Research on Sensorless Fuzzy PID Control of BDCM based on Improved State Observer

Hanghang Qu[1, a], Jie Zeng[1, b], Ran Sheng[1] and Yongwei Guo[1]
[1]School of Electrical Information, Dalian Jiaotong University, Dalian, Liaoning , People's Republic of China

Keywords: BLDCM, state observer, line back-EMF, fuzzy PID.

Abstract: Relative to traditional methods of back-EMF zero crossing points (ZCPs) delay detect, a new method to detect the rotor position of BLDCM is proposed by constructing a state observer to estimate line back-EMF based on line voltage and line current in this paper.And improve the observer, the linear error function is added to the original nonlinear error feedback coefficient of the observer. The combination of the two functions helps accelerate the convergence of the observer and improve the stability of the observer.In order to make its rotate speed more stable, the fuzzy PID is used to replace the traditional PID for the outer ring of the rotate speed.Finally, the simulation results show that this method can accurately estimate the position information of the rotor. With the help of the fuzzy PID control method, the precise control of BLDCM can be realized in a wide speed range.

1 INTRODUCTION

Compared with DC motor, BLDCM is widely used in various fields due to its strong anti-interference ability, high operating efficiency and excellent speed control performance. The traditional control method of BLDCM usually uses position sensor to collect rotor position information to controll commutation.However, the increase of position sensor makes the internal circuit connection of the whole system more complex, the anti-interference becomes worse and the size of the whole system is increased. Moreover, in some special working environments with high temperature and humidity, the precision and reliability of sensors are required to be higher, which additionally increases the difficulty of sensor technology. Therefore, sensorless control technology of BLDCM has become an important research direction.

The first problem to be solved by sensorless control is rotor position detection. A method to obtain rotor position by back-EMF Integration and phase compensation is described in (Shengjin L.et al., 2008), but this method needs to obtain the phase offset angle of the back-EMF detection circuit at different rotational speeds, which requires high hardware memory; In (Umesh Kumar S.et al, 2017), Umesh Kumar proposed a new position-free sensor six-switch variable structure input permanent magnet brushless DC motor back EMF zero differential detection scheme. This technique is based on the comparison of the back electromotive force and the detection of points crossing each other in the back electromotive force waveform to obtain a commutation point; In (Shuai Y.et al., 2016), the back-EMF is calculated by calculating the back electromotive force by the sampling line voltage, which is easy to implement in hardware, and the software operation is simple, and the control CPU consumption is low; In (Tae-Sung K.et al., 2006), a state observer is used to detect the back-EMF of a brushless DC motor to estimate the rotor position, and the control effect is good.

Observer gain is a key factor affecting the fast convergence and stability of the observer. Inspired by literature (Shuai Y.et al., 2016; Tae-Sung K.et al., 2006; Chang cheng Y, 2017), based on the relationship between the line back-EMF and the commutation point, this paper constructs the line back-EMF state observer to estimate the rotor position information online and added a linear error function, accelerates the convergence of the observer and improves the stability of the observer. In order to further make the motor speed more stable, fuzzy PID is used to correct the speed. The simulation results shows that the method can accurately predict the rotor position to achieve the purpose of sensorless control and

Qu, H., Zeng, J., Sheng, R. and Guo, Y.
Research on Sensorless Fuzzy PID Control of BDCM based on Improved State Observer.
DOI: 10.5220/0008868704160420
In *Proceedings of 5th International Conference on Vehicle, Mechanical and Electrical Engineering (ICVMEE 2019)*, pages 416-420
ISBN: 978-989-758-412-1

achieve fast response and smooth operation of the motor.

2 MATHEMATICAL MODEL OF BLDC MOTOR

The control circuit topology of BLDC motor is shown in figure 1. Three-phase winding of motor is star connected. To facilitate the analysis, we assume that the three-phase winding of BLDCM are symmetrically distributed, the internal hysteresis losses and eddy current losses are neglected, and the power switches are ideal switches. Then the stator winding voltage equation of BLDC motor can be expressed as:

$$\begin{bmatrix} u_a \\ u_b \\ u_c \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} L & M & M \\ M & L & M \\ M & M & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \tag{1}$$

Where, ua, ub and uc are the three-phase stator winding terminal voltage, ia , ib and ic are the currents of phase winding, ea, eb and ec are back-EMF of each phase winding, R is resistance of each phase winding, L is self-inductance of each phase winding, M is mutual inductance of each phase winding.

