I.J. Information Technology and Computer Science, **2011, 5, 51-58**
Published Online November 2011 in MECS (http://www.mecs-press.org/)
DOI: 10.5815/ijitcs.2011.05.07

Control System of Sensorless Brushless DC Motor Based on TMS320F240

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***Abstract*—A brushless DC(BLDC) motor with the characteristics of high speed and high power density has been more widely used in industrial area. The BLDC motor requires the position and speed sensors for control. However the position sensors are undesirable from standpoints of size, cost, maintenance and reliability. There are some different ways that can solve this problem, depending on the flux distribution. This paper describes a control system of sensorless BLDC motor. The back-EMF is adopted to detect the rotor position. The back-EMF is very small in the motor starting process, and it is difficult to obtain rotor position efficiently. A re-setting method of the rotor is proposed in the paper, and current closed loop is used for high-speed and safety in the motor starting process. A good speed and current double closed loops system is designed. The speed and current regulators are implemented by a digital signal processor(DSP). A simple algorithm is used to calculate motor speed indirectly by the software, which simplifies the system hardware structure. The hardware structure and software design of sensorless BLDC motor control system are described in details. The simulation and experimental results have shown the validity of the sensorless control system and the accuracy of the detective position signal obtained.**

***Index Terms*—sensorless, brushless DC motor, back-EMF, digital signal processor**

I. Introduction

Brushless DC(BLDC) motor has been applied to practice, because of its high efficiency and good controllability. Brushless DC motor is a new-style motor of mechanical and electrical integration, which requires an inverter and position sensors to perform electrical commutation instead of a DC motor with brushes and commutators. Usually, three Hall sensors are used as rotor position sensors for a Brushless DC motor. However, the rotor position sensors bring several disadvantages from the standpoint of total system cost, size and reliability. For this reason, it is desired to eliminate these sensors from the motor, i.e. sensorless control[1]. In recent years, sensorless BLDC motor has been studied. The rotor position signal of the motor is detected by motor voltages, currents, fundamental machine equations, algebraic manipulations, back-EMF, observers, etc[2-4]. Among the methods of rotor position estimation, the back-EMF estimation is one of the most typical approaches. However, the back-EMF is too small in the process of motor starting, and the commutation point is not easy to achieve. For the reason, the conventional sensorless drive needs a complicated starting procedure[4-6]. This paper proposes a rotor re-setting method which based on the rotor pre-setting method. Current closed loop is applied in the process of motor starting. The method makes the system fast and safely during the starting. The double closed loops control system is implemented by using a 400W, 300V, 10-pole sensorless BLDC motor. The control algorithm has been performed by software on a digital signal processor(DSP) (TMS320F240). The simulation and experimental results have shown accuracy of the detective position signal and validity of the proposed scheme of re-setting method in motor starting.

II. Zero-Crossing Of Back-EMF Detection Method

The zero-crossing of back-EMF detection method is used to obtain the rotor position signal. The method is one of the most popular schemes of rotor position detection. The brushless DC motor is usually supplied with a six-step discontinuous inverter, as shown in Fig. 1.

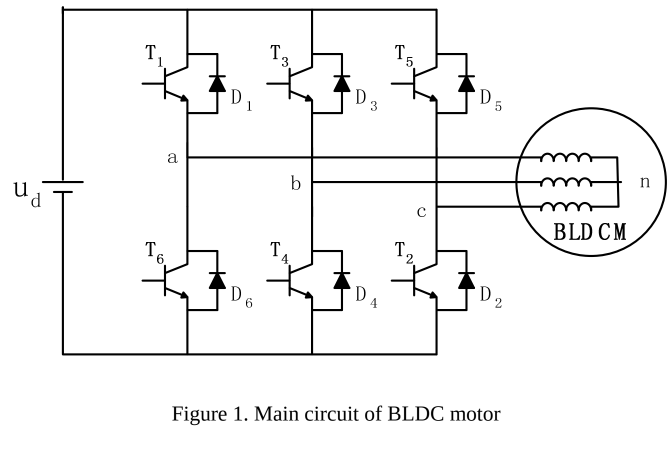


Figure 1. Main circuit of BLDC motor

The brushless DC motor has a trapezoidal flux density distribution in the air-gap, and thus the induced back-EMF in the stator windings is trapezoidal. Fig. 2 is ideal back-EMF and phase current waveforms of brushless DC motor which working in two phase power at any time with six-step commutation. Theoretically, the rotor's six key positions can be estimated by detecting the zero-crossings of the back-EMF. Switching instants of the converter can be obtained by knowing the zero-crossing of the back-EMF and a speed-dependent period of time delay.

As shown in Fig. 2 that the phase back-EMF waveform has a zero-crossing point every 60^o electrical angle in the process of open phase, which is located in the mid-point trapezoidal bevel. When motor rotates every cycle, each phase back-EMF has two zero-crossing points. By monitoring the phase back-EMF in the unexcited-phase, the zero-crossing of back-EMF delayed by 30^o is real commutation point, which completes the control of the inverter.

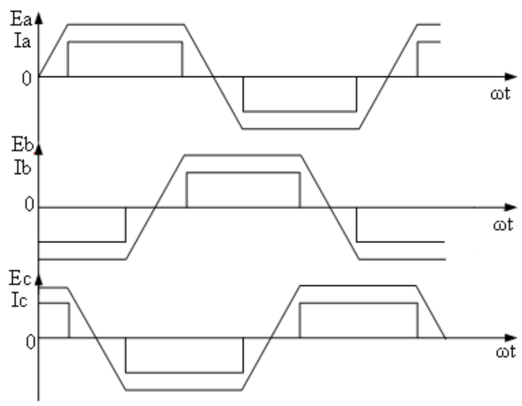


Figure 2. Ideal back-EMF and phase current waveforms of motor

III. STARTING METHOD

Since the amplitude of the back-EMF is proportional to the rotating speed, it is impossible to detect the back-EMF signal at a standstill or a lower speed. Normally the back-EMF is expired in the process of motor starting, and a proper starting procedure is necessary to the position sensorless brushless DC motor drive. A pre-setting method is that direct current is injected to two-phase pre-windings, which makes the rotor stability in composite magnetic force's axis location of the two-phase windings. The location is the initial rotor position, achieving the desired position. As shown in Fig. 3(a), switch phase A and phase B stator windings on, and disconnect phase C, which forces the rotor in the direction of Fa. Due to rotor position uncertainty, if the rotor is in the position as shown in Fig. 3(b), it will not rotate to the position as shown in Fig.3(a), and it is failure to locate. To solve this problem, a re-setting method is presented in this paper. The method ensures the rotor in the desired position. After an initial rotor position is set, current closed loop is adopted in the motor starting process.

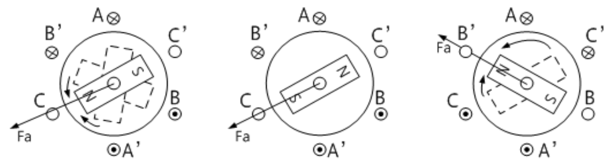


Figure 3. Process of motor starting

Starting process is divided into four steps:

1. Firstly, switch phase A and phase B windings on, and disconnect phase C. It will be lasted for some time to complete the pre-setting. Then the rotor may be in the position as shown in Fig. 3(a), or in Fig. 3(b). Secondly, switch phase A and phase C windings on, and disconnect phase B. This state continues for some time to implement the re-setting. Regardless of the success or failure of the pre-setting, the rotor will rotate to the position as shown in Fig. 3(c).
2. A commutation delay time is needed to set in starting algorithm, so that rotor will spend the time to rotate 60° electrical angle. This interval is controlled by the software delay, and unchanged.
3. In accordance with the direction of motor rotation to the next state, switch two-phase windings on. Let rotor rotate clockwise, according to the order of commutation (BA (current from B to A)→CA →CB→AB→AC→BC), and the motor completes a commutation cycle. At the same time the system adopts current closed-loop control algorithm to adjust the PWM duty ratio and to control output voltage.
4. Rotor rotation should be a certain speed after a cycle, and the zero-crossing of back-EMF detection method is adopted. After two cycles, the rotating speed can be estimated from the position detection signals. The time can also be calculated spending on rotor rotation every 60^o electrical angle, which can be used to update a pre-set time of commutation. At this time the system comes into position sensorless closed-loop status.

IV. SYSTEM CONFIGURATION

Fig. 4 describes a configuration of control system of sensorless BLDC motor. The system has speed and current double closed loops. The outer one is speed loop, which could continuously readjust the speed value based on observation of the speed error. An integral separated PI regulator is used in the speed loop. The inner one is current loop, which ensures the motor start with the maximum current allowed and causes the system to take connective action if actual value of current deviates from desired current value. The current loop is used to improve the dynamic performance of control system. A PI regulator is adopted in the current loop. TMS320F240 has high-performance processing capabilities, which can implement double digital regulators of speed and current. That will not only eliminate most of the analog devices, but also improve the system reliability.

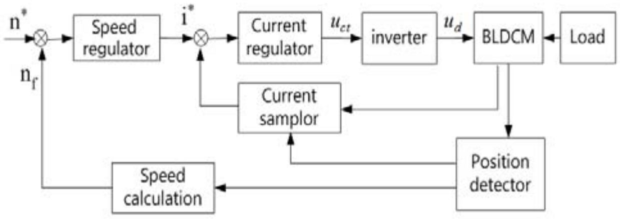


Figure 4. The system configuration of a sensorless BLDC motor

V. Hardware Design

The system uses TMS320F240 for the system microcontroller, and double closed loops control system of sensorless brushless DC motor is established. As TMS320F240 integrates a large number of peripheral circuits for motor control, the exterior circuits of the system are very simple. The system hardware configuration shows in Fig. 5.

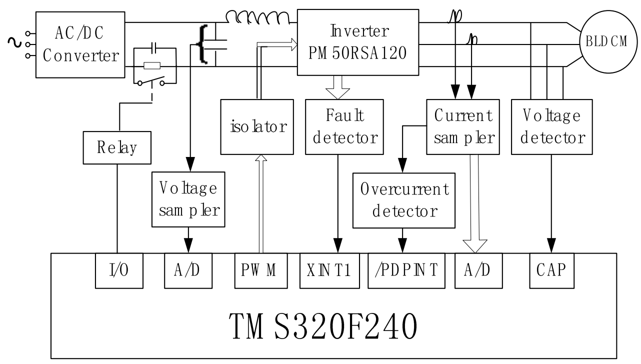


Figure 5. The system configuration of a sensorless BLDC motor

The system hardware consists of BLDCM, power circuit, terminal voltage detector, current sampler, overcurrent detector, voltage sampler, isolator, IPM fault detector and TMS320F240.

TMS320F240 offers a high performance, 10-bit analog-to-digital converter (ADC), which offers 16 channels of analog input and can sample voltage and current in real time. The system has not speed detection part. According to the rotor position signal, a simple algorithm is designed to calculate the rotating speed indirectly. The algorithm is implemented by DSP. It simplifies the system hardware structure, so that the system is more economical and reliable. TMS320F240 offers an event-manage module which has been optimized for digital motor control and power conversion applications. The system uses the event-manage module to generate up to 6 PWM outputs, which control power switch on or off through a circuit of isolating and driving and achieve the proper commutation of the motor.

A. *Rotor position detection circuit*

As the back-EMF is difficult to obtain directly, the zero-crossing of back-EMF is actually detected by three-phase windings terminal voltage indirectly. Fig. 6 is phase-A winding terminal voltage detection circuit.

