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Research on Sensorless Control of Permanent Magnet Synchronous Motor for Electric Vehicle

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Abstract

Motor speed can't change suddenly during the operation of motor because of inertia. In the short process of motor being not driven by motor controller, the operation of motor can be thought of as a uniform motion process. Making use of this property, it can be estimated next or next several cycles by measuring previous one or several cycles of motor. So the motor speed can be Figured out according to measured cycles. The phase angle can be estimated by zero crossing point of induced electromotive force produced in the running process of motor. Then the magnetic field position is estimated, and the angle measured by position sensors can be replaced by estimated angle. At last, bench test proves that this method can improve the reliability and safety of the motor control and has a good fault tolerance so as to be used as an auxiliary control method in motor control of electric vehicle and realize multi-mode control.

Keywords: *sensorless, permanent magnet synchronous motor, counter electromotive force, control method, electric vehicle*

1. Introduction

The permanent magnet synchronous motor, which has the advantages of small size, high efficiency, high torque current ratio, low moment of inertia, are widely used in modern vehicles [1, 2]. The high-performance control of permanent magnet synchronous motor used in vehicle requires precise rotor position and speed signal to realize the field orientation [3]. The common method is to detect the magnetic field position by position sensors [4]. However, the position sensors exists hidden dangers in the process of detection, and measurement error makes the fault of motor control occur instantly, resulting in excessive noise of motor control [5]. In order to solve the above problems, it is necessary to research sensorless control technology as the vehicle drive motor fault-tolerant supplementary measures. Therefore, this paper proposes a novel sensorless control method for permanent magnet synchronous motor used in vehicles.

This paper is organized as follows. Section 2 describes the control principle and process of the permanent magnet synchronous motor. In Section 3, the hardware and software of control system is designed. In Section 4, the theory analysis and calculation of control system is described and Section 5 shows the experiment result and analysis. The conclusions are discussed in Section 6.

2. Control Principle and Process

During the operation of motor, motor speed can't change suddenly because of inertia. It can be thought of as a uniform motion process [6]. Making use of this property, it can be estimated next or next several cycles by measuring previous one or several cycles of motor. It can be Figured out the motor speed according to measured cycles. The phase angle can be estimated by induced electromotive force produced through the running process of motor. In the process of motor drive, the wave form of motor counter electromotive force can't be measured accurately because of the interference of pulsed voltage [7]. Therefore, the driving force of motor needs to be stopped if motor speed and angle want to estimated correctly. After estimated the motor speed and angle, the driving force recovers again. And the angle measured

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by position sensors can be replaced by the angle estimated during the forbidding the driving force time. So the motor sensorless vector control can be realized through estimated speed and angle.

First, simulation model is set up by means of Matlab/Simulink and the simulation results are analyzed. The Figure 1(a) is three-phase counter electromotive force of PMSM. The square wave in Figure 1(b) can be got through wave shaping of counter electromotive force. Then the monostable circuit is triggered by the rising edge and the falling edge of square wave. And the pulse train can be obtained through the OR door addition of output pulse of monostable circuit, as shown in Figure 1(c).

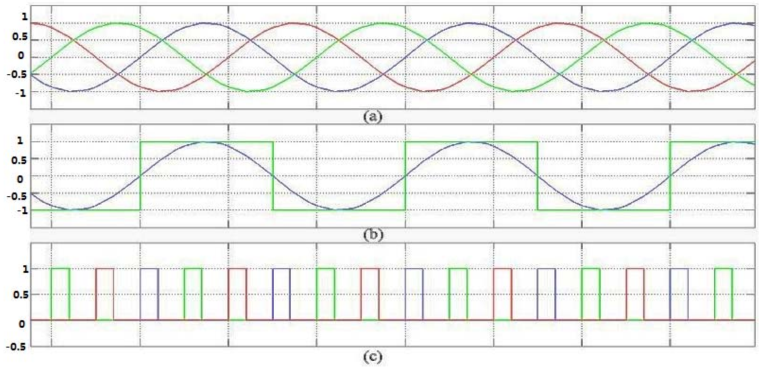

Figure 1. The Curve Graphs of Simulation

Each pulse cycle represents 15 mechanical angles for the motor of 4 poles. The rising edge of each pulse stands for the fixed location of rotor field. The motor speed can be got by measuring the pulse period. Positional information of rotor can be got by detecting the rising edge. Then vector control can be realized. However, the motor control voltage is fluctuant. Actually, it is difficult to detect the counter electromotive force of PMSM [8, 9]. In order to detect counter electromotive force, drive power tubes need to be turn off. When the power tubes are turned off, the ideal waveform of motor back electromotive force can be obtained. According to the waveform of motor back electromotive force at the time when the power tubes are turned off, we can estimate the motor speed and rotor flux position. But in order to capture a full cycle sine wave, make sure that the power transistor off-time is at least one cycle, otherwise, it will be difficult to capture the cycle size of the counter electromotive force. But the power transistor off-time is not too long, else it will affect the output of the motor electromagnetic torque. The electromagnetic torque of motor is zero. In other words, the driving torque will decrease. In the meantime, because of the enormous inertia of vehicle, the motor speed will not be influenced obviously by drive power tubes. According to rotor speed can't be changed suddenly, after detecting the position and speed of rotor, the magnetic field real-time position in normal working period of drive power tubes can be forecasted [10].

3. Hardware and Software of Control System

3.1. Hardware Design

In this paper, the motor phase angle is estimated by zero crossing point of induced electromotive force. In order to accurately capture the zero crossing point of induced electromotive force, sensorless control circuit is expanded based on existing circuit of motor controller, as is shown in Figure 2. The expanded sensorless control circuit includes rectification circuit, comparison circuit, isolation circuit, protection circuit, interface circuit etc. The main purpose of the hardware design of the circuit is to make use of the stop time when the drive power tube has ineffective effort on motor drive, and the waveform of motor counter electromotive force, which can be produced by motor and captured, is processed. And it will be transported to the motor controller for the formation of pulse waveform the main chip can handle.

Hardware circuit designed by the paper chooses dsPIC33F family chip of microchip as the core control chip [11]. The chip has a modified Harvard architecture, flexible and powerful addressing modes, and the 4M instruction word linear program memory space and 64KB of linear data storage space can be maximally addressed. In addition to that, the fastest processing speed is up to 40MIPS and it can be able to debug, simulate online, thus it well adapts to the requirements of the live debug. The dsPIC33F family of devices supports a variety of motor control applications. Rapid processing speed and large storage space make it extensive in motor control applications [12].

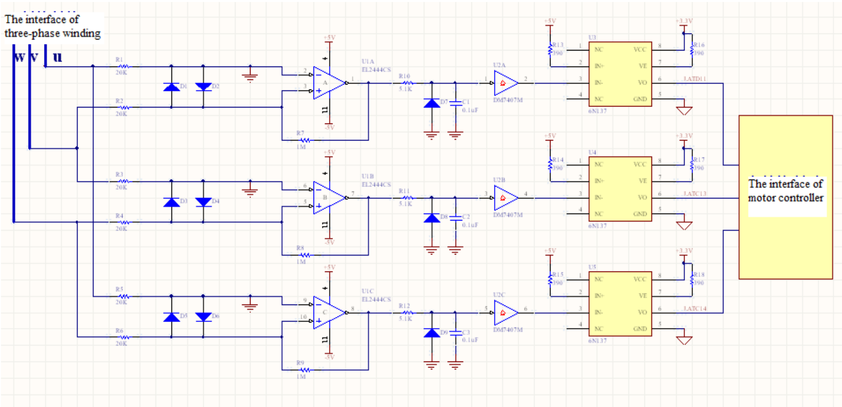

Figure 2. The Expanded Sensorless Control Circuit

In Figure 2, u, v, w is connected with motor winding A, B, C separately. The output of expanded circuit is connected with motor controller. The speed and location of rotor is estimated by the counter electromotive force produced by motor. Then vector control can be realized through estimated magnetic field position without position sensor. The estimated program of speed and angle is programmed in the interrupt program of motor controller. According to inertia, periodic drive is inflicted to the PMSM by motor controller. The counter electromotive force of stator winding is obtained when the motor is not driven. The counter electromotive force is to change to periodic pulse waveform. And it is easy to be deal with by DSP. In order to prevent circuit interference and protect motor controller, the photoelectric coupler 6N137 is chosen as isolation circuit between expanded circuit and the control chip [13, 14].

3.2. Software Design

The software, matched with the previously described hardware circuit, is designed to complete sensorless vector control. Its main purpose is to give motor a periodic driving force by the motor controller and according to the signal of hardware circuit to estimate the motor speed and rotor flux position.

According to the motor vector control principle [15-17], based on the existing hardware, this paper builds a good software platform, writes good software vector control program, and expands the sensorless vector control procedures [18]. The key control is reflected in the interrupt program of motor controller. It includes modulation of motor drive, estimation of motor speed and estimation of rotor magnetic field etc. And the main program is mainly responsible for communication with the PC. Most of the program is written by C programming language. However, the division is necessary when the speed and angle is estimated. Therefore, considering processing speed of DSP, the division program is written by assembly language and nested in the C programming language.

Among them, the interrupt program is the core of the whole position sensorless control and used to realize the control of motor drive, the estimation of motor speed, the estimation of rotor magnetic pole position. The interrupt period is set 100μs. And the communication with PC is realized by the CAN communication module installed in the motor control chip so as to obtain the real-time angles estimated by sensorless and position sensor, respectively. The control program flow chart is shown as Figure 3.

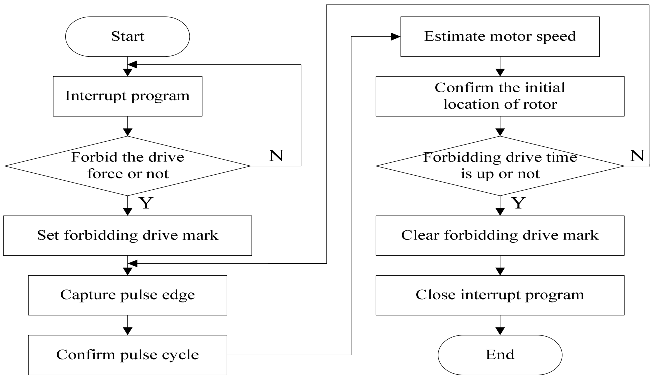

Figure 3. The Control Program Flow Chart

4. Theory Analysis and Calculation

Through the construction of the software and hardware, the motor controller has been able to capture the motor counter electromotive force. That how to change the information about motor counter electromotive force into the one about the motor speed and rotor flux position requires theoretical derivation and calculation. The description below is the estimation and analysis of motor.

4.1. Speed Estimation

When the program does not drive the motor to run, a complete periodic signal of three-phase stator winding is captured through the software. The signal is used to be the basis for calculating the speed and rotor position.

When the motor runs smoothly, the relation between speed, frequency and cycle is as follows:

$$n = \frac{60 \times f}{p} = \frac{60}{p \times T} \tag{1}$$

Where, n is motor speed, *rmp*; f is the frequency of the power supply, H_z ; T is capture cycle, s; p is the number of pole.

This formula is calculated in the interruption program of motor control. The interrupt cycle is 100μs. So the cycle size can be estimated by figuring out the number of interruptions of a cycle. Then according to the formula above, the current speed can be estimated.

4.2. Location Estimation

The estimation of rotor position is accumulated according to the angular variation of interruption at a time in the motor interruption program. The formula of angle is as follows:

$$\Delta\theta = \frac{360^{\circ}}{N} \times k \tag{2}$$

Where, $\Delta\theta$ is the accumulated angle, N is the total number of interruption at current speed, k is cumulative number with the increase of interruption, k=0,1,2⋯; When k is equal to N, it means that the angle has changed a cycle. The dimension of the angle variation changes from 0°~360° to 0~65535 for the convenience of the write and calculation of DSP program.

5. Experiment Result and Analysis

5.1. Speed Analysis

The motor speed is estimated by the periodic signal, which is captured during the time when the motor stops driving. When the bench test is conducted, the given periodic drive force is set by software. The given periodic drive force is that the drive force is imposed in six cycles and not imposed in three cycles, this moment the experimental effect is better. In the process of motor operating, the periodic drive force is always imposed. The motor speed can be set through dynamometer machine. At the same time, the estimated speed can be compared with the speed calculated by the signal captured by the sensorless control circuit. The contrast relationship between the speed estimated by the sensorless control circuit and the speed measured by dynamometer machine is shown in Table 1.

Table 1. The Contrast Relationship between the Speed Estimated by the Sensorless Control Circuit and the Speed Measured by Dynamometer Machine

Speed set by dynamometer machine/rpm	Speed measured by dynamometer machine/rpm	Speed estimated by sensorless/rpm	Maximum relative error compared to set speed
100	98-102	96-103	4.00
200	196-204	193-204	3.50
300	299-302	290-311	3.67
400	399-402	395-406	1.50
500	500-502	487-513	2.60
600	600-602	583-609	2.83
700	699-701	691-704	1.29
800	801-802	797-802	0.38
900	900-903	892-909	1.00
1000	1000-1002	986-1013	1.40

It can be seen from the table, there is a good correlation between the speed estimated by the sensorless motor vector control and the actual speed measured by the dynamometer. The relative error is bigger in the low-speed case, smaller in the high-speed case, which is determined by the size of the waveform of motor counter electromotive force. In addition to that, owing to the estimation algorithm is in the motor interrupt program, the interrupt time is 100μs, so the error will be 200μs when the cycle length of the counter electromotive force is captured. However, the bench experiment shows that the error has almost no effect on motor control, with its size being within reasonable limits.

5.2. Location Analysis

What the position of the rotor is accurately calculated is the necessary conditions for the motor continuous operation. In this paper, the contrast method is adopted to verify the accuracy and rationality of the position estimation when conducting bench experiments, that is, the author use the rotary transformer to measure the angle and sensorless control to estimate the angle; then the angles obtained by the above two methods are sent from the motor controller to the PC by means of CAN communication circuit; the required data are stored in PC using the software. The Figure 4 and Figure 5 are the contrast curves of the two kinds of method to obtain the angle when the speed is 500rpm and 700rpm, respectively.

From the above two graphs, we can analyzes that the variation trend of angle measured by position sensor and by sensorless is consistent. The curve is irregular in Figure 4 because of lost data caused by the bus when CAN communication, but it does not affect the estimates of the magnetic field position. In order to more clearly see the variation trend of angle measured by position sensor and by sensorless, a constant is man-made set in the software so as to make two keep a fixed phase difference, further making the two curves more distinct, as is shown in Figure 5. The required angle position to meet the motor operation can be obtained by getting rid of the fixed value by means of program after comparing the relationship between the two above angles.

5.3. Experimental Analysis of Mode Switch

It can be known from the above bench test, the sensorless control of permanent magnet synchronous motor can be achieved, but the motor has to have a certain initial velocity, which requires the sensorless control and position control of motor. Two kinds of control modes should be able to switch each other so as to meet the control requirements.

When the multi-mode control experiments are conducted in this paper, we set the motor speed 600rpm for the critical point. When the motor speed does not exceed 600rpm, the angle measured by rotary transformer is used to control motor; When the motor speed exceeds 600rpm, the angle measured by sensorless is used to control motor. The Figure 6 is the curve of speed change for the motor mode switch.

