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Low speed sensorless control method of brushless DC motor based on pulse high frequency voltage injection

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KEYWORDS

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Abstract A low speed sensorless position control method for brushless DC motor based on pulse pulse high frequency voltage injection is proposed according to the characteristic that the brushless DC motor (BLDCM) which is produced at present makes the counter electromotive force waveform show sinusoidal waveform in view of the problem that it is difficult to accurately obtain the rotor position and speed of the brushless DC motor at zero and low speed. Its principle is to inject high frequency sinusoidal voltage signal on the estimated direct axis of the synchronous rotating coordinate system so that the motor can generate saturated salient effect, obtain the estimation error containing the rotor position information, and by detecting the output current of PI regulator of quadrature axis current loop, and then estimate the initial position of the rotor and judges the magnetic pole, realize the determination of the actual rotor position, finally, realize the non-position static low speed control of BLDCM by adding current and speed rings. According to the simulation test, it shows that this method can detect the position and speed of the motor rotor well at both zero speed and low speed.

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1. Introduction

Brushless DC Motor (BLDCM) has been widely used in industrial automation, household appliances, automotive electronics, aerospace and other fields due to its simple structure, high output torque, long lifetime and high efficiency. However, the key to its control process is how to get the accurate information of rotor position and speed. The most common method is to obtain rotor information by installing mechanical sensors, it greatly limits its wider application although this method can accurately detect the position of the rotor due to some disadvantages, for example, it is difficult to manufacture, easy to be disturbed, with high requirements of working environment and it increases the complexity of the system. Therefore, sensorless position control technology has become a very promising direction [1–6].

Some achievements have been made in the research of non-position control technology of brushless DC motor after decades of research by scholars at home and abroad. The counter electromotive force method is the most mature method in application at present, and it can obtain commutation

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information at a time delay of 300 by detecting the counter electromotive force signal extracted from the terminal voltage of the motor. But it is difficult to detect the counter electromotive force at low speed, at the same time, the existence of filter circuit makes the problem of phase shift more serious at high speed, even may lead to the failure of commutation. Inductance method is to magnetize or demagnetize the armature based on the saturation effect of the iron core and the different directions of the magnetic field of the permanent magnet, thus changing the inductance of the phase winding, and detect the rotor position at zero speed and low speed by detecting the change of inductance. However, this method is only applicable to the salient pole brushless DC motor, and the practical application is very difficult. The freewheeling diode method is to determine the position of the zero-crossing counter electromotive force of the phase by detecting the on–off condition of the freewheeling diode of disconnection phase near the zero-crossing counter electromotive force, and then determines the position of the rotor. However, this method needs additional circuits and the control mode is complicated. The flux linkage function method is to obtain commutation information by indirectly constructing flux linkage correlation function. However, the detection of rotor information is delayed due to the large amount of calculation and complex integral calculation, which leads to inaccurate commutation. The observer method is to construct the state equation by measuring the current and voltage of the brushless DC motor as state variables, and calculate the position information of the motor rotor by integrating the theories including adaptive control and optimal control. The algorithm is complex and the amount of computation is large although this method has a good anti-interference ability. These methods are effective for medium speed brushless DC motor, but it is difficult to estimate the position of stationary and low speed region.

The basic principle of sensorless technology for the static or low speed operation control of brushless DC motor is to detect the space convexity of the motor, this kind of method is mostly applied to brushless DC motors with salient pole structure, which is less affected by motor parameters, such as rotating high frequency injection method. Rotating high-frequency injection method is to inject high-frequency voltage (or current) signals into the two-phase static coordinate system after coordinate transformation, cause the corresponding response to change by using the spatial salient pole effect of the motor rotor, calculate the rotor angle information by detecting this change, which is suitable for brushless DC motor with rotor salient polarity. The initial magnetic pole position is often estimated by pulse pulse high-frequency voltage injection method as the hidden pole brushless DC motor has no salient polarity, in the estimated d-q coordinate system, a high frequency voltage signal is given to excite the motor to produce magnetic circuit saturation, capturing the current response with rotor position information.

Based on the high-frequency model of brushless DC motor and the inductance saturation effect, this paper proposes a new low-speed sensorless control method of pulse high-frequency voltage injection through in-depth study of the basic principle of pulse high-frequency voltage injection method to detect the output current of the quadrature axis current loop PI regulator by injecting a high-frequency sinusoidal voltage signal into the direct axis of the estimated synchronous rotating coordinate system, obtain the estimation error containing the rotor position information, and then estimate the initial position of the rotor and determines its magnetic poles, realizes the determination of the actual rotor position, finally, realize the static and low speed control of brushless DC motor without position by adding current loop and speed loop.

2. Mathematical model of brushless DC motor

For the hidden pole brushless DC motor, it is assumed that the stator electromotive force changes according to the sinusoidal law, ignoring the influence of magnetic saturation, hysteresis and eddy current. After Clarke and Park transformation of the brushless DC motor in the three-phase static coordinate system, the space vector diagrams of the two-phase static coordinate system, the two-phase rotating coordinate system and the rotor position are obtained [7–9]. The schematic diagram is shown in Fig. 1.

The axis of A-phase winding is set as the reference axis of the stator three-phase static coordinate system, which is recombined with the axis in the two-phase static coordinate system. The axis of rotor excitation magnetic field is defined as d-axis, and the one with 900 electric angle ahead of d-axis is defined as q-axis. The two axes are perpendicular to each other, which is called two-phase synchronous rotating coordinate system.

The flux linkage and voltage equations in dq two-phase synchronous rotating coordinate system are as follows:

$$\begin{bmatrix}\psi_d\\ \psi_q\end{bmatrix}=\begin{bmatrix}L_d & 0\\ 0 & L_q\end{bmatrix}\begin{bmatrix}i_d\\ i_q\end{bmatrix}+\begin{bmatrix}\psi_f\\ 0\end{bmatrix} \quad (1)$$

$$\begin{bmatrix}u_d\\ u_q\end{bmatrix}=r_S\begin{bmatrix}i_d\\ i_q\end{bmatrix}+\begin{bmatrix}p & -\omega_r\\ \omega_r & p\end{bmatrix}\begin{bmatrix}\psi_d\\ \psi_q\end{bmatrix} \quad (2)$$

In which ψ_d,ψ_q,L_d,L_q are flux linkage and inductance in rotating coordinate system of dq,ψ_f is the rotor flux linkage of permanent magnet,ω_r is the electric angular velocity of synchronous rotation, r_S is the stator resistance of the motor.

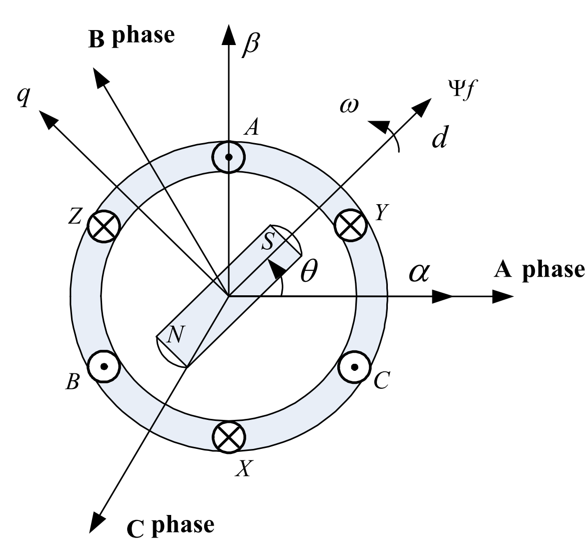


Fig. 1 Schematic diagram of motor model in rotating coordinate system.

For the hidden pole brushless DC motor, the above mathematical model can be transformed into:

$$\begin{bmatrix} u_d \\ u_q \end{bmatrix} = \begin{bmatrix} r_s & -\omega_r L_q \\ \omega_r L_d & r_s \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} p \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega_r \psi_f \end{bmatrix} \tag{3}$$

3. Pulse high frequency voltage injection method

3.1. Principle of pulse high frequency voltage injection method

The basic principle of pulse high frequency voltage injection method is to inject high frequency pulse voltage signal into the estimated direct axis to excite the saturation salient polarity of the motor, and then, the rotor position of the motor is extracted from the electric signal of the motor by modulating the current signal through using the saturation convexity. In order to get the relationship between voltage and current in the $\hat{d}-\hat{q}$ rotating coordinate system, when the synchronous rotation coordinate system of the actual rotor is the dq axis system, and the included angle between d axis and A phase winding axis is θ,When the synchronous rotation coordinate system of estimated rotor is $\hat{d}\hat{q}$ axis, the included angle between $\hat{d}$ axis and A phase winding axis is $\hat{\theta}$,When the two-phase stationary coordinate system is $\alpha\beta$ axis, α axis and A phase winding coincide. The estimation error of the position $\Delta\theta$ is:

$$\Delta\theta = \theta - \hat{\theta} \tag{4}$$

In which, θ is the actual position of the rotor,$\hat{\theta}$ is the estimated rotor position in $\hat{d}-\hat{q}$ coordinate system, and the relationship between the coordinate systems is shown in Fig. 2.

The injected voltage signal frequency ω_h of the motor is much higher than the angular frequency ω corresponding to the rotor speed under zero, low speed and high frequency excitation, therefore, the fundamental wave angular frequency and back electromotive force terms in the voltage equation of the motor can be ignored, and the motor can be simplified to R-L load [10],equivalent circuit as shown in Fig. 3 .

After simplification, the high-frequency voltage balance equation in the rotating coordinate system is[11–12]

$$\begin{bmatrix} u_{dh} \\ u_{qh} \end{bmatrix} = \begin{bmatrix} r_s + pL_{dh} & 0 \\ 0 & r_s + pL_{qh} \end{bmatrix} \begin{bmatrix} i_{dh} \\ i_{qh} \end{bmatrix} = \begin{bmatrix} Z_{dh} & 0 \\ 0 & Z_{qh} \end{bmatrix} \begin{bmatrix} i_{dh} \\ i_{qh} \end{bmatrix} \tag{5}$$

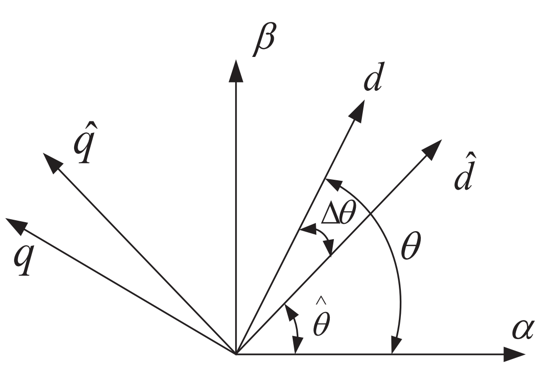
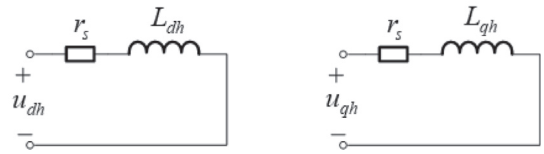


Fig. 2 The relation diagram of each coordinate system.



(a) d-axis equivalent circuit *(b) q-axis equivalent circuit*

Fig. 3 Equivalent circuit of Brushless DC motor in two-phase rotating coordinate system.

In which,u_{dh},u_{qh},i_{dh},i_{qh},L_{dh} and L_{qh} are the high frequency voltage, current and inductance of dq axis in dq rotating coordinate system respectively, $Z_{dh} = r_s + j\omega_h L_q$ and $Z_{qh} = r_s + j\omega_h L_d$ are the impedance of dq axis in dq rotating coordinate system,ω_h axis is the angular frequency of high-frequency signal injection.

3.2. Principle of extracting rotor information by pulse high-frequency voltage injection method

According to Fig. 1 and Equation (5), the voltage and current relationship between the actual synchronously rotating coordinate system and the estimated coordinate system can be deduced, as shown in Equations (6) and (7).

$$\begin{bmatrix} \hat{u}_{dh} \\ \hat{u}_{qh} \end{bmatrix} = \begin{bmatrix} \cos\Delta\theta & -\sin\Delta\theta \\ \sin\Delta\theta & \cos\Delta\theta \end{bmatrix} \begin{bmatrix} u_{dh} \\ u_{qh} \end{bmatrix} \tag{6}$$

$$\begin{bmatrix} \hat{i}_{dh} \\ \hat{i}_{qh} \end{bmatrix} = \begin{bmatrix} \cos\Delta\theta & -\sin\Delta\theta \\ \sin\Delta\theta & \cos\Delta\theta \end{bmatrix} \begin{bmatrix} i_{dh} \\ i_{qh} \end{bmatrix} \tag{7}$$