Put terminal voltage Ua into DSP's I/O port through divider circuit, filter circuit, zero-crossing detection circuit, photocoupler isolating circuit. As inverter adopts PWM mode, the terminal voltage waveform is also PWM wave, which changes into smooth voltage wave through filter. In order to ensure the safety of DSP, the voltage input I/O port should be below 5V. The detection signal must be sent to DSP through the isolation circuit.

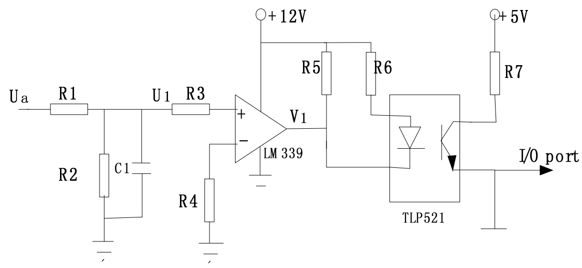


Figure 6. Terminal voltage detection

B. *Power circuit*

The power circuit includes the AC/DC converter, filter, inverter. In order to reduce the DC pulse, a large capacitor is used to filter in the output terminals of the AC/DC converter. The power switching device adopts intelligent power module (IPM) and switching frequency is 10KHz. If the inverter output voltage is adjusted, the current value of the brushless DC motor will be changed, and the electromagnetic torque can be adjusted. When the electromagnetic torque is equal to load torque, the motor speed reaches to a given value.

One termination of control circuit in IPM module is connected to main circuit of high voltage, another termination is connected to control signals what generated by controller, the control signals should be low voltage. So that control signals of the controller must enter IPM module through isolation circuit. Fig. 7 is the isolation circuit of one power element. Driving signal UU output to input terminal Up of driving circuit of IPM module through HCPL4504, thus on-off of the corresponding power elements can be controlled.

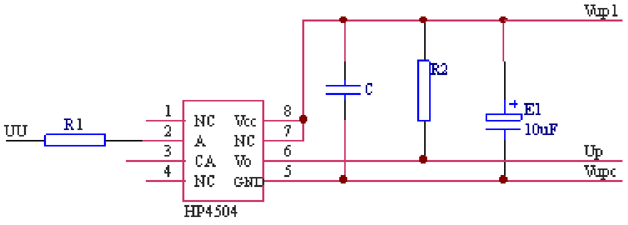


Figure 7. Isolation circuit

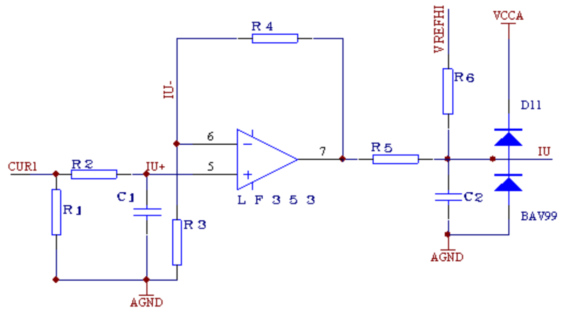


Figure 9. Current sampling circuit

C. Protection circuits

The system protection circuits include overvoltage, overcurrent and IPM fault detection circuitry. As current changes very fast, the paper has designed an overcurrent detection circuit, by means of hardware interrupt to achieve the overcurrent protection. Bus voltage changes slow correspondingly, so only voltage sampling circuit is designed, and the overvoltage protection is completed in the software design.

The IPM is Mitsubishi Intelligent Power Module (PM50RSA120) in the system, which is isolated base module designed for power switching applications. Built-in control circuits provide optimum gate drive and protection for the IGBT and free-wheel diode power devices. Once the IPM is faulty, it can block automatically. After a while, IPM will resume automatically, therefore the IPM's fault signal is sent to DSP. Fig. 8 is IPM fault detecting circuit. Once the fault of IPM occurs, the signal IPMERROR is put into DSP through TLP521. Appropriate measures will be taken by DSP to block IPM drive signal entirely. That will improve the system reliability using the dual protection design.

