Design of a Multi-Channel Expandable High-Precision Isolated Current Source Module

Jin Chuanxi¹, Liu Minghui¹, Chen Panhui¹
(¹School of Nuclear Science and Technology, Naval University of Engineering, 430033, Wuhan)

* Corresponding Author: Liu Minghui; email: byesbuter@163.com; phone:18202734315.

Abstract: Small current source module has low accuracy, big ripple and cannot be used for multi-channel expansion and isolated output. In view of this, a high-precision isolated current source module for multi-channel expansion is designed. The current source module consists of an isolated power supply circuit, an A/D conversion circuit, a linear current stabilizer circuit, and a digital isolation circuit. MCU can implement control of the module through only three ordinary IO ports, and one MCU can simultaneously control multiple current source modules to complete multi-channel isolated output. The output accuracy of each channel can reach a level of 0.001mA.

1. Introduction

Nowadays, micro current with low signal distortion, low transmission cost and long-distance transmission has been widely used in various industries as a signal transmission method in the field of instrument control [1-2]. The research on high-precision small micro-current source has always been a difficult problem that plagues many industries [3-5]. As the existing calibration equipment is too large to be used for on-site testing, the circuit of the tested unit can only be disassembled and sent to the production unit or workshop for testing and calibration, which greatly reduces the maintenance efficiency and significantly increases the maintenance cost. Moreover, the current source in the current market has low output current accuracy and big ripple. If the system uses multiple current source modules at the same time, there is no electrical isolation between the modules, resulting in great mutual noise interference between the modules [6-7]. To improve on-site maintenance efficiency of the equipment and accuracy of calibration, this paper studies and designs small, multi-channel expandable high-precision current source, