Design of Compensated Hall High Current Sensor Control System

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Abstract. Based on the principle and characteristics of the zero-flux Hall current sensor, traditional Hall current sensors mostly use analog drive circuits, which have low output power, poor anti-interference ability and are inconvenient to debug. Aiming at the disadvantages of traditional sensors, a method based on the composition and technical realization of a digital drive system with DSP as the core is given. DSP is used as the main controller which combined with CPLD to realize the distribution of information. The hardware circuit of the drive system is designed that includes operational amplifier circuit, DSP processing circuit, optocoupler circuit and power amplifier circuit. Also, the system application software is designed and it includes the DSP program of the main control board, the CPLD information distribution program and the upper computer application software. Through analyzing the waveforms and data of the experimental test, the results show that the designed sensor digital drive system has good uncertainty, linearity, and anti-interference. All indicators have reached the design requirements and have a wide range of practicability.

1. Introduction
The development of sensor technology is the commanding height for countries to compete for high-tech technology in the future, and it is also one of the three pillars of modern information technology. The three major information technologies are sensor technology, communication technology and computer technology. As one of the most widely used and one of the largest number of sensors in the world, the Hall current sensor has the advantages of high sensitivity, high accuracy, low temperature drift, long working life, high reliability and high safety.[1]

Based on the advantages of the above Hall current sensor, this article designs a 30kA high current Hall sensor drive circuit for nuclear fusion based on the closed-loop zero-flux Hall current sensor. This drive circuit is based on a DSP chip to handle signals. This design separates the drive circuit and the measuring head while ensuring the accuracy of the sensor, avoiding the interference of the drive circuit in a strong magnetic field environment. The closed-loop parameters can be adjusted directly through the upper computer, which facilitates the debugging of the sensor. Furthermore, it can really meet the needs of the nuclear fusion field.
Traditional high current sensors use analog drive circuits (mainly composed of analog integrators and comparators) to generate PWM signals that drive the secondary coil. This drive circuit has the advantages of simple structure and high accuracy. However, in actual use, the shortcomings of analog drive circuit are also very obvious, that is, the circuit has poor anti-interference ability, insufficient output power and inconvenient debugging. Therefore, traditional high-current sensors are difficult to meet the needs of the actual working environment in the field of nuclear fusion [2].

2. Working principle of zero flux hall current sensor

2.1. Hall effect phenomenon
The Hall effect was first discovered when studying the relationship between energized metal and magnetic field. Later, people used semiconductor materials to replace metal materials and achieved better results. The specific process is as follows: put the energized semiconductor material into a magnetic field, and place the magnetic field at an angle of 90 degrees with the direction of the current. At this time, the carriers in the conductor will be shifted due to the Lorentz force. There will be a voltage difference between the two sides of the sheet, and the movement of the carrier will reach an equilibrium state under the action of the electric field and the magnetic field. This process is called as the Hall effect, and the voltage generated is called as the Hall potential [3]. Hall potential $V_h$ is:

$$V_h = K_h \cdot I \cdot B = \frac{R_h}{d} \cdot f\left(\frac{L}{b}\right) \cdot I \cdot B$$

In the formula:

- $I$ —— current through the Hall element
- $B$ —— Magnetic induction intensity perpendicular to Hall element
- $K_h$ —— Sensitivity coefficient of Hall material

$$K_h = \frac{R_h}{d} \cdot f\left(\frac{L}{b}\right)$$

Among them:

- $R_h$ —— Hall coefficient
- $L, b, d$ —— The length, width and height of the Hall element
- $f(L/b)$ —— Correction factor