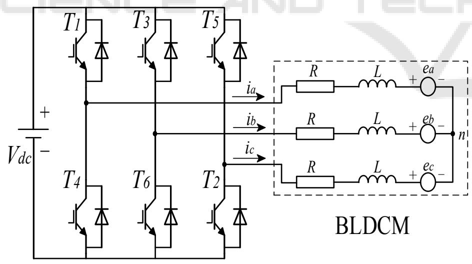

Figure 1. The control circuit topology of BLDC motor.

The motor is in normal operation, the electromagnetic power of the motor is the sum of three-phase winding electromagnetic power, ignoring the mechanical and other losses of the motor itself, the electromagnetic power will be transformed into the rotating mechanical power, expressed as:

$$P_e = e_a i_a + e_a i_a + e_a i_a = T_e \cdot \omega_m \tag{2}$$

Where, Te is the electromagnetic torque and ωm is the mechanical angular velocity.

3 ROTOR POSITION ESTIMATE BASED ON LINE BACK-EMF

3.1 Improved State Observer based on Line Back-EMF

Because the mutual inductance between three-phase windings is very small, it can be neglected (Surya Susan A&Asha Elizabeth D, 2019).By subtracting formula (1), the line current, line voltage and line-back-EMF equations (3) can be obtained.

$$\begin{bmatrix} u_{ab} \\ u_{bc} \\ u_{ca} \end{bmatrix} = \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} + \begin{bmatrix} L & 0 & 0 \\ 0 & L & 0 \\ 0 & 0 & L \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} + \begin{bmatrix} e_{ab} \\ e_{bc} \\ e_{ca} \end{bmatrix} \tag{3}$$

As can be seen from the above formula, except that the back-EMF is unknown, all other variables can be measured, so the above formula is rewritten to the equation about current (4).

$$\begin{bmatrix} \hat{i}_{ab} \\ \hat{i}_{bc} \\ \hat{i}_{ca} \end{bmatrix} = -\frac{1}{L} \begin{bmatrix} R & 0 & 0 \\ 0 & R & 0 \\ 0 & 0 & R \end{bmatrix} \begin{bmatrix} i_{ab} \\ i_{bc} \\ i_{ca} \end{bmatrix} + \frac{1}{L} \begin{bmatrix} u_{ab} \\ u_{bc} \\ u_{ca} \end{bmatrix} - \frac{1}{L} \begin{bmatrix} e_{ab} \\ e_{bc} \\ e_{ca} \end{bmatrix} \tag{4}$$

Where, $\hat{i}_{ab} = \frac{di_{ab}}{dt} = \hat{i}_a - \hat{i}_b$, uab, iab as the known variable,can all be measured in practice.eab as an unknown variable,iab and uab can be used to construct the eab's equation of state for observation.

In order to make the system get faster convergence speed and improve the stability of the estimator, a linear error function Sgmf (x) is added based on equation (5).

$$\begin{bmatrix} \hat{i}_{ab} \\ \hat{e}_{ab} \end{bmatrix} = \begin{bmatrix} -\frac{R}{L} & -\frac{1}{L} \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \hat{i}_{ab} \\ \hat{e}_{ab} \end{bmatrix} + \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix} u_{ab} + \begin{bmatrix} k_1 \\ k_2 \end{bmatrix} \begin{bmatrix} (i-\hat{i})\ Sgmf\,(i-\hat{i}) \\ (i-\hat{i})\ Sgmf\,(i-\hat{i}) \end{bmatrix} \tag{5}$$

Where, k1 and k2 are the nonlinear error feedback gains of the observer, which can be obtained by pole configuration;and "Sgmf" represents a linear error function, denoted Sgmf(x)=1/1+e-cx, where c is a tunable parameter (Surya Susan A&Asha Elizabeth D, 2019).

The improved observer differs from the traditional observer in that it consists of a linear error function term and a nonlinear error term characterized by gains k1 and k2. Linear error function help accelerate the observer error to zero and the nonlinear error term weakens the fluctuation of the estimated state quantity, which ensures the robustness of the observer. The gain value is calculated offline based on different speed and load torque conditions and stored in a table from which the gain value is selected based on operating conditions.

Subtracting primitive state equation of current from equation (5) to obtain,

$$\begin{cases} i_{ab} - \hat{i}_{ab} = -\frac{R}{L}(i_{ab} - \hat{i}_{ab}) - \frac{1}{L}(e_{ab} - \hat{e}_{ab}) - k_1[(i_{ab} - \hat{i}_{ab}) + sgmf(i_{ab} - \hat{i}_{ab})] \\ e_{ab} - \hat{e}_{ab} = -k_2[(i_{ab} - \hat{i}_{ab}) + sgmf(i_{ab} - \hat{i}_{ab})] \end{cases} \quad (6)$$

According to the synovial control theory, $S = i - \hat{i} = 0$ is defined as the synovial surface. To prove the stability of the observer in the above theory, the Lyapunov stability function is defined as $V = \sum (i - \hat{i})^2 / 2$ .The condition for stability is $\dot{V} \le 0$ for V>0.The calculation shows, the estimation error is made to converge faster with the proper choice of the observer gains satisfying the conditions k1>0 and k2/k1<0 (Surya Susan A&Asha Elizabeth D, 2019).

3.2 Estimation of Motor Rotor Position

The ideal back-EMF of brushless DC motor distributes in a trapezoidal shape with 120 degrees flat top width. Above, the relationship between line voltage, line current and line back-EMF is deduced, and the state equation is constructed to calculate line back-EMF. The relationship between line back-EMF and back-EM is given below, as shown in Figure 2.

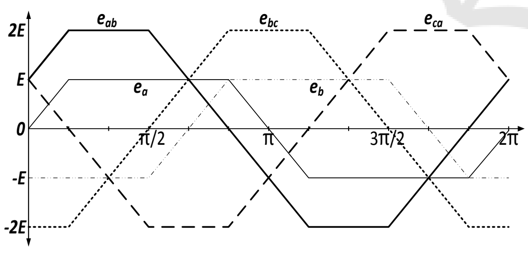

Figure 2. The relationship between the line back-EMF and the back-EMF.

Taking ea as an example, when ea is at π/ 6, ea value is the largest and electromagnetic torque is the largest, which is the commutation point.As can be seen from figure 3 above, when ea is at π/6, the line back-EMF eca = 0, so it can be concluded that the zero crossing point of line back-EMF is the best commutation point for brushless DC motor rotor. Similarly, eb and ec are similar. The method can effectively avoid the error caused by the traditional method delay of 30 degrees. At the same time, the line back-EMF is estimated by line voltage and line current, it is also applicable in the case of low speed motor. According to the previous formula (6), Take eab as an example, the design of line back-EMF state observer in the Simulink model is shown in figure 4.

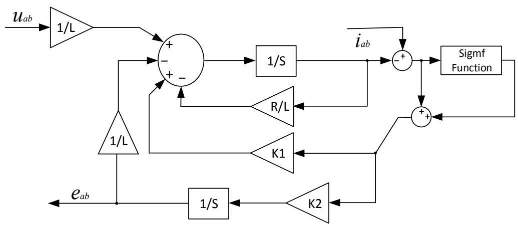

Figure 3. The relationship between the line back-EMF and the back-EMF.

When the motor works normally, the line back-EMF is proportional to the constant of back-EMF and the speed of motor (Tang L, 2014). At any time, the maximum of the line-back-EMF is twice the maximum of the back-EMF.

$$\hat{\omega}_e = E_{\max} / 2k_e = \hat{\omega}_m \cdot p \quad (7)$$

Where, Emax is the maximum value estimated from line back-EMF, ke is the constant of back-EMF. $\hat{\omega}_e$ is estimated value of electric angular velocity of motor. p is the polar logarithm of the motor.

The position information of the motor's rotor is the integral of its electric angle, which is expressed as follows.

$$\hat{\theta} = \int \hat{\omega}_e dt + \theta_0 \quad (8)$$

θ0 is the initial angle of the rotor of the motor, which is usually taken as 0.The rotor position information is obtained according to the estimated value of the line back-EMF, and then the commutation signal is got to drive the three-phase full-bridge switch tube, and the position sensorless control of the brushless DC motor is realized.

4 DESIGN OF FUZZY PID CONTROLLER

In order to ensure the smooth operation of motor speed and achieve accurate speed control. In this paper, the parameters of conventional PID controller are intelligently adjusted by using velocity deviation e and deviation change rate ec as input of the controller.Figure 4 illustrates the block diagram of an fuzzy PID controller.

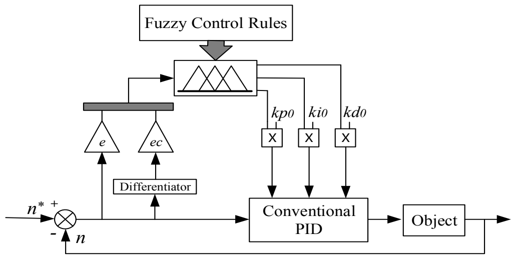

Figure 4. The block diagram of an adaptive fuzzy PID controller.

5 DESIGN OF FUZZY PID CONTROLLER

According to the previous analysis, in order to verify the effectiveness of the algorithm, a simulation platform for sensorless control of BLDCM is built by using MATLAB/Simulink, as shown in figure 5.

c

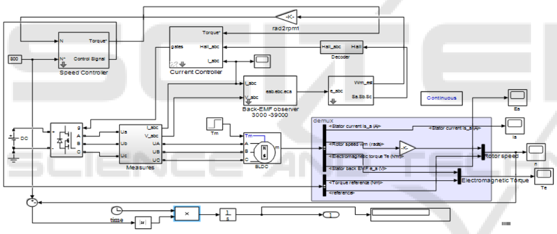

Figure 5. Sensorless Control Model of Brushless DC Motor.

The parameters of the motor are set as follows: V=300Vdc, stator resistance Rs=0.2, stator inductance Ls=8.5e-3H, moment of inertia J=0.089kg/m2, Back-EMF coefficient ke=0.175V/rad/s, pole logarithm p=4, Observer gain k1, k2 and linear error function coefficient c select the best value.

The motor is accelerated with a speed reference of 300 rpm and give a full load torque at 0.5 s. Figure 6 is a waveform diagram of the line back-EMF and back-EMF. By comparison, the estimated line back-EMF of the design used in this design is indeed twice the back-EMF measured on the motor side, which is consistent withthe previous analysis, which proves the correctness of the design method.

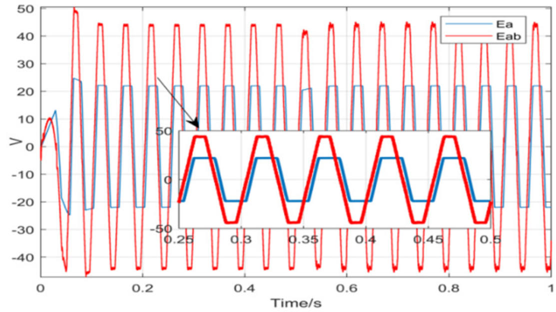

Figure 6. Waveform comparison of line back-EMF and back-EMF.

Figure 7 illustrates that the estimated speed follows closely with the actual speed.This establishes the effectiveness of the observer with optimal gain values. Figure 8 shows the error value of the speed estimation. When the speed is low, the initial load is half load start, the error is less than 1.5rpm, and the load is fully loaded at 0.5 seconds, and the error value is less than 2.5rpm.

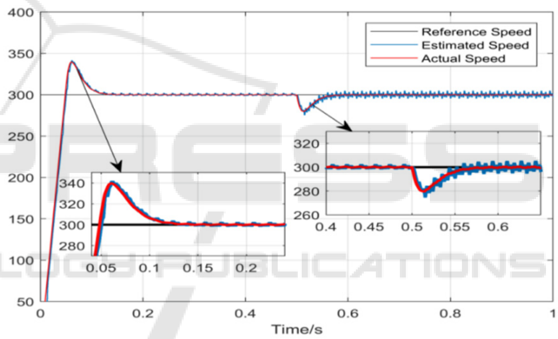

Figure 7. Estimated and actual rotor speed.

