Design of sensorless high speed BLDCM controller for molecular pump

Qiang Li1*, Xiaojing Huang1, Jian Li1, Guangmin Liu1 and Jizhong Tao1

1Institute of Machinery Manufacturing Technology, China Academy of Engineering Physics, Chengdu, Sichuan, 610200, China
*liq6286@yinhe596.cn

Abstract. The brushless direct current motor (BLDCM) of the molecular pump needs to run at high speed for a long time, which puts forward the requirements of high reliability, high speed range and so on. The traditional sensor methods of using hall sensors for BLDCM commutation will reduce the reliability of the system and increase costs. Therefore, sensorless control methods are widely used in the field of molecular pumps. In this paper, a sensorless BLDCM control system of the molecular pump is designed, and the back-EMF zero crossing detection method is used to obtain the motor position information. Based on this method, the hardware and software of the control system are designed. Driven by the controller, the molecular pump speed can reach 90000rpm, and its steady speed fluctuation is ± 60rpm.

1. Introduction

In the motor control industry, there is an increasing trend to move towards using BLDCM [1-2]. BLDCM usually require Hall sensors to measure rotor position in order to select the appropriate commutation time [3-4]. In the application of molecular pumps, due to cost sensitivity and space constraints, sensorless commutation solutions are required [5-6].

The traditional sensors were Hall sensors mounted in the machine. This requires more complex machine construction and can reduce the reliability of the overall system [7-8]. Sensorless commutation solutions usually estimate rotor position through physical parameters such as winding voltage, current and back-EMF. Extended Kalman filtering [9-10] and back-EMF zero crossing detection [11-12] are common sensorless control approach for BLDCM. The back EMF zero crossing detection method is adopted in this paper.

In this paper, the control system of high speed BLDCM, which is the core unit of molecular pump, is studied. Following the introduction, Section 2 describes the back EMF characteristics of BLDCM. Then, the hardware design and software design of the control system are introduced in section 3 and 4. Experimental results are presented in section 5. Finally, section 6 presents the conclusion of this paper.

2. Back-EMF characteristics of brushless DC motors

Consider the BLDCM as shown in figure1. When driven as a trapezoidal motor only two of the windings are active at any one time, and the inactive winding is used to measure the back-EMF [13]. Each 60 electrical degrees the motor windings are commutated in accordance with the sequences indicated by figure 1. In the curve shown in figure 1, the two lines represent the phase current and the back-EMF, respectively.
Consider the steady state condition for an electrical position from 30 degrees to 90 degrees. In this sequence, the ‘Q1’ high side MOSFET is modulated and the ‘Q6’ low side MOSFET is switched on. The current flows into the BLDCM from ‘a’ and flows out from ‘b’, and the A-phase winding and B-phase winding are active. Assuming that the rotor is spinning, a back-EMF voltage will be induced in each of the windings as shown. When the electrical position is 60 degrees, the back-EMF of C-phase winding crosses zero potential. There is 30 degrees offset between the back-EMF zero crossing point and commutation point, therefore, after the back-EMF zero crossing event is detected, the motor commutates after 30 electrical degrees time.

The actual stator winding neutral point of the BLDCM is called ‘n’, as shown in figure 1. Taking C-phase as an example, when C-phase winding is inactive, we can have:

\[ E_c = U_c - U_n \]  

where \( E_c \) is the back-EMF of phase C, \( U_c \) is the voltage between ‘c’ and ground, \( U_n \) is the voltage between ‘n’ and ground.

However, it is difficult to connect the actual neutral point out of the motor in practice[14], which makes \( U_n \) cannot be measured directly. In order to obtain back-EMF, in this paper, three resistors with equal resistance are used to form a star network. The midpoint of the star network is a virtual neutral point called ‘m’. We can get

\[ E_c = U_c - U_m \]  

where \( U_m \) means voltage between point ‘m’ and ground. By measuring the voltage difference between the virtual neutral point and the winding, the zero crossing information of back-EMF can be obtained by judging the change of the voltage difference symbol.

3. Hardware design

Figure 2 shows the block diagram of the system for speed and rotor position estimation of a BLDCM. The system can be functionally divided in two basic parts: the control module and the back-EMF zero crossing detection module. The control module consists of drive circuit (inverter and BLDCM) and control circuits which perform two functions: speed control and commutation logic. The function of the second part is mainly to obtain the back-EMF zero crossing information as rotor position and speed feedback signals.
3.1. Design of control module
The chip selected for the control module is dsPIC30F2010, which is a 16-bit high performance signal controller dedicated to motor control. The full bridge three-phase drive circuit is selected in the inverter circuit. In the inverter circuit, the upper-side MOSFET uses PWM modulation, and the lower-side MOSFET is constant-pass(H-PWM-L-ON mode). The BLDCM cannot be driven directly due to the low PWM signal voltage of the dsPIC30F2010 output. Hence, a driving circuit is designed to amplify the PWM signal transmitted by the microcontroller in this paper. The driving circuit designed is mainly composed of integrated driving chip IR2103. In addition, a bootstrap floating power supply can be provided by setting up a bootstrap circuit around the IR2103. In this way, only one power supply is needed to power three IR2103 to drive six MOSFETs, thus greatly simplifying the drive circuit and saving power supply. Schematic diagram of control module is shown in figure 3.