2.2. Working principle
The primary side current $I_1$ of the zero-flux Hall current sensor generates a balance between the magnetic field $B_1$ generated in the magnetic core and the magnetic field $B_2$ generated by $I_2$ in the four-side coil on the secondary side. So that the four Hall elements can always maintain zero magnetic field. Compensating current $I_2$ generation mode: After the Hall element senses the unbalance of the magnetic field, it generates the Hall voltage $V_h$. And then, through circuit of proportional amplification and integral adjustment, it is converted into a PWM signal for driving the power amplifier circuit. Finally, the power amplifier circuit provides by the. The voltage provides the corresponding duty cycle voltage and forms the compensation current $I_2$ on the secondary side. When the entire sensor system is stable, the primary and secondary magnetic fields always maintain a balance point [4], that is:

$$N_1 \cdot I_1 = N_2 \cdot I_2 \quad (3)$$

Considering that the magnetic core used is a square frame shape, the magnetic field strength at different positions on the magnetic core is different. In order to improve the overall accuracy of the system, the Hall elements is designed to install at the midpoints of the four sides of the frame in the sensor system that are symmetrical to each other of the magnetic core. There are 4 Hall elements in total, which are used to sense the magnetic field strength at 4 points. The sum of these 4 Hall voltages is used to measure the unbalanced amount of the magnetic field as the feedback amount of the system [5]. The working principle of the zero-flux Hall current sensor is shown in Figure 1.
3. Digital drive circuit

The drive circuit system of the closed-loop Hall current sensor is divided into four parts:

1) Operational amplifier circuit adjusts the Hall voltage obtained from the Hall element to a range suitable for input to the DSP.

2) DSP processing circuit is mainly used to realize A-D conversion, PI adjustment, over-temperature and over-voltage protection, which is communicated with the host computer. So that it can realize the operation of open-loop debugging and other functions.

3) Optocoupler circuit plays a role of isolation between the DSP processing circuit and the power amplifier circuit before the digital circuit and the analog circuit. The circuit can limit the size of the drive signal to play a role in overvoltage protection.

4) Power amplifier circuit, principle of which is that PWM wave drives the MOSFET to turn on to form a voltage signal with a certain duty cycle that added to both ends of the compensation coil to form a feedback current.

Its driving work flow chart, as shown in Figure 2.

3.1. Operational amplifier circuit

When the current on the primary side changes and the magnetic field balance is broken, the sensitive element induces the magnetic field imbalance to generate a weak Hall voltage $V_h$. Because the voltage is very small, this signal needs to be amplified and adjusted. The OPA2277 high-precision operational amplifier is used which can change the resistance to change the magnification. The resistance between pin 1 and pin 2 of OPA2277 forms a proportional amplifying circuit, and the resistance and capacitance between pin 6 and pin 7 form an integral adjustment circuit\(^6\). The circuit of this design adjusts the magnification by adjusting the adjustable resistance connected to the capacitor. The circuit diagram is shown in Figure 3.
3.2. DSP processing circuit

The DSP used in the digital drive circuit is TMS320F28335PGFA produced by TI. This device is a common chip with high precision, low cost, low power consumption, high integration of peripherals. Also, it has large data and program storage, and the accurate A/D conversion is fast [7].

The sampling channels 1-4 in the DSP signal processing board respectively receive the Hall voltages of the 4 Hall elements. After processing, these signals are sent to the DSP for A-D conversion and PI adjustment, and then the DSP sends the processed signals to the CPLD. The CPLD distributes the information sent by the DSP through programming, and distributes the signal to the optocoupler circuit in the form of a PWM wave, which is used to drive the MOSFET in the power amplifier circuit. This function is realized thanks to that the CPLD can easily change the output definition pin. Secondly, CPLD can also play a protective role, that is, after receiving the protection signal by changing the corresponding flag to block the pulse, the protection signal that can be received includes the over-temperature protection signal sent from the temperature sensor and from over-voltage protection signal sent by the optocoupler circuit. Any protection will make the CPLD no longer send PWM waves to the optocoupler circuit of the next stage. The principle of the DSP signal processing board is shown in Figure 4.

