Research on Control System of Three-phase Brushless DC Motor for Electric Vehicle

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Abstract. In order to study the three-phase brushless motor control system of electric vehicle, Freescale9S12XS128 chip is used as the control core, and the power MOSFET is used as the inverter device. The software is compiled by Codewarrior software. The speed control link adopts open-loop control, and the control chip collects the external sensor signal voltage change control PWM signal output control three-phase brushless DC motor speed. The whole system consists of Hall position detection module, current detection module, power drive module and voltage detection module. The basic functions of three-phase brushless DC motor drive control are realized.

1. Introduction
While the car has brought convenience to mankind, its emissions are causing great pollution to the human environment. In the process of exploring the solution, electric cars once again become a hot topic of concern. Brushless DC motor has a DC motor speed performance, high efficiency, while overcoming the brush DC motor brush and commutator operation generated by the spark, noise, radio interference and short working hours and other shortcomings, but also have AC motor running stable, simple structure, easy maintenance and a series of advantages, so the use of brushless DC motor can be used as a motor vehicle drive source of the preferred motor \cite{1}. In this paper, Freescale9S12XS128 microcontroller as the main control chip to MOSFET for the inverter design brushless DC motor control system.

2. Overall design

2.1. Structure of Brushless DC Motor
Brushless DC motor structure is generally composed of motor body, rotor position sensor and electronic commutator three parts. The structure of the schematic diagram shown in Figure 1.
Figure 1 Schematic diagram of brushless motor

The motor body includes the rotor and the stator. The position of the rotor pole is detected by the position sensor. The position signal of the rotor pole is converted into an electric signal under the action of the sensor. After the logic circuit is processed, the stator winding commutation is controlled. Brushless DC motor position sensor has three kinds: electromagnetic type, photoelectric type and Hall position sensor [2]. As the Hall position sensor can detect magnetic field and magnetic field changes, but also can be used in complex magnetic field environment, subject to lower environmental impact, so the use of Hall position sensor. The electronic commutator includes the inverter power switch and the position signal processing module, which can control the energization timing of each winding of the stator.

2.2. The working principle of brushless DC motor

Brushless DC motor Hall sensor output electrical signal by 74HC14 chip logic changes to the MCU, MCU according to the collected electrical signal to determine the brushless motor rotor position, MCU output PWM signal control brushless motor control circuit board power switch Conduction sequence and time, so that the armature winding in turn power, so as to produce a jump on the stator rotating magnetic field, driving the rotor rotation.

Brushless DC motor in accordance with the winding structure can be divided into two types of star and triangle, according to the control circuit can be divided into full-bridge and half-bridge two ways [3]. Full bridge star mode control circuit has a torque stability, the output torque of the characteristics of large, so the use of full-bridge star way.

Figure 2 three-phase full-bridge star drive circuits
Figure 2 Q1 to Q6 for the N-channel MOS power tube, high-level conduction, MCU detection of the logic changes after the Hall sensor HA, HB, HC three output signal level, 6 MOS tube off is controlled, according to the inverter bridge every time there are two or three power switch at the same time, can be divided into two conduction and three three conduction two control methods. Three-phase full-bridge star structure using two-way conduction mode, the motor in the run-time two-phase winding conduction, the third phase vacant. When two power tubes are turned on, they have six trigger modes. If the 360 ° for a cycle, every 1/6 cycle commutation, each time to replace a MOS tube, each MOS tube conduction 120 ° angle. In the case of Hall sensor, the three Hall sensors H-A, H-B and H-C induce a set of cyclic signals. MCU collects MCU-A, MCU-B and MCU-C via 74HC14 logic.

When the Hall signal is 101, the MOS transistors Q1, Q5 conduction, the current flow is: U phase → V phase. This state to maintain 1/6 cycle commutation, MOS tube Q5 off, MOS tube Q6 conduction, the current flow is: V phase → W phase, V, W conduction. This state to maintain 60 ° electrical angle commutation, MOS tube Q6 closed, MOS tube Q2 conduction, then current flow direction: W phase → U phase, to maintain 60 ° electrical angle commutation, MOS tube Q4 closed, MOS tube Q5 conduction, Current flow direction: W phase → V phase, to maintain 60 ° electrical angle commutation, MOS tube Q3 turns on, W, U phase conduction, current flow direction: W phase → U phase, to maintain 60 ° electrical angle commutation, MOS tube Q4 closed, MOS tube Q5 conduction, W, V phase conduction, Current flow direction: W phase → V phase, to maintain 60 ° electrical angle commutation, MOS tube Q3 turns on, W, U phase conduction, current flow: U phase → V phase, this time A cycle ends [4]. The conduction order of the entire cycle power tube is: Q1Q5-Q1Q6-Q2Q6-Q2Q4-Q4Q3 -Q3Q5. The current state is UV, UW, VW, VU, WU, WV six states, each commutation period, the motor of each phase conduction 120 ° electrical angle.