According to Equations (5), (6) and (7) above, the voltage and current equations under the estimated rotation coordinates can be obtained, as shown in Equation (8).

$$\begin{bmatrix} \hat{i}_{dh} \\ \hat{i}_{qh} \end{bmatrix} = \frac{1}{Z_{dh}Z_{qh}} \begin{bmatrix} Z - \Delta Z\cos(2\Delta\theta) & -\Delta Z\sin(2\Delta\theta) \\ -\Delta Z\sin(2\Delta\theta) & Z + \Delta Z\cos(2\Delta\theta) \end{bmatrix} \begin{bmatrix} \hat{u}_{dh} \\ \hat{u}_{qh} \end{bmatrix} \tag{8}$$

In which,$Z = \left(Z_{dh} + Z_{qh}\right)/2$ is called average impedance, $\Delta Z = \left(Z_{dh} - Z_{qh}\right)/2$ is called half difference impedance.

The high frequency voltage signal as shown in formula (9) is injected into the straight axis position.

$$\hat{u}_d = U_{mh}\cos(\omega_h t) \tag{9}$$

In which,U_{mh} ω_h are the amplitude and frequency of high frequency voltage injection signal, then the equation (8) can be transformed into,

$$\begin{aligned} \hat{i}_{qh} &= \frac{-\Delta Z \cdot \sin(2\theta)}{Z_{dh} \cdot Z_{qh}} \cdot U_{mh} \cdot \cos(\omega_h t) \\ &= \frac{\omega_h \cdot \Delta L \cdot \sin\left(\omega_h t - \varphi_{qh} - \varphi_{dh}\right)}{|Z_{dh}| \cdot |Z_{qh}|} \cdot \sin(2\Delta\theta) \end{aligned} \tag{10}$$

In which,$|Z_{dh}|$ $|Z_{qh}|$ 和 φ_{dh} ,φ_{qh} are the amplitude and phase angle of the high frequency impedance of dq axis respectively, $\Delta L = \left(L_d - L_q\right)/2$.

According to formula 10, the saturated salient polarity makes $\hat{i}_{qh}$ contain position estimation error $\Delta\theta$, and the specific estimation angle position can be obtained if the response current amplitude on the Q axis is extracted and then the amplitude of the current response signal tends to zero through PI adjustment.

3.3. Detection of initial position

If the high-frequency response current $\hat{i}_{qh}$ of q axis is multiplied by $\sin(2\Delta\theta)$ for modulation, it can be obtained

$$\hat{i}_{qh} \cdot \sin(\omega_h t) = \frac{U_{mh} \cdot \Delta L \cdot \omega_h}{2 \cdot |Z_{dh}| \cdot |Z_{qh}|} \cdot \left[\cos\left(\varphi_{dh} + \varphi_{qh}\right) - \cos\left(2\omega_h t - \varphi_{dh} - \varphi_{qh}\right)\right] \cdot \sin(2\Delta\theta) \tag{11}$$

The equation (11) contains DC component and higher harmonic component, by extracting the DC component through the low-pass filter to, we can get the rotor position error function is

$$\begin{aligned} f(\Delta\theta) &= LPF\left(\hat{i}_{qh} \times \sin(\omega_h t)\right) \\ &= \frac{U_{mh} \cdot \Delta L \cdot \omega_h \cdot \cos\left(\varphi_{qh} + \varphi_{dh}\right)}{2|Z_{dh}| \cdot |Z_{qh}|} \cdot \sin(2\Delta\theta) \end{aligned} \tag{12}$$

We can obtain the estimated position $\hat{\theta}$ of the initial position by adjusting $f(\Delta\theta)$ to 0 with PI regulator.