DSP will maintain real-time communication with the host computer through the serial interface, so that the operator can remotely operate and obtain information on the host computer, thus achieving the following functions [8]:

1) Accept the fault signal and display it on the program interface of the host computer.
2) The host computer can store the received PWM signal in the form of waveform or data.
3) Through the program of the host computer, the user can choose two modes of open-loop debugging and closed-loop operation. Open-loop debugging mode directly input the duty cycle on the host computer to directly control the DSP to send a PWM wave with a fixed duty cycle to the next stage, which is used to debug the system with a given fixed duty cycle. Closed-loop operation is the normal operating state of the sensor system, the user can manually input the \( K_p \) and \( K_i \) parameters of the DSP for PI adjustment on the upper computer.
3.3. Optocoupler circuit

The optocoupler module chooses the gate drive optocoupler ACPL-332J produced by Avago. Its advantage is that the output drive current is up to 25 A, and it can make the protection of the $V_{CE}$ and $V_{DS}$ of the power tube very simple \[9\]. The driving voltage DRV1+ and DRV1- of the optocoupler circuit are provided by the power module WRB2424S-3WR2. The function of using this DC/DC chip is to isolate and redefine the output reference voltage point. That is, E1 is the reference voltage, and +24 V is divided into DRV+ for +16 V and DRV- for -8 V.

The optocoupler circuit is located between the DSP processing circuit and the power amplifier circuit. It is used to transmit the 4-channel PWM signal output from the DSP, and can isolate the digital part and the analog part of the drive circuit, which greatly reduces the interference between the digital circuit and the analog circuit. In addition, the optocoupler circuit can also easily realize the overvoltage protection function of the switch tube. Since the drive power amplifier circuit needs 4 independent PWM signals, the optocoupler circuit also needs 4 mirror circuits, which are used to transmit and adjust the 4 PWM signals. One of them is taken as an example of specific introduction and analysis, as shown in Figure 5.

![Figure 5. Optocoupler circuit diagram](image)

The working principle of the optocoupler circuit is that the XPWM1 signal (amplitude +5 V) output by the DSP processing circuit is the PWM signal after negation and it is input to the $V_{in+}$ pin of the optocoupler chip. At the same time $V_{in-}$ is input +5 V high level which can make the actual output signal equivalent to the complementary signal of XPWM1. Through photoelectric coupling, the $V_{out}$ signal is separated from the XPWM1 signal, their frequencies are the same, and the sum of the duty ratios is 1, which realizes the negation of the XPWM1 signal while isolating. Then the $V_{out}$ signal enters the auxiliary circuit. When $V_{out}$ is high, transistor Q2 is turned on, Q3 is turned off, and PWM1 is high. When $V_{out}$ is low, transistor Q2 is turned off, Q3 is turned on, and PWM1 is low. Therefore, the difference between the PWM1 signal and the $V_{out}$ signal is only the change of the amplitude and the change of the parameter potential, and the reference potential of the PWM1 signal is the potential of the $V_E$ pin of the optocoupler chip, that is, the potential of E1.

The principle of overvoltage protection is that when the voltage of the DESAT pin exceeds 7 V, the level on the FAULT pin will change from high to low within 5 \(\mu\)s according to the ACPL-332J Datasheet. The FAULT output is an open set allows multiple ACPL-332Js in the circuit to be connected together. Only one of the FAULTs needs to be converted to low level, and the FAULT potential is low and locked at low power. At this time, all ACPL-332Js output will all be blocked to low level, the FAULT signal received by the DSP processing circuit is also low, and the circuit protection information is transmitted to the upper computer \[10\].

3.4. Power amplifier circuit

The power supply voltage of the power amplifier circuit is a positive and negative DC voltage, in which the absolute value of VDC+ and VDC- are equal, and 0 is 0 potential. The power amplifier circuit adopts a positive and negative symmetrical design. In order to output forward or reverse voltage at the lead-out position (that is, the secondary side coil is connected in series with a sampling
resistor); 4 PWM waves drive T1, T2, T3, T4, and control the voltage at the lead-out position by controlling the on and off of 4 MOSFETs. The specific working principle is illustrated by taking the forward direction as an example: When a forward voltage needs to be generated, PWM2 is high, MOSFET T2 is always on, and the corresponding PWM4 is low, and MOSFET T4 is always off. PWM1 is a PWM wave with a good duty cycle, which is used to control MOSFET T1. PMW3 and PMW1 are negated. At this time, the state of MOSFET T3 has no effect on the circuit. When T1 is turned on, the current direction is VDC+ → T1 → T2 → lead position → 0. When T1 is turned off, the current direction is lead position → D1 → T2 → lead position, forming a freewheeling loop and the lead position is connected to the secondary side coil. The coil inductance is very large and the compensation current on the secondary side coil is controlled by controlling the duty cycle of PMW1\(^{[11]}\). The schematic diagram of the power amplifier circuit is shown in Figure 6.

![Figure 6. Schematic diagram of power amplifier circuit](image)

4. Steady state error analysis

According to the working principle of the sensor closed-loop system, each part of the sensor can be equivalent to a transmission block diagram\(^{[12]}\), as shown in Figure 7.

![Figure 7. Block diagram of closed loop system](image)

The system block diagram after equivalent transformation is shown in Figure 8.

![Figure 8. System block diagram after equivalent transformation](image)

From Figure 7 and Figure 8, we can get:

\[
G(s) = K_1K_2K_3K_4
\]  

(4)
The steady-state error of the system:

\[ E(s) = I_i(s) - NI_s(s) \]  

Its time domain form is:

\[ e(t) = I_i(t) - NI_s(t) \]  

Let the input of the system \( I_i(t) = 1 \), then \( I_i(s) = \frac{1}{s} \), the steady-state error of the system:

\[ e_{ss} = \lim_{s \to 0} e(t) = \lim_{s \to 0} e(s) \]

\[ e_{ss} = \lim_{s \to 0} \frac{I_i(s)}{1 + K_2K_3K_4K_5K_6} = \lim_{s \to 0} \frac{1}{1 + K_2K_3K_4K_5K_6} \]  

In formula (8), it is obvious that the larger the larger the \( K_2K_3K_4K_5K_6 \), the smaller the steady-state error turns. Among them, \( K_2, K_3, \) and \( K_6 \) are constants, \( K_4 \) is the gain of the power amplifier circuit. From the perspective of energy consumption, \( K_4 \) has a limited range of selectable sizes and is inconvenient to adjust. It is fixed as a constant \(^{[13]}\); \( K_3 \) is the gain of the primary amplification and is easy to adjust, so you only need to adjust the value of \( K_3 \) to be large enough to make the steady-state error of the sensor system meet the measurement requirements. Compared with the traditional analog drive circuit, it is necessary to modify the physical parameters of the operational amplifier circuit to adjust the primary amplification. This digital drive circuit is superior and convenient. Because the primary amplification is composed of the operational amplifier and the gain adjustment of the DSP, only by operating the host computer to control the DSP adjustment gain, the purpose of adjusting the primary amplification gain and changing the output power can be achieved. This operation can be realized at any time during the use or debugging of the sensor \(^{[14]}\).

5. Measurement results and processing

5.1. Measurement methods
The selected test power supply is a high-precision inverter power supply. The output current of this power supply can be positive and negative DC and AC. The output is connected to the load through a wire. The load is a large toroidal coil. The sensor and the traditional sensor are designed to be sleeved in the large toroidal coil arm (That is, the power supply outputs a small current to double the current by the equivalent ampere-turn method). In addition, the output wire of the high-precision inverter power supply is covered with a standard current sensor; and the entire test system is placed around the EAST nuclear fusion device (there is a strong Electromagnetic field).

The sensor circuit is designed to collect AC and DC signals. The board control circuit uses a DC 12 V power amplifier circuit with a supply voltage of DC ± 80 V.

Connect the signal output end of the designed sensor to a precision resistor and the other end of the resistor is connected to the 0 potential of the ±80 V power supply. Collect the voltage signal at both ends of the precision resistor and the output voltage signal of the standard current sensor respectively.