2.3. Mathematical model of brushless DC motor

In order to simplify the analysis, assume that the motor is saturated magnetic circuit, excluding hysteresis loss, eddy current loss and armature reaction; ignore the cogging effect; drive system power tube and rectifier diode as the ideal component; rotor no damping, air gap magnetic field distribution Approximate rectangular wave.

2.3.1. Voltage equation. Based on the above assumptions, the phase voltage of each phase winding of the brushless motor consists of the resistance drop and the winding induced electromotive force, where the voltage balance equation is

\[
\begin{bmatrix}
U_u \\
U_v \\
U_w \\
\end{bmatrix}
= \begin{bmatrix}
R & 0 & 0 \\
0 & R & 0 \\
0 & 0 & R \\
\end{bmatrix}
\begin{bmatrix}
I_u \\
I_v \\
I_w \\
\end{bmatrix}
+ \begin{bmatrix}
L_u & L_v & L_w \\
L_u & L_v & L_w \\
L_u & L_v & L_w \\
\end{bmatrix}
\begin{bmatrix}
\frac{dI_u}{dt} \\
\frac{dI_v}{dt} \\
\frac{dI_w}{dt} \\
\end{bmatrix}
+ \begin{bmatrix}
E_u \\
E_v \\
E_w \\
\end{bmatrix}
\]

(1)

In (1), for each of the opposite electromotive force, for each phase current, for each phase voltage, for each phase winding resistance, for each phase winding self-inductance, for each phase winding mutual inductance. Since the brushless DC motor rotor is a permanent magnet, it can be approximated that the mutual inductance between the phases is constant, that is, (2-1) can be simplified

\[
\begin{bmatrix}
U_u \\
U_v \\
U_w \\
\end{bmatrix}
= \begin{bmatrix}
R & 0 & 0 \\
0 & R & 0 \\
0 & 0 & R \\
\end{bmatrix}
\begin{bmatrix}
I_u \\
I_v \\
I_w \\
\end{bmatrix}
+ \begin{bmatrix}
L_u & L_v & L_w \\
L_u & L_v & L_w \\
L_u & L_v & L_w \\
\end{bmatrix}
\begin{bmatrix}
\frac{dI_u}{dt} \\
\frac{dI_v}{dt} \\
\frac{dI_w}{dt} \\
\end{bmatrix}
+ \begin{bmatrix}
E_u \\
E_v \\
E_w \\
\end{bmatrix}
\]

(2)

\[I_u + I_v + I_w = 0, MI_u + MI_v + MI_w = 0, L = L_n - M\]

Substitute (2) available
2.3.2. Electromagnetic torque equation. Brushless DC motor in normal operation, the armature winding through a current, current carrying conductor in the magnetic field by the force generated by the total torque for the electromagnetic torque. Set the current peak, the peak electromotive force, because each time there are two-phase winding conduction, the two-phase winding can be seen as series, the electromagnetic power can be, brushless DC motor:

\[
T_m = \frac{P_n}{\omega} = \frac{2n_pE_pI_p}{\omega} = 2n_p\psi_p I_p
\]  

(4)

In the formula (4), the peak value of the brushless motor flux. From (4) we can see that the current is proportional to the motor.

2.3.3. Brushless DC motor regulation characteristics. There is physics that the conductor cutting magnetic field lines produce electromotive force E

\[
E = NBL\nu = NBL\frac{n}{60}2\pi
\]  

(5)

Where N is the equivalent winding number of the phase windings; B is the magnetic field strength; L is the effective length of the conductor; N is the brushless motor speed; r is the winding radius of rotation;

(5) into (3), then the brushless motor speed characteristic equation (6), the finishing formula (7).

\[
n = \frac{30}{NBLx\pi} \left( U - R \cdot I - L \cdot \frac{dI}{dt} \right)
\]  

(6)

\[
n = \frac{60}{\pi} \frac{K_T U_d - 2RT_m}{K_T K_T}
\]  

(7)

In equation (7), the torque coefficient of the motor is the line back electromotive force, \(U_d = U_{uv} = U_{vw} = U_{wu}\).