3.2. Design of back-EMF zero crossing detection module
In H-PWM-L-ON mode, we can have the equation:

\[ U_n = U_3 - \left( e_x + e_y \right) / 2 + U_d \left( 1 - PWM \right) / 2 \]  

(3)

As a coefficient term, the PWM modulation signal affects the voltage detection of the neutral point, which has a great influence on back-EMF zero crossing detection. For example, PWM noises trigger
the wrong zero crossing signal, causing the motor commutates at the wrong time. In order to reduce the interference of PWM to back EMF, a low-pass RC filter circuit module is designed in this paper, as shown in figure 4. In this RC filter circuit, we can obtain the phase delay formula:

\[
U_a / U_d = R_d / (R_i + R_d + j2\pi fC / (R_i R_d))
\]

\[
a = \arctan[2 \pi fC / (R_i R_d)]
\]

(4)

Figure 4. Principle of back-EMF zero crossing detection circuit.

where \(a\) is the phase delay caused by the RC filter circuit. It can be seen from equation (4) that the phase delay is affected by the frequency of rotor. Therefore, it is necessary to divide 0-90,000rpm into multiple speed intervals, and make appropriate phase delay compensation for each interval. In a large number of experiments, it has been proved that the RC circuit can filter the interference of PWM effectively.

A voltage comparison circuit is used to obtain back-EMF zero crossing information in this paper. The two inputs of the voltage comparator are the three-phase terminal voltage and the voltage of the virtual neutral point. When the voltage at the same phase end is greater than the voltage at the reverse end, the comparator outputs high potential, and vice versa zero potential. The outputs of the comparator enter the optocoupler, and the outputs SA, SB and SC of the optocoupler enter the controller.

3.3. Phase delay in circuit

In the ideal case, commutation logic starts after 30 degrees electrical time of zero-cross event. The timer of dsPIC30F2010 can be used to measure the time from one zero crossing event to the next, which equivalents to 60 electrical degrees. Assuming there is no phase delay when a back-EMF zero crossing event is detected, the next commutation should occur in 30 degrees. Half of the timer capture value is the time of 30 electrical degrees. Theoretically, this value can be loaded into the period register for another timer, called as the commutation timer. When the interrupt for the commutation timer occurs, it is time for the motor windings commutate to the next state.

However, several sources of phase delay must be subtracted from the 30 degrees electrical time, as shown in equation (5). The first one is the phase delay of the RC filter circuit, which is related to the motor speed. The second is the delay of components such as optocouplers, which takes about 60us.
The last one is the controller interrupt processing delay, which takes about 1.7us. Each of these delays must be subtracted from the 30 degrees electrical time before it is loaded in the commutation logic.

\[ PR = T_{30} - D_{\text{FILTER}} - D_{\text{COMPONENT}} - D_{\text{PROCESS}} \]  

where \( PR \) is the value of period register, \( T_{30} \) is the value computed for 30 electrical degrees, \( D_{\text{FILTER}} \) is the value of RC filter phase delay, \( D_{\text{COMPONENT}} \) is the phase delay caused by components, and \( D_{\text{PROCESS}} \) is the interrupt processing delay.

4. Software design

4.1. Software system framework

The software system mainly includes three parts: initial, interrupt and subprogram. The main function of initial part is to complete the initialization of the control system. After initializing, the program enters the main loop, starts to call the subprogram and waits for the interruption. The interrupt part completes important functions such as the commutation logic and PWM interrupt. Subprogram part is mainly used to implement the logic control of the motor.

4.2. Starting sequence

In order to reach the rated speed, the following starting sequence is designed in subprogram part.

- Pre-positioning: the initial position of the rotor is unknown due to the lack of a position sensor. Therefore, by setting an initial duty cycle of PWM, and activating the two-phase windings of the BLDCM, the rotor can be fixed to the target position.
- Open-loop: it is difficult to detect the back-EMF at low rotor speed, therefore, the molecular pump needs to be started in open-loop. The initial voltage and step size of the acceleration can be set by setting PWM duty cycle and value of commutation timer. The open-loop starting process forces the motor to raise speed. As the rotor speed gets faster, the back EMF can be detected gradually.
- Closed-loop: when the speed is increased to 5000 RPM by open-loop, the program can detect back-EMF zero crossing information multiple times, which means there is a speed feedback. Then, the closed-loop control of the motor can be realized through the PID controller. During this period, in order to protect the motor and controller, the winding will be temporarily shut down for a while when the current is large, and then the speed will be raised again after adjusting the control parameters.

5. Experiments results

This paper implements the circuit principle on a PCB circuit board, and a series of experiments are carried out to test the performance of the control system. Figure 5 shows the molecular pump and its controller. The controller’s hardware consists of two PCB boards. The large-sized PCB implements the driving function, and the other implements the back-EMF zero crossing detection. The molecular pump will speed up to 90000 rpm in the order of pre-positioning, open loop and closed loop.