5.2. Measurement process
This test is tested under the condition that the output current of the primary side high-precision inverter power supply is positive and negative DC. Turn on the power supply to stabilize the sensor system for half an hour, adjust the high-precision inverter power supply, so that the current output starts from 0 A and increase positively, and pause at every 5kA interval. After the point is stable, read once, and the sequential current reaches 30 kA then retreat to zero. The current starts from 0 A and increases in the negative direction, pauses every -5 kA, and reads once after the point is stable. The
current in sequence reaches -30 kA and then retreats to zero. Special attention must be paid when reading. Keep the current stable at each current point and read [15]. By analyzing the experimental waveforms, it is found that the design sensor has small ripple and small burrs and the traditional sensor has large ripples and large burrs. The experimental test waveform is shown in Figure 9.

5.3. Measuring range and accuracy level (precision)
In the experimental data, $I_0$ is the current value of the standard current sensor on the primary side. $I_1$ is the current value of the secondary side design sensor. $I_2$ is the current value of the traditional secondary side sensor. $\delta$ is the relative error, $\delta=(X-X_s)/X_s \times 100\%$, Where $X$ is the indication value of the design sensor or the traditional sensor, $X_s$ is the indication value of the standard sensor, and $\delta_1$ and $\delta_2$ are the indication errors of the design sensor and the traditional sensor respectively. Test is operated
at room temperature, and the experimental data are shown in Table 1.

| No. | $i_1/A$ | $i_2/A$ | $I_1/A$ | $I_2/A$ | $\delta$ |
|-----|---------|---------|---------|---------|---------|
| 1   | -0.5642 | -5.0117 | -30015  | -30070  | 0.18%   |
| 2   | -0.4679 | -4.1588 | -24892  | -24953  | 0.24%   |
| 3   | -0.3731 | -3.3172 | -19848  | -19903  | 0.27%   |
| 4   | -0.2810 | -2.4990 | -14994  | -15003  | 0.30%   |
| 5   | -0.1878 | -1.6710 | -9990   | -10026  | 0.35%   |
| 6   | -0.0939 | -0.8360 | -4995   | -5015   | 0.41%   |
| 7   | 0.001   | 0.0107  | 53.2    | 64      | -a      |
| 8   | 0.0961  | 0.8558  | 5112    | 5135    | 0.44%   |
| 9   | 0.1909  | 1.6990  | 10155   | 10194   | 0.38%   |
| 10  | 0.2812  | 2.5011  | 14959   | 15006   | 0.31%   |
| 11  | 0.3885  | 3.4533  | 20668   | 20720   | 0.25%   |
| 12  | 0.4751  | 4.2235  | 25275   | 25341   | 0.26%   |
| 13  | 0.5660  | 5.0287  | 30111   | 30172   | 0.20%   |

a. The seventh group of data is the output value of each sensor at zero current (e.g. zero drift value).

In the table, the maximum relative error of the designed sensor is 0.43%, which appears at the point where the current is the smallest in the experiment. It is obvious that the relative error is larger when the current is small. The reason for this is that the zero drift is not completely eliminated. When the data is small, the zero drift of the acquisition and measurement affects the accuracy level of the sensor. But the overall accuracy level has reached 0.5 level (precision is 0.5%). The maximum relative error of the traditional sensor is too large and the linearity is poor. Through analyzing Figure 9 and Table 1, the feasibility and anti-interference of the drive system design is verified.

6. Concluding remarks

In order to meet the needs of the circuit with high output power, easy debugging and strong anti-interference ability. This paper designs a digital drive system based on DSP based on in-depth research on traditional sensors which aims at the disadvantages of traditional Hall sensor analog drive. The system is divided into a hardware part and a software part. The hardware part includes operational amplifier circuit, DSP processing circuit, optocoupler circuit, power amplifier circuit. The software part mainly includes DSP program, CPLD information distribution program, upper computer application software. The experimental platform is used for experimental testing. The experimental test fully verified the rationality and effectiveness of the hardware design and software design. The experimental waveforms and data show that this drive system improves the anti-interference ability of the circuit and increases the output power while ensuring the accuracy of the sensor. Since the closed-loop parameters can be adjusted directly through the upper computer, it is convenient for the sensor debugging.

Acknowledgments

National Magnetic Confinement Nuclear Fusion Energy Development Research Project (2015GB103002).
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