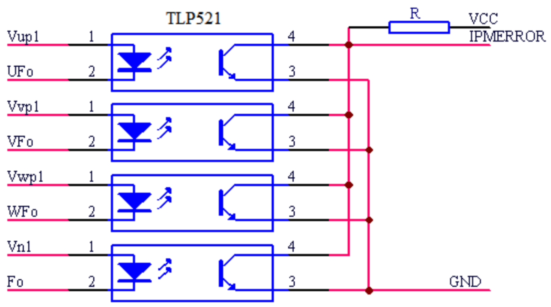


Figure 8. IPM fault detecting circuit

D. Current and voltage sampling circuits

In order to detect the phase currents of the motor, two current sensors (LAP-25) are placed on the two phase windings. Both currents phase A and phase B are detected, and the current value of phase C could be calculated.

Since the output currents of the current sensors could be positive or negative. After these currents must be changed into voltage signals, they could be put into DSP's A/D conversion unit through low-pass filter, zero-potential shifter and clipping circuit. The current sampling circuit is shown in Fig. 9.

The current waveforms of the stator and the signals of the rotor position are shown in Fig. 10. According to the signals of the rotor position, a phase current which among two live windings is selected as the current feedback. The direction of the current what selected should be not changed. One current loop is used to implement the current control, which simplifies the structure of system hardware and makes debugging easily. The position signals and correspondence of current feedback are shown in table I.

DC bus voltage is sampled, and its main purpose is to protect the whole system from overvoltage or undervoltage, but it is not participate in the calculation of motor control algorithm. DC Voltage is detected by voltage sensor LVP-25. Voltage sampling circuit is similar with current sampling circuit.

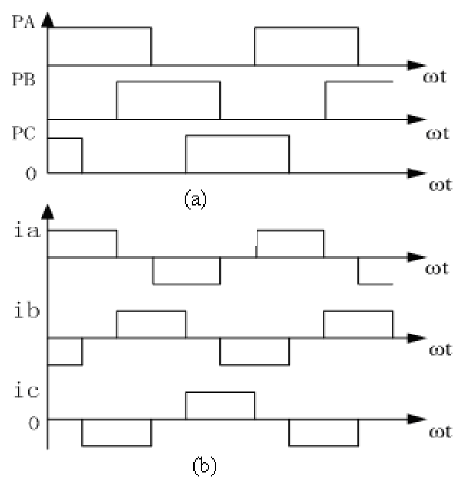


Figure 10. Ideal current waveforms and rotor position signals

TABLE I.
CURRENT FEEDBACK AND ROTOR POSITION SIGNAL

Signal	Value					
PC*PB*PA	101	001	011	010	110	100
i_X	i_A	i_B	i_C	i_B	i_A	i_C

VI. SOFTWARE DESIGN

The entire software program uses DSP assembly language. The software includes three parts: main program, Timer1 underflow interrupt (T1UFINT), IPM protection and overcurrent protection interrupt.

A. Main program

The main program completes the system initialization, including interrupt vectors, watchdog timer module, registers, I/O ports, event manager, ADC modules and so on. The flowchart of main program is shown in Fig. 11.

There is time delay of relay in the main program. The role of time delay is to prevent strong pulsed current from dampening the system hardware when the current is switched on. As shown in Fig. 5, there are a relay and a current limiting resistor on the bus bar. The resistor could limit the impulse current when the current is switched on. If the bus voltage were set up during the time delay, the resistor will be short circuited due to the relay working. Be careful, in case of occurred suddenly, interrupt should to be shut down at the beginning of the main progress, and also the interrupt should to be switched on after initialization.

After the initialization, the system enters into an infinite loop to wait for those interrupts. The most important interrupt is T1UFINT program, which is the core of the system control algorithms.

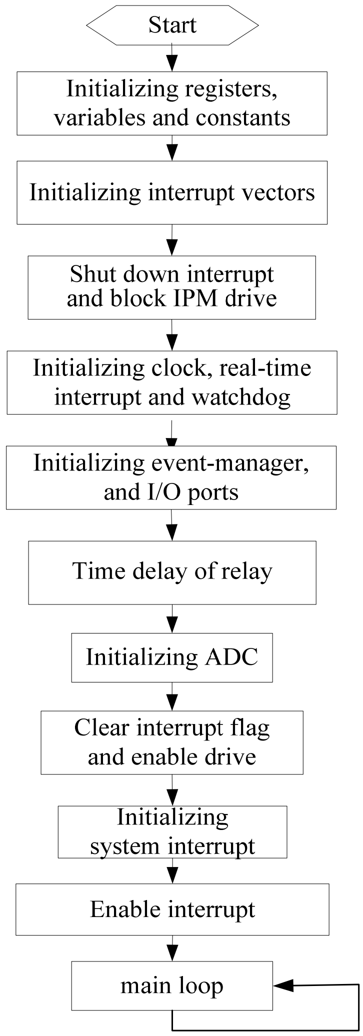


Figure 11. The flowchart of main program

B. Timer1 underflow interrupt

T1UFINT program includes motor starting, judging commutation (including the rotor position signal detection, phase shift calculation, amendment of the phase shift, delay filter), current sampler and calculation, current regulator (current feedback selection and PI algorithm), speed regulator (speed calculation and integral separation PI algorithm), changing PWM duty ratio, overvoltage protection and so on. The process is completed within a sampling period 100 μs. T1UFINT flowchart is shown in Fig. 12.

Contrary to the current, the bus voltage changes slowly, so overvoltage protection is complemented by T1UFINT. Once T1UFINT works, bus voltage would be sampled to determine if it is fault or not. Once bus voltage exceeds the safe value, a corresponding procedure will be handled and an overcurrent fault symbol will be set.

According to the motor starting method which described above, the paper achieves the motor starting with the software program. This method simplifies the system hardware structure. In software program, a delay filter is adopted to eliminate back-EMF interference which will appear at each commutation instant.

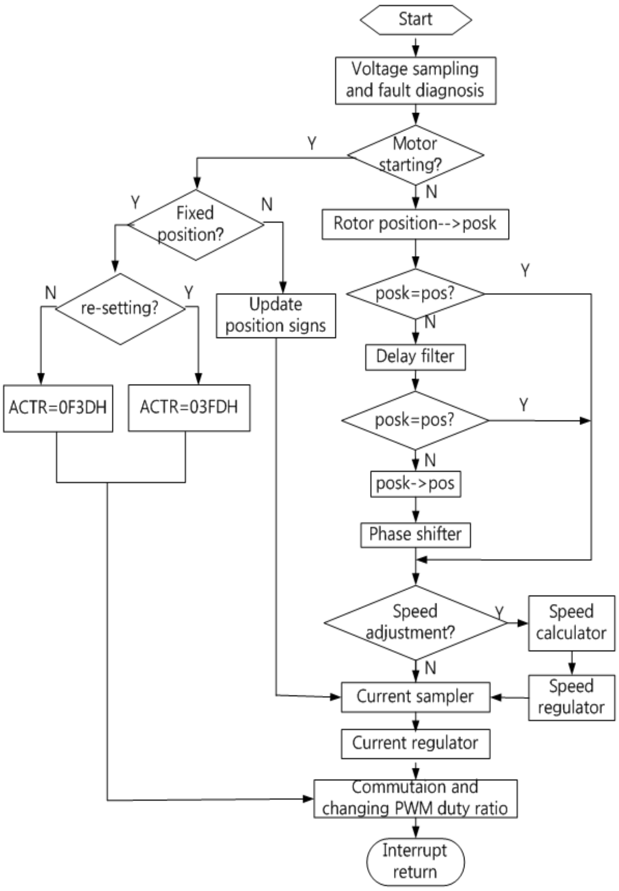


Figure 12. Timer1 underflow interrupt flowchart

In the paper, the speed feedback is completely calculated by the software program without any speed detection device. The motor selected by the system has 5 double poles. The capture unit will have six signal transitions in the course of rotor rotation every 30° electrical angle, and 30 signal transitions in the course of rotor rotation every cycle. According to the count(N) recorded in the moment of commutation, the rotating speed(n) is calculated as follows:

$$n = \frac{60}{T \times N \times 30} \qquad (1)$$

Here, T is the count period of Timer1; N is the count of Timer1.