When the estimated Angle approaches the actual Angle, there is $2\Delta\theta \approx 0$, i.e., $f(\Delta\theta)$ approaches zero. After the rotor is adjusted by traditional PI regulator, we obtained the estimated rotor velocity $\hat{\omega}$ after $f(\Delta\theta)$ is adjusted by traditional PI regulator, and get the required estimated angle $\hat{\theta}$ after $\hat{\omega}$ is integrated.

3.4. Determination of initial position

According to formula 12, when $\Delta\theta = 0, \frac{\pi}{2}, \pi, \frac{3\pi}{2}$ can make $f(\Delta\theta) = 0$, and the system can be in a stable state, But according to formula 4, The position of the rotor can be accurately estimated only when $\Delta\theta = 0$.

In order to eliminate the interference and determine the rotor position, Assume that the initial value of estimated rotor position is zero, The position error in $[0, 2\pi]$ is divided into four intervals, which are respectively $\left(0, \frac{\pi}{2}\right)$ $\left(\frac{\pi}{2}, \pi\right), \left(\pi, \frac{3\pi}{2}\right)$, $\left(\frac{3\pi}{2}, 2\pi\right)$. When $\Delta\theta \in \left(0, \frac{\pi}{2}\right)$, According to formula (12), $f(\Delta\theta) > 0$, the estimated rotation rate is positive and the estimated position increases after PI adjustment, according to formula 4, $\Delta\theta$ gets smaller, finally, it converges to 0, when $f(\Delta\theta) = 0$, the estimated position remains unchanged. Similarly, we can judge that, in $\left(\frac{\pi}{2}, \pi\right)$ and $\left(\pi, \frac{3\pi}{2}\right)$ region,$\Delta\theta$ converges to π,$\left(0, \frac{\pi}{2}\right)$ and $\left(\frac{3\pi}{2}, 2\pi\right)$ region,$\Delta\theta$ converges to 0. In the same way, we can judge that, at the special time 0,$\Delta\theta$ converges to 0.At $\frac{\pi}{2}$, π, $\frac{3\pi}{2}$,$\Delta\theta$ converges to π. Therefore, the estimated position is equal to the actual position only when the initial position of the motor is in the interval $\left(0, \frac{\pi}{2}\right)$ or $\left(\frac{3\pi}{2}, 2\pi\right)$ at the special time 0, and the estimated value may be equal to the actual value, and may differ by π from the actual value when the initial position of the motor is in other states. Therefore, after the completion of the initial position estimation, it is necessary to judge the direction of the magnetic poles to accurately find the initial position of the rotor.

3.5. Judgment of magnetic pole

We must find a way to determine the actual position of the rotor as there may be an error of 180 degrees between the initial position of the electronic rotor and the actual rotor position detected by the above method. The saturation effect of magnetic circuit affects the equivalent inductance of D-axis when the brushless DC motor is static, and the model can be equivalent to RL series circuit. The saturation effect of magnetic circuit can affect the time constant of RL circuit, therefore, the magnetic pole of the brushless DC motor can be determined by the different time when the zero-input response current of the RL circuit decays [7].

According to the $\Psi - i$ characteristic curve of the DC magnetic circuit of the brushless DC motor, the equivalent inductance L_d^+ when the direct axis of the motor is connected to the forward current is smaller than the equivalent current L_d^- when the direct axis is connected to the reverse current. The voltage pulse of equal amplitude is injected into $\hat{d}$ axis at the estimated initial position, and the positive direction of the direct axis of the rotor is determined by comparing the time of response current attenuation from the steady state to the zero state. Due to $L_d^+ < L_d^-$,then the time constant $\tau^+ < \tau^-$, when $t^+ < t^-$,the estimated angular position is at $\hat{\theta} + \pi$,when $t^+ > t^-$,the estimated angular position is $\hat{\theta}$,thus, the actual position of the motor rotor is determined, as shown in Fig. 4.

