5(a)-(d) show the response performance of the proposed sensorless drive at 100 rpm. The simulation condition is that the 1/2 rated load was injected at 0.2 sec. As shown in Fig. 8(a) and (b), rotor speed and position are exactly estimated under no load. Although the small deviation from the real values was observed after injecting the load, the performance is generally good. Fig. 5(c) and (d) shows the estimated beta-axis back-EMF by an state observer and A phase stator current. Some peak value near an annex of the line-to-line back-EMF is observed. Fig. 6(a)-(d) show the response performance of the proposed sensorless drive at 1500 rpm. A condition of the simulation is that the 1/2rated load is injected at 0.2 seconds. These profiles also show comparatively good estimation and control performance in low and high speed range.



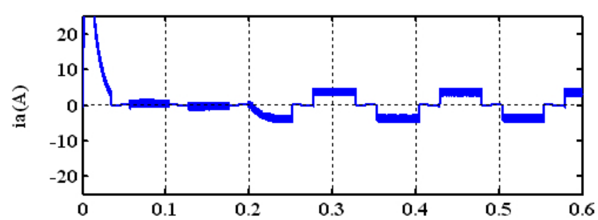
(a) Rotor speed



(b) Rotor position



(c) Beta-axis back-EMF



(d) Phase A current

Fig. 7. Simulation results of the proposed DTC scheme at 100 rpm

VI. Conclusion

In this paper, a novel sensorless Fuzzy-DTC for BLDC motors was proposed to achieve torque ripple reduction. The scheme eliminates the flux linkage control and only has the torque control in the system. Fuzzy logic control is applied to the system, which properly fuzzify the torque error and rotor position into several subsets to accurately select the

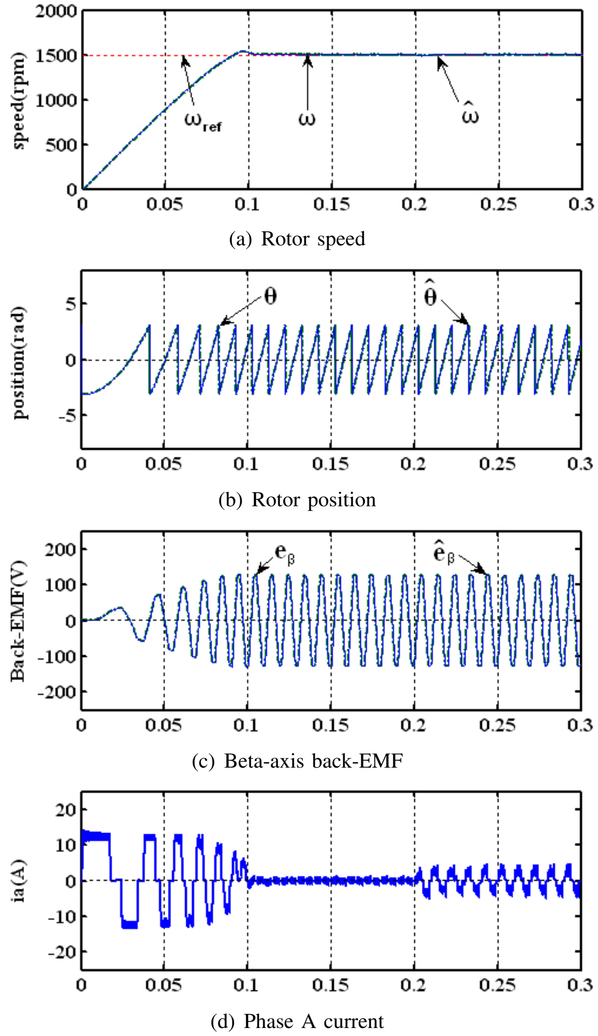


Fig. 8. Simulation results of the proposed DTC scheme at 1500 rpm

voltage space vector. Considering the torque, the rotor position and speed of BLDC are difficult to calculate directly, a state observer is designed to obtain the back-EMF, then, the torque, the rotor position and speed can be calculate from back-EMF easily. The simulation results show that the proposed scheme has good estimation performance in low and high speed range and good control performance, compared with the PWM method.

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References

[1] Kim Gwang-Heon, Kang Seog-Joo et al., "Analysis of the commutation torque ripple for BLDCM fed by HCRPWM-VSI," Applied power electronics conference and exposition, Boston, MA USA, 1992.

[2] Won Chang-hee, Song Joong-Ho,lck Choy, "Commutation torque ripple reduction in brushless DC motor drives using a single DC current sensor," Power Electronics, IEEE Transactions on, vol. 19, no. 2, pp, 312-319, 2004.

[3] ZHANG Xiang-jun, CHEN Bo-shi, "Influence of PWM Modes on Commutation Torque Ripples in Sensorless Brushless DC Motor Control System," Journal of Shanghai University, vol. 5, no. 3, pp. 217-223, 2001.

[4] WEI Kun, HU Chang-sheng, ZHANG Zhong-chao, "A novel PWM scheme to eliminate the diode freewheeling in the inactive phase in BLDC motor," Front. Electr. Electron. Eng. China, vol. 2, pp. 194-198, 2006,

[5] Takahashi I, Naguchi T, "A New Quick-response and High-efficiency Control Strategy of an Induction Motor ," IEEE Transactions on Industry Applications (S0093-9994), vol. 22,no. 5, pp. 820-827, 1986.

[6] M. Depenbrock, "Direct self-control of Inverter-fed machine," IEEE Trans Power Electron, pp. 420-429,1988.

[7] L. Zhong, M. F. Rahman, W. Y. Hu, K. W. Lim, "Analysis of Direct Torque Control in Permanent Magnet Synchronous Motor Drivers," IEEE Trans. on Power Electronics, vol. 12, no. 3, pp. 528-535, 1997.

[8] M. Ehsani, R. C. Becerra, "High-speed torque control of brushless permanent magnet motors," IEEE Trans. Ind. Electron.. vol. 35, no. 3, pp. 402-406, 1988.

[9] S. J. Kang, S. K. Sul, "Direct torque control of brushless DC motorwith non-ideal trapezoidal back-EMF," IEEE Trans. Power Electron., vol. 10, no. 6, pp. 796-802, 1995.

[10] Z. Q. Zhu, Y. Liu, and D. Howe, "Comparison of performance of brushless DC drives under direct torque control and PWM current control," Korean IEE Int. Trans. Elect. Mach. Energy Convers. Syst., vol. 5-B, no. 4, pp. 337-342,2005.

[11] Y. Liu, Z. Q. Zhu, D. Howe, "Direct torque control of brushless DC drives with reduced torque ripple," IEEE Trans. Ind. Appl., vol. 41, no. 2, pp. 599-608, 2005.

[12] Z. Q. Zhu, Y. Liu, D. Howe, "Steady-state dynamic performance of a direct torque controlled PM brushless DC drive accounting for influence of PWM chopping and cogging torque," in Proc. IEE Int. Conf. Power Electron., Mach. and Drives, pp. 556-560, 2006.

[13] Y. Liu, Z. Q. Zhu, D. Howe, "Instantaneous torque estimation in sensorless direct torque controlled brushless DC motors," IEEE Trans.Ind. Appl., vol. 42, no. 5, pp. 1275-1283, 2006.

[14] S. B. Ozturk, H. A. Toliyat, "Direct torque control of brushless dc motor with non-sinusoidal back-EMF," in Proc. IEEE-IEMDC Annu. Meeting, 2007.