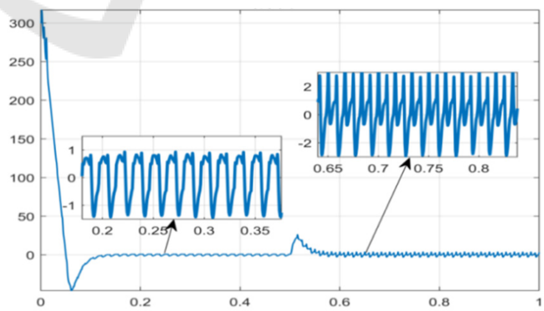

Figure 8. The speed estimation error value.

In order to achieve precise control of speed, eliminate overshoot, add fuzzy controller to the improved observer control system. The simulation results are shown in Figure 10 and Figure 11.

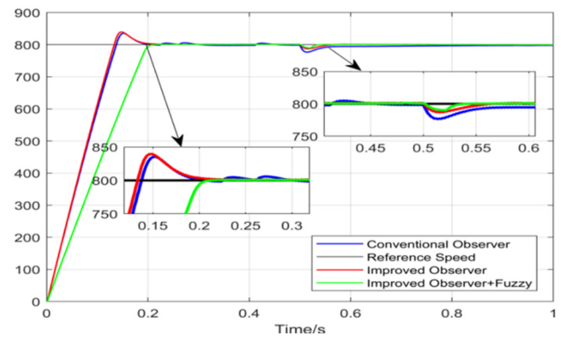

Figure 9. Contrast of Speed of different loads under Conventional Observer, Improved Observer and added fuzzy controller.

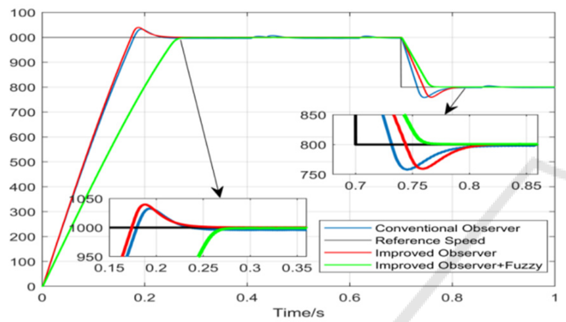

Figure 10. Contrast of Different Speed Motor under Conventional Observer, Improved Observer and after adding Fuzzy Controller.

Figure 9 shows the results of the sudden load test. It can be seen from the figure that before the fuzzy controller is added, the conventional observer and the improved observer have overshoot in the startup process. But it is seen from the simulation results that the rotational speed waveform of the traditional back-EMF observer is unstable at the later stage. The load is suddenly increased at 0.5 seconds, the traditional observer speed drop value is larger than the improved observer. After adding the fuzzy controller, the speed overshoot disappears. Figure 10 shows the response of different control systems to different speeds.

6 CONCLUSION

Aiming at the defects of traditional sensorless control based on back EMF, this paper proposes a state observer based on line voltage and line current, and improves the observer, adding a linear error function to accelerate the convergence of the observer and improve the observer stability. The simulation experiments show that the method is effective and has a certain promotion effect on the operation of brushless DC motor in special environment, which is of great significance.

ACKNOWLEDGMENT

The paper has been funded by Science Projection of Liaoning Province Education Bureau (JDL2017039 &JDL2017040).

REFERENCES

Changcheng Y. 2017. Design of Sensorless Brushless DC Motor Control System, Hefei Polytechnic University, HeFei, China.

Shengjin L.et al., 2008. BLDCM control based on integral compensation of back EMF. Micro-Special Motor, (6), p.36-39.

Shuai Y.et al., 2016. A New Method for Determining Rotor Position of Brushless DC Motor by Line Voltage. Micro-Special Motor, (44), p. 37-40.

Surya Susan A&Asha Elizabeth D., 2019. Optimal Gain Selection Strategy in Back EMF Observer for Position Sensorless Operation of BLDC Motors. Arabian Journal for Science and Engineering.

Tae-Sung K.et al., 2006. Unknown Input Observer for a Novel Sensorless Drive of Brushless DC Motors,Twenty-First Annual IEEE Applied Power Electronics Conference and Exposition, p.679-684.

Tang L., 2014. Research and Implementation of Sensorless Brushless DC Motor Control System, Hunan University, Changsha, China.

Umesh Kumar S.et al., 2017. Novel Back-EMF Zero Difference Point Detection Based Sensorless Technique for BLDC Motor, IEEE International Conference on Industrial Technology (ICIT), p.330-335.