DC Motor Speed Control System Based on PI Controller

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Abstract. This paper designs a closed-loop DC motor drive speed control system based on PI regulator [1], which has the advantages of dead zone control, simple structure and high stability. The system main control is a MCU, with peripheral functions such as key input and liquid crystal display, and human-computer interaction is good. The H-bridge driver circuit adopts discrete component design, and adds IR2104 half-bridge driver with bootstrap circuit to realize control of MOS transistor. In addition, the logic circuit added in the circuit realizes one PWM signal to drive the motor, which reduces the requirement of the single chip microcomputer, and uses less single chip resources to achieve the same driving effect. The PI controller based on the op amp design allows the system to effectively track the speed and the speed can be stabilized to a given value.

1. System hardware design
The hardware design of the system can be divided into the minimum system of the MCU and its peripherals, power supply circuit, motor drive circuit, Hall sensor speed feedback circuit, LCD display, key input and other modules. The hardware design structure is shown in Figure 1. The core circuit is the motor drive circuit. The power circuit module provides 5V voltage for the minimum system of the MCU. The LCD display module realizes human-computer interaction and can display the motor speed. The key input module can input forward rotation. Control commands such as reverse rotation and motor speed regulation.

![Figure 1. Hardware design structure](image)

1.1. device selection
The core of this design is the motor drive circuit module. This paper mainly introduces the device analysis and calculation involved in this module. The motor used in this design is 24V, 40W DC motor,
and the drive mode is driven by H-bridge motor. A schematic diagram of the H-bridge motor drive circuit composed of a triode is shown in FIG. 2. When driving the motor, it is important to ensure that the two MOS transistors on the same side of the H-bridge are not turned on at the same time due to the delay of the device being turned on and off. If the two MOS transistors are turned on at the same time, the short-circuit current generated will burn the H-bridge. Therefore, this design uses the IR2104 bridge driver to fabricate the bootstrap circuit to drive the MOS transistor. The internal application bootstrap technology can simultaneously output the channel signals of the high-voltage side and low-voltage side of the two driving inverter bridges, and design the suspension for the bootstrap circuit. Power [3]. At the same time, the IR2104 also has dead-band delay and over-current protection for the upper and lower arms. These functions will greatly simplify the H-bridge circuit composed of MOS transistors.

1.1.1. Transistor. Both the triode and the MOS tube can form the bridge arm of the H-bridge. However, since the MOS tube requires a small driving power and a small switching loss, it is a voltage-controlled device, and the control is convenient. The driving of the 24V DC motor is more suitable for the MOS tube. When selecting a MOS tube, attention must be paid to the selection of four parameters: switching time, on-resistance, maximum operating voltage, and maximum operating current [2]. In summary, the MOSFET IRF540N is selected, and its maximum drain-source voltage is $V_{ds}$ 100V, and the maximum continuous leakage current $I_d$ is 23A.

1.1.2. Freewheeling diode. When the power is turned on or off, and the motor is switched forward and backward, the motor coil will generate a large reverse induced electromotive force [4]. At this time, the diode needs to be freewheeled in the circuit to prevent the MOS transistor from being broken down. Although there is a parasitic diode inside the MOS tube, in order to ensure the stability and reliability of the circuit, a freewheeling diode needs to be connected in parallel with the MOS tube on both sides of the circuit. When the switch in the circuit is disconnected, the freewheeling diode is turned on, and the current at this time is

$$I = \frac{V - V_f}{R_s}$$

(1)

Where $V_f$ is the forward bias voltage of the freewheeling diode, $R_s$ is the equivalent series resistance of the winding of the motor winding, and $V$ is the power supply voltage.

In addition, since the conduction process of the diode requires a certain period of time to establish, the counter electromotive force may still cause breakdown of the semiconductor device during this time (semiconductor breakdown also takes time), so try to select a diode with a fast speed. In summary, the fast recovery diode 1N4148 is selected, which has a reverse withstand voltage of 75V and a maximum forward current of 150mA.