In conclusion, the initial position estimation of the brushless DC motor is realized by pulse high-frequency voltage injection method, which is divided into two steps: initial position estimation and pole direction judgment, and the speed change and current loop are added to realize the zero low speed control of the brushless DC motor after the accurate initial rotor position is obtained. The zero low speed control block diagram of pulse vibration high frequency voltage injection method is shown in Fig. 5.The control scheme consists of the following modules: speed and current regulator module, rotor speed and position estimation module (sensorless algorithm estimation and position sensor estimation), park transform module, anti Park transform module, Clark transform module, SVPWM generation module, etc.The phase current i_a,i_b can be obtained by current sensor or resistance sampling,and i_a and i_b are transformed into two-phase static coordinate system component i_α and i_β.The rotor position

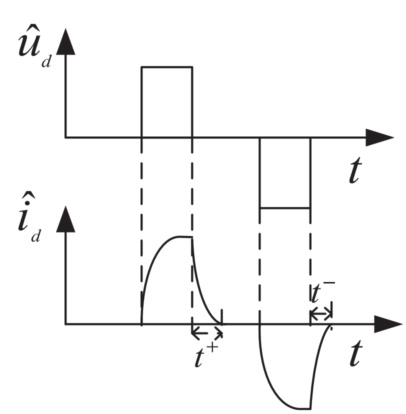


Fig. 4 Schematic diagram of magnetic pole judgment.

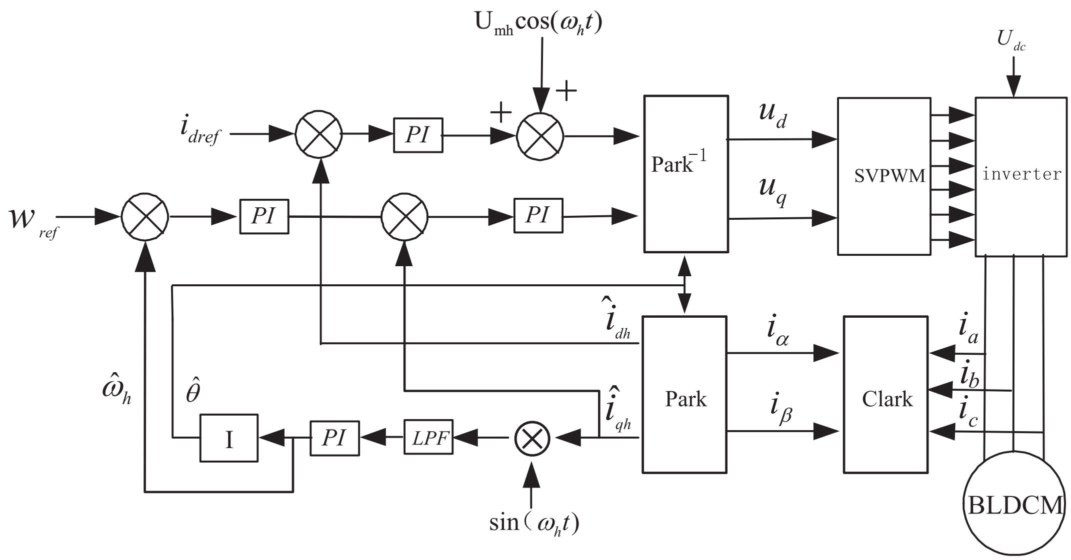


Fig. 5 BLDCM zero low speed control block diagram of pulse high frequency voltage injection method.

Table 1 the parameters of the brushless DC motor.

Rated voltage	Rated torque	Rated speed	Pole logarithm	Stator resistance	Stator inductance
48 V	0.18 N.M	3000r/min	5	1.75	2.56mH

angle and speed information are obtained through the rotor speed / position feedback module (sensorless algorithm estimation and position sensor estimation). i_α and i_β use the angle information $\theta(\theta^*)$ to convert into two-phase rotating coordinate system components i_d and i_q through park transformation. The rotor speed information $\omega(\omega^*)$ and speed reference information ω_{ref} are adjusted by PI to obtain the quadrature axis current reference iq_{ref}.The error between i_d, i_q and their reference values id_{ref} and iq_{ref} are controlled by current PI regulator to control torque and flux respectively. The regulator outputs the signal obtained by inverse Park transform to the space vector modulation module, and the output signal controls the motor to rotate at the set speed through the inverter.

4. Simulation analysis

In order to verify that the method can realize the rotor position monitoring of the brushless DC motor and the operation of the low-speed no-position sensor, the major parameters of brushless DC motor showing in Table 1 are selected for simulation analysis.