At an experiment, the motor speed is increased to 40 rpm every 30 seconds. The curve 'a' represents the theoretical value of the motor speed change; the range of curve 'b' and 'c' is the fluctuation range of the actual motor speed change. The change of motor speed can be clearly seen in the Figure 6 in the process of mode switch.

Some ideas can be provided for the choice of motor control on the basis of the mode-switch experiment so as to enhance the safety and reliability of control. When this method is applied to the practical, fault inspection can be realized by setting the software, namely, the angle measured by position sensor and by sensorless can be simultaneously obtained, and then compare the former angle with the latter one, if the angle difference is within reasonable limits, the motor vector control is correct, otherwise the angle measurement fails this moment, which requires mode switch. The rotor magnetic field will be estimated by the angle calculated by the sensorless to finish motor vector control.

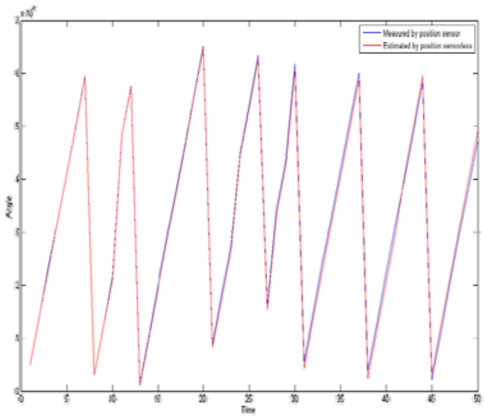

Figure 4. The Contrast Curve Speed is 500rpm

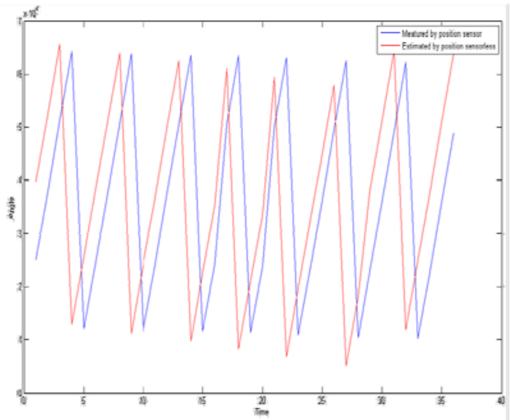

Figure 5. The Contrast Curve of Angle when Speed is 700rpm

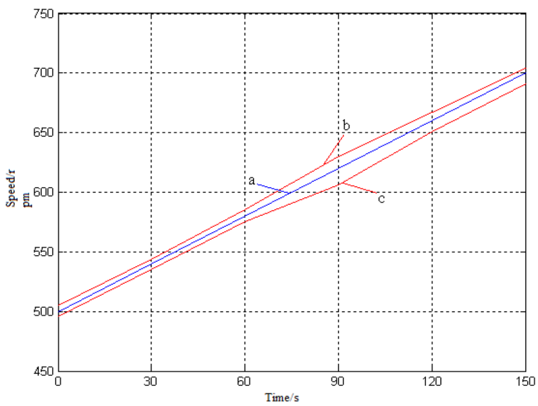

Figure 6. The Curve of Speed Change for the Motor Mode Switch

6. Conclusion

Through the analysis of the sensorless vector control of permanent magnet synchronous motor at home and abroad, this paper proposed a suitable sensorless vector control method for permanent magnet synchronous motor used in vehicle. The relationship between the position sensor vector control and sensorless vector is contrasted, and there is a combination between the estimation of motor angular position with sensorless and the one with position sensor to realize the multi-mode switch. At last, the feasibility and effectiveness of the proposed method is verified by experiments. What's more, the proposed sensorless vector control method can be regarded as an auxiliary control method for automobile motor control, enhancing reliability and fault tolerance of the calculation of motor angular position.

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