1.1.3. Bootstrap circuit. The bootstrap circuit, also called the boost circuit, uses a bootstrap boost diode, a bootstrap boost capacitor, and other electronic components to superimpose the capacitor discharge voltage and the power supply voltage, thereby increasing the voltage [4].

![Figure 2. Schematic diagram of H Bridge](image-url)
The bootstrap circuit is the key to the entire driver circuit. In the bootstrap circuit, the capacitor stores the voltage and the diode prevents the current from flowing back. These two devices should be carefully selected and designed. It should ensure that the bootstrap diode can reverse the cut-off function, without reverse breakdown, blocking the high voltage. Ensure that the bootstrap capacitor capacity is appropriate and provide sufficient voltage for the circuit. The choice of the bootstrap capacitor is related to the operating frequency, the driven MOSFET parameters, and the operating voltage. The choice of these two devices has a corresponding theoretical formula [4].

The minimum charge of the bootstrap capacitor:

\[ Q_{bs} = 2Q_g + I_{qbs(max)} + \left( I_{Son} + I_{Soff} \right)t_w + \frac{I_{Cbs(leak)}}{f} \]  

Where \( Q_g \) is the gate charge of the high-end device, \( f \) is the operating frequency, \( I_{Cbs(leak)} \) is the bootstrap capacitor leakage current, \( I_{qbs(max)} \) is the maximum quiescent current of the high-end driver circuit, \( I_{Son}/I_{Soff} \) is the level-shifting current required for HO to turn on/off, and \( t_w \) is the pulse width of the level-switching current.

The minimum capacitance value can be calculated by:

\[ C \geq \frac{2Q_{bs}}{V_{CC-V_f-V_{LS}}} \]  

Among them, \( V_f \) is the forward voltage drop of the bootstrap diode, \( V_{LS} \) is the low-side device voltage drop or high-end load voltage drop, and \( Q_{bs} \) is the result of (2) calculation.

Bootstrap diode

When the high-side device is turned on, the bootstrap diode must be able to block the high voltage and should be a fast recovery diode to reduce the charge from the bootstrap capacitor to the power supply \( V_{CC} \). The rated current of the diode is derived from the product of the minimum charge of the bootstrap capacitor and the operating frequency.

\[ I_F = Q_{bs} \times f \]  

In addition, in the general H-bridge motor drive circuit, each motor drive requires two PWM signals. The design has higher requirements for the selection of the single chip microcomputer. In this design, a logic control circuit composed of three non-gates is added, so that the whole circuit only needs to occupy two MCU IO ports, one is a PWM port, one control motor is reversed, the structure is simple, and the control is convenient. The complete circuit diagram is shown in Figure 3.
2. PI controller design

In order to stabilize the motor speed, the PI controller is added to form a single closed-loop feedback system [5]. There are many types of PI controllers. In this design, analog electronic control technology is used, and an operational amplifier is used to implement the PI regulator, as shown in Fig. 4. When designing a calibrated PI controller, the main research tool is the Bode diagram (asymptote of the open-loop logarithmic frequency characteristic) that provides exactly information on stability and stability margin, and can roughly measure the steady-state of the closed-loop system. Dynamic performance. The main components of the closed-loop DC speed control system are power electronic converters and DC motors. The transfer function of each link is calculated to obtain the open-loop transfer function of the system. The open-loop characteristics of MATLAB are analyzed by the powerful drawing ability, and the parameters of the PI controller are calculated according to the relevant parameters and formulas [6].
2.1. System open loop characteristics analysis

PWM converter

When the switching frequency is 10 kHz, $T=0.1$ ms. In the general electric drag automatic control system, the lag link with such a small time constant can be approximated as a first-order inertia link, so its transfer function is:

$$W_1(s) \approx \frac{K}{Ts + 1}$$

Where $K$ is the converter voltage amplification factor, which is 21; for the delay time, it is 5ms.

DC motor

The motion control system knows the structure diagram of the DC motor transfer function as shown in Figure 5:

![Figure 5. DC motor transfer function structure diagram](image)

If it is ideally idling, then $I_{dl} = 0$. Then the DC motor transfer function is:

$$W_2(s) = \frac{1/C_e}{TmT_1s^2} + T_m s + 1$$

Among them, $C_e$ is the electromotive force coefficient of the motor, which is 0.6 $V.min/r$; $T_m$ is the electromechanical time constant of the electric drive system, which is 0.053s; $T_1$ is the electromagnetic time constant of the armature circuit, which is 0.012s.

Control and feedback

Both the amplifier and the speed feedback feedback can be considered instantaneous, so their transfer function is their amplification factor.

Proportional amplifier:

$$W_3(s) = K_p$$

Speed feedback link:

$$W_4(s) = \alpha$$

The transfer function of each link is combined by interaction, and the block diagram of the closed-loop motor speed control system is shown in Fig. 6.
Figure 6. Closed loop system block diagram

The system open loop transfer function is

$$W(s) = \frac{K_p K_o/C_e}{(T_s s + 1)(T_m T_1 s^2 + T_m s + 1)}$$

(9)

Substituting known parameters

$$W(s) = \frac{0.004453}{(0.005 s + 1)(0.0178 s + 1)(0.0357 s + 1)}$$

(10)

Its Bode diagram is shown in Figure 7:

Figure 7. System open loop Bode plot

After MATLAB measurement and analysis, the gain margin and phase margin are both negative, and the original closed-loop system is unstable. The PI controller needs to be designed to stabilize it. The PI controller transfer function is:

$$W_{pi}(s) = \frac{K_p s + 1}{\tau s}$$

(11)
In order for the corrected system to have sufficient stability margin, its logarithmic amplitude-frequency characteristic should traverse the 0dB line with a slope of −20dB/dec, at which time the new cutoff frequency $\omega_c < 1/T_2$. At this time, $T_1 = K_{pi} \tau = 0.032$ s, and $\omega_c = 50$ is taken to make $\omega_c < 1/T_2 = 56 s^{-1}$. Then there is

$$50 = -20 \log \frac{K_p}{K_{pi}}$$  \hspace{1cm} (12)

Solve $K_{pi} = 0.0632$, $\tau = \frac{T_1}{K_{pi}} = 0.506$ s, so the PI controller transfer function is

$$W_{pi}(s) = \frac{0.032s + 1}{0.506s}$$  \hspace{1cm} (13)

2.2. Closed loop system MATLAB simulation

Add the PI controller to the original system, and the closed-loop structure of the system is shown in Figure 8.

The simulation results are shown in Figure 9-10.

It is easy to see from the simulation diagram that after adding the PI controller, the system's speed response has an overshoot, but it can reach a steady state faster, and the steady state value is a given speed value.

2.3. Operational PI Controller Parameter Design

The key to realizing a PI controller with an operational amplifier is to determine the proportional resistor...
and the size of the integrated capacitor. According to the relevant calculation formula of the PI amplifier designed by the operational amplifier, the balance resistor (R0) can be used as the middle. The parameter theory calculates the size of the two devices. Since the magnification Kp=20 in this paper, R0=40KΩ.

\[
R_1 = K_p R_0 = 2 \times 52k\Omega
\]

\[
C_1 = \frac{\tau}{R_d} = 12.65\mu F
\]

So \( R_1 = 3k\Omega \), \( C_1 = 12\mu F \).

3. Design summary

The closed-loop DC motor drive speed control system based on PI controller designed in this paper can realize the operation of starting, stopping, positive and negative control, acceleration and deceleration of the motor. The circuit uses a half-bridge driver IR2104 with a bootstrap circuit to drive the MOS transistor. The IR2104's built-in dead-band delay and over-current protection function make the entire driver circuit simple and easy to debug. The PI regulator is verified by MATLAB simulation, which allows the system to reach steady state quickly with a small amount of overshoot.

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