The actual rotor position θ, namely 1 rad, 3 rad is selected for the simulation of the rotor position at zero speed. The actual rotor position $\theta = 1$rad is selected while a positive selected voltage signal with the amplitude of 15 V and a frequency of 1KHZ is injected into $\hat{i}_d$. The positive and negative pulse with the amplitude of 10 V is injected at 0.2 s, while the pulse interval is 0.03 s and the action time is 0.01 s, as shown in Fig. 6(a). After the positive pulse has finished acting, the time for $\hat{i}_{dh}$ to decay from the steady state to zero state is 0.0086 s; when the negative pulse is acting, the time for $\hat{i}_{dh}$ to decay from the steady state to zero state is 0.0061 s, as shown in Fig. 6(b), $t^+ > t^-$ can judge that $f(\Delta\theta) = 0$, and the estimated position is equal to the actual position, as shown in Fig. 6(c). The actual rotor position $\theta =$ 3rad is selected, while it can be found from the injection of same sine signal and positive and negative pulse signals that the time for $\hat{i}_{dh}$ to decay from the steady state to zero state is 0.0055 s, when the negative pulse is acting, the time for $\hat{i}_{dh}$ to decay from the steady state to zero state is 0.0076 s, which can be derived from Fig. 7(a) for $t^+ < t^-$, and the estimated position angle is $\hat{\theta} + \pi$, which can be seen from Fig. 7(b) that after 0.0253 s, the estimated position is equal to the actual position.