3. Hardware design

3.1. System overall hardware design process
Brushless DC motor controller hardware circuit includes voltage detection module, speed control module, MOSFET driver module, MOSFET circuit module, control module, as shown in Figure 3 hardware block diagram.
3.2. Control module
Using the control chip for the MC9S12XS128 microcontroller, the main function modules include [5]: memory, internal PLL phase-locked loop module, 2 asynchronous serial communication SCI, 1 serial peripheral interface SPI, MSCAN module, 8-channel IN / OUT Compare timer module TIM, periodic interrupt timer module PIT, 16 channel A / D converter module ADC, 1 8-channel pulse width modulation module PWM.

3.3. Power drive board
Power board includes MOSFET driver module, power supply module, current detection module, Hall module, power board.

3.3.1. MOSFET driver module. MCU output PWM cannot directly act on the MOS tube, must go through the power amplifier, MOSFET driver module using IR2113S chip, Figure 4 for the MOS tube drive module circuit. The bootstrap capacitor is an internal suspension power supply for the driver of the upper arm MOS tube and is the output drive signal of the power switch of the upper and lower arms of the inverter bridge and outputs a signal level of 10 to 20 V, and the output signal is driven by HIN and LIN (HIN and LIN), otherwise HO is low; when HIN and LIN are low, LO is high, otherwise the input signal is high (HIN and LIN) LO is low, Figure 5 for the input and output timing logic.
Figure 4 MOSFET driver module circuit R17, R21 series gate protection, PWM maximum voltage of 5v, HIN and LIN input signal range of 3V ~ 5V, to meet the chip requirements.

**Figure 5** Input and output timing logic relationship

3.3.2. Voltage detection module. Voltage detection circuit using the principle of resistance step-down, the power supply voltage in accordance with a certain proportion of reduced within 5V, can make MUC AD detection. Figure 6 shows the voltage detection circuit.

**Figure 6** voltage detection circuit diagram

By the output voltage formula:

\[
U_{AD} = U_{12} \cdot \frac{R_4}{R_4 + R_1 + R_2}
\]

\[
U_{AD} = 12 \cdot \frac{5}{5 + 6 + 6} \leq 3.6V ,
\]

Reverse thrust can be up to 17V, according to 12V saturation voltage for the rated voltage of 1.2 times the saturation voltage of 14.4V. Therefore, the battery voltage signal can be controlled within 5V, easy to MCU acquisition and control, when the battery signal voltage is lower than a certain value, indicating that the battery undervoltage, when the battery voltage is on the control system and the battery itself will be affected And the damage, when the undervoltage condition is detected by the MCU, the PWM output is stopped and the brushless DC motor stops working.

3.3.3. Current detection module. Current detection using HBC25LSP module will be converted into a current signal voltage signal, the detection signal OUT1 by LM358 buffer sent to the microcontroller. Figure 7 for the current detection module
4. Software Design

MCU to replace the dedicated brushless DC motor control chip can achieve more features. MCU bus frequency and the frequency of PWM depends mainly on the actual situation, too high frequency easily lead to loss of MOS tube, the control chip may also be hot, too low frequency prone to noise pollution, taking into account the frequency of PWM to take 10kHz. The software features of the controller are: commutation control, current limit protection, PWM pulse width calculation, PWM increment program, under voltage protection, speed calculation. Figure 8 for the main program block.

![Figure 8 main program block diagram](image)

5. Experiment

Figure 9 shows the three-phase brushless motor control system experimental map.
Figure 9 three-phase brushless motor control system

Figure 10 waveform (1) for the C-phase voltage waveform, (2) for the C-phase bridge control signal waveform. Figure 10 shows that the C-phase voltage and C-phase control signal has a good consistency.

Figure 10 C-phase voltage and control signal waveform

6. Conclusion

(1) The operation structure and control principle of the brushless DC motor are systematically analyzed, and the mathematical model is established, which paves the way for the further control of the brushless main motor.

(2) Select the high performance Freescale9S12XS128 as the master chip, the peripheral circuit is reduced, reducing the overall cost.

(3) Design and optimization of the control system software part, MCU program control in the use of the original circuit on the basis of an increase of undervoltage protection, start compensation and other functions.

(4) The analysis and circuit program design for the actual electric vehicle brushless DC control system to provide a reliable theoretical basis and practical experience, help to reduce the development time, saving R & D funding.

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