Figure 5. The molecular pump and control system.
Figure 6 shows the speed curve of the molecular pump. It can be seen that the speed reached 90000rpm within 88 seconds, and then maintained the error of ±60RPM. As expected, the molecular pump was accelerated to 5000rpm during the open-loop period. The acceleration of the motor increases during a short period of time from the open loop to the closed loop. When the speed is about 14000rpm, the controller detected an excessive current in the winding, and the motor stopped briefly and then began to speed up again. During the closed loop, the measured speed of the motor changes abruptly sometimes, and it has been confirmed through a large number of experiments that this is related to the vibration of the molecular pump. If the vibration state becomes worse, the back-EMF zero crossing detection approach will be difficult to detect the real speed of the motor.

Figure 6. Experimental results.

In order to evaluate the performance of the designed control system, two methods are used to measure motor speed: oscilloscope and vibration monitoring system. The output waveforms of the three optocouplers are shown in figure 7. The three waveforms from top to bottom are SA, SB and SC, respectively. The speed displayed by the control system is maintained at 90000±60RPM, and the frequency of feedback signal analyzed by oscilloscope is 1500±1Hz. It can be seen from the waveform diagram that there is no wrong back EMF zero-cross event. At the same time, the radial and axial vibration of molecular pump is monitored by vibration monitoring system. The results show that the vibration value is 1500±1Hz.

Figure 7. The waveform of SA, SB and SC.
6. Conclusion
This paper introduces the design of a sensorless high speed BLDCM controller for molecular pump. The controller is designed using the method of back-EMF zero crossing approach. Driven by the designed control system, the molecular pump accelerates to 9000rpm in 88 seconds, and the speed error of steady state is ±60rpm. At the same time, the experimental results show that the influence of vibration on the back-EMF zero crossing point needs to be optimized during the acceleration process.

References
[1] Gao, Yuanlou , and Y. Liu . "Research of sensorless controller of BLDC motor. " IEEE International Conference on Industrial Informatics IEEE, 2012.
[2] Firmansyah, Eka , P. Rendy, A. M. Imaduddin, and N. Yuliyanto . "Low cost platform for BLDC controller." 2013 Joint International Conference on Rural Information & Communication Technology and Electric-Vehicle Technology (rICT & ICeV-T) IEEE, 2013.
[3] Nama, Tako , A. K. Gogo , and P. Tripathy . "Application of a smart hall effect sensor system for 3-phase BLDC drives." 2017 IEEE International Symposium on Robotics and Intelligent Sensors (IRIS) IEEE, 2017.
[4] Hung, Chung Wen , J. H. Chen , and K. C. Huang . A correction circuit of Hall-sensor-signal-based speed measurement for BLDC motors. Springer-Verlag New York, Inc. 2012.
[5] Tae-Hyung Kim, and Mehrdad Ehsani. "Sensorless Control of the BLDC Motors From Near-Zero to High Speeds." IEEE Transactions on Power Electronics 19.6(2004):1635-1645.
[6] P. Damodharan, and K. Vasudevan. "Indirect Back-EMF Zero Crossing Detection for Sensorless BLDC Motor Operation." Power Electronics and Drives Systems, 2005. PEDS 2005. International Conference on IEEE, 2005.
[7] Li, Wenzhuo , et al. "Position Sensorless Control without Phase Shifter for High-speed BLDC Motors with Low Inductance and Nonideal Back EMF." IEEE Transactions on Power Electronics 31.2(2015):1-1.
[8] Fang, Jiancheng , H. Li , and B. Han . "Torque Ripple Reduction in BLDC Torque Motor With Nonideal Back EMF." IEEE Transactions on Power Electronics 27.11(2012):4630---4637.
[9] Bolognani, S. L. Tubiana, and M. Zigliotto. "Extended Kalman filter tuning in sensorless PMSM drives." 2003.
[10] Bolognani, S., Oboe, R., and Zigliotto, M. "Sensorless full-digital PMSM drive with EKF estimation of speed and rotor position." IEEE Trans Industrial Electronics 46.1:0-191.
[11] Rao, K. S. Rama , Nagadeven, and S. Taib . "Sensorless control of a BLDC motor with back EMF detection method using DSPIC." IEEE International Power & Energy Conference IEEE, 2009.
[12] Damodharan, P., and Vasudevan, Krishna. "Sensorless Brushless DC Motor Drive Based on the Zero-Crossing Detection of Back Electromotive Force (EMF) From the Line Voltage Difference." IEEE Transactions on Energy Conversion 25.3:661-668.
[13] Pindoriya, R. M. , Mishra, A. K. , Rajpurohit, B. S. , and Kumar, R. "Analysis of position and speed control of sensorless BLDC motor using zero crossing back-EMF technique." 2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES) IEEE, 2016.
[14] Chenjun Cui, Gang Liu, Kun Wang, and Xinda Song. "Sensorless Drive for High-Speed Brushless DC Motor Based on the Virtual Neutral Voltage." Power Electronics IEEE Transactions on 30.6:3275-3285.