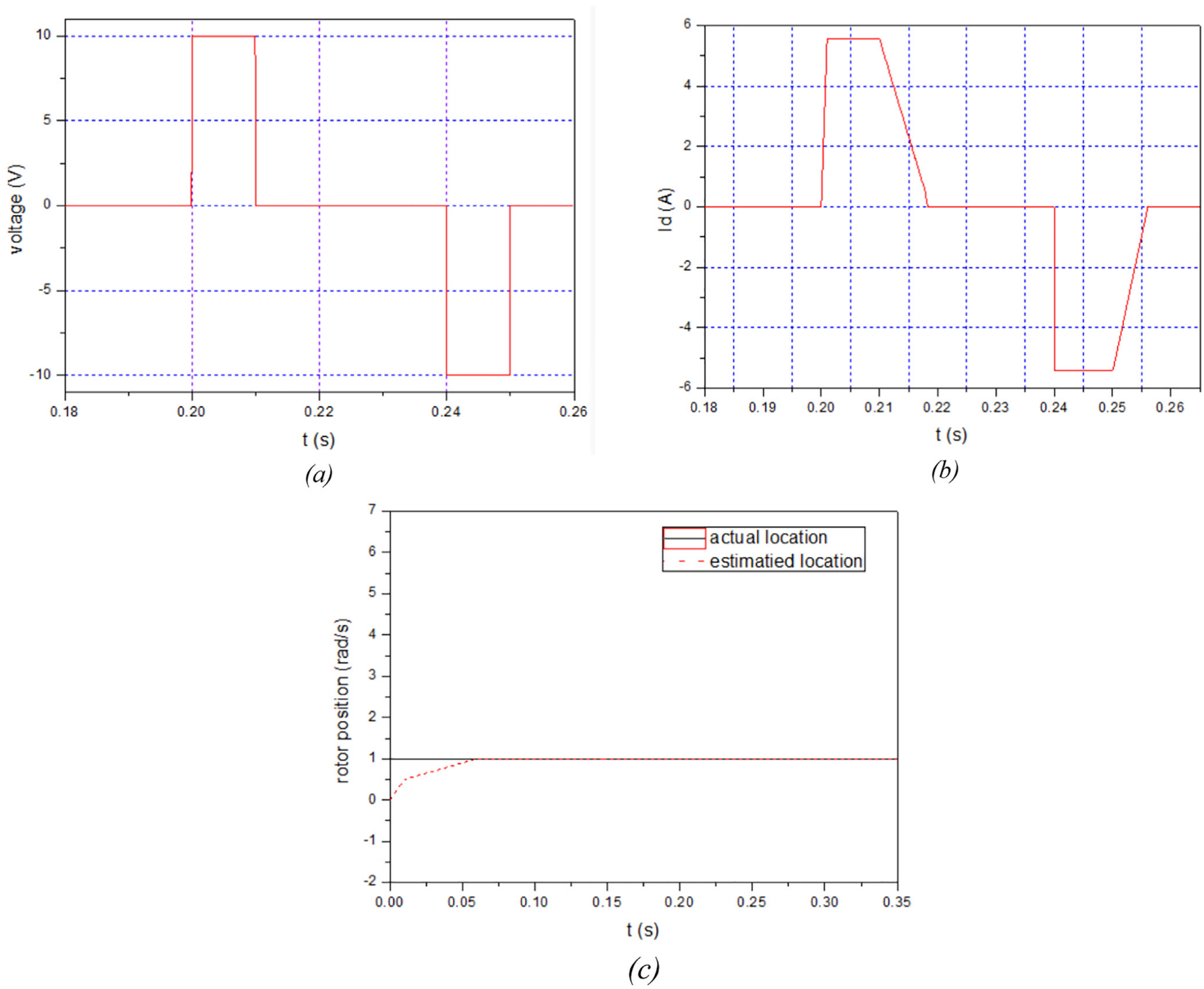


Fig. 6 $\theta = 1rad$ Rotor position estimation.

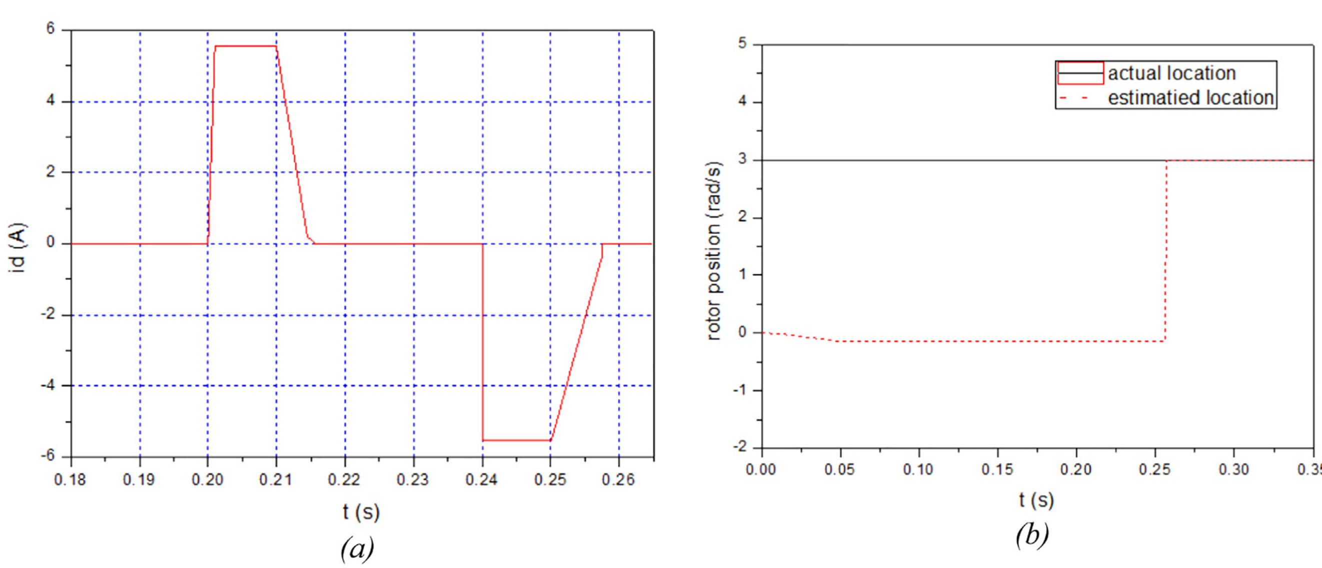


Fig. 7 $\theta = 3rad$ Rotor position estimation.

5. Conclusion

In order to solve the problem that the rotor position cannot be accurately judged due to the weak convex polarity of brushless DC motor, this paper adopts the method of pulsating high frequency voltage injection to produce saturated convex polarity in countless DC motors, extracts the motor rotor pole position information from the cross-axis current response and obtains the actual rotor position, so as to verify the correctness and feasibility of the method through simulation experiments.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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