After detecting the zero-crossing signal of the estimated back-EMF, an additional 30° phase shifter is required to perform correct commutation. But the RC filter exists in the terminal voltage detection circuit, which leads to the phase lag of the detection signal. That is, commutation point is not the point delayed by 30°, but including the modified phase shifter.

C. IPM protection and overcurrent protection interrupt

IPM protection shares the same interrupt source with overcurrent protection. Once interrupt occurs, the system will block IPM signal and set IPM or overcurrent fault symbol. When overcurrent, overvoltage or IPM fault occur, system will set a fault symbol, which makes designer find the problem easily.

VII. Results And Conclusions

A. Simulation results

Base on the principle above, this paper presented a simulation model of a BLDCM control system with MATLAB/Simulink, which could obtain rotor position by back-EMF. Simulation parameters of the BLDC motor are,

Stator resistance R=7.82Ω;

Stator inductance L-M=400mH;

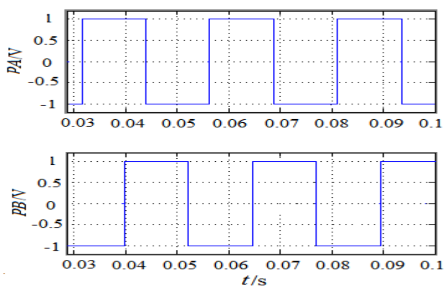
Number of poles p=10;

Load torque T=1.3N.m;

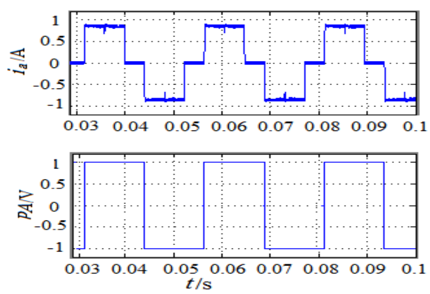
Inertia of rotor J=1.23×10^{-4}Kgm^2;

EMF constant Ce=0.76V/rad/s.

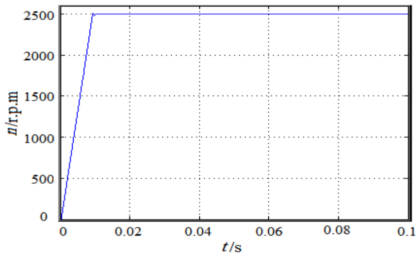
A PI regulator is adopted in the speed loop. The BLDC motor starts with load torque 1.3N.m. Both position signals PA and PB estimated by terminal voltage detection are shown in Fig. 13(a). It can be seen from Fig. 13(b) that estimated position signal and phase current waveform. Fig. 13(c) shows the simulation results of a starting control response from standstill to 2500 rpm. According to the above results in the Fig. 13, it proves that the proposed strategy of estimated position is correct and effective.



(a) Position signals estimated by terminal voltage detection



(b) Estimated position signal and phase current waveform



(c) n from standstill to 2500rpm

Figure 13. Simulation waveforms in 2500rpm

B. *Experimental results*

The parameters of the experimental BLDC motor are 10-pole, 400-W, 300-V, 2-A, 3-phase windings in Wye. The experimental motor works in two phase power, six-step commutation. Based on the hardware circuits and software design above, a lot of experiments were carried out. These experimental results prove that the system is simple and reliable. It can be seen from Fig. 14 that commutation signals estimated by terminal voltage detection in the steady state. Fig. 15 shows the estimated commutation signal PA and phase current i_a waveform. Fig. 16 shows the experimental results of a starting control response from standstill to 1000 rpm (Fig. 16 (a)) and to 2500 rpm (Fig. 16 (b)). Fig. 17 shows phase current in the starting process. The vertical axis is fixed-point of the current (format Q10), and the maximum value of current is 1936(Q10) in the starting process. Whereas actual current value is 1.89A(1936*10-10), which is below rated current. According to the above result in the Fig. 17, it proves that the motor starting process is fast and safe, and the starting means is correct and effective.

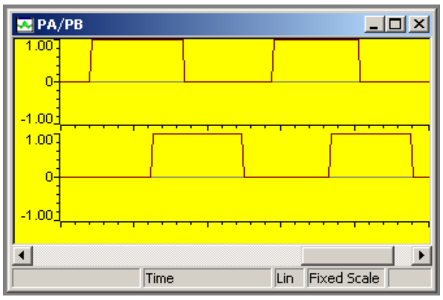


Figure 14. Commutation signals estimated by terminal voltage detection

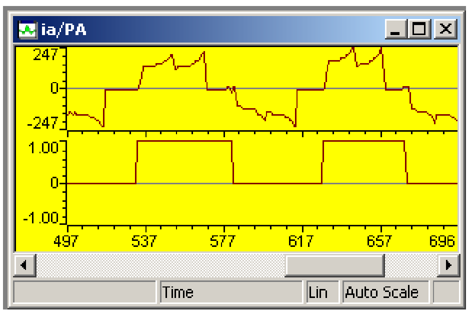
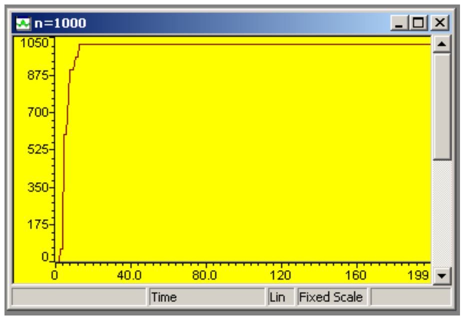
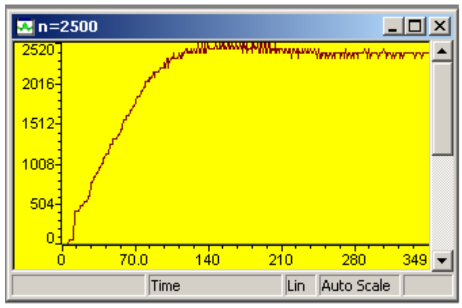


Figure 15. Estimated commutation signal and phase current waveform



(a) n from standstill to 1000rpm



(b) n from standstill to 2500rpm

Figure 16. Transient response of the motor speed

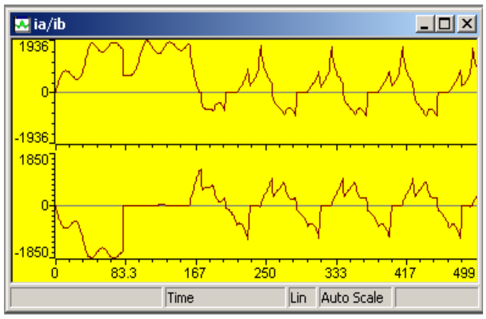


Figure 17. Phase currents in the starting sequence

C. *Conclusions*

The sensorless drive scheme for brushless DC motor is proposed in the paper. Moreover, the paper proposes the rotor re-setting method, and current closed loop control is used in the process of motor starting. The rotor position can be estimated by back-EMF zero-crossing detection, and the motor speed can be also estimated by the speed algorithm which is calculated by DSP. The use of TMS320F240 makes the system simply and reliable, because several advanced peripherals, optimized for digital motor and motion control applications, have been integrated to provide a true single chip DSP controller. The validity of the proposed sensorless drive system is performed well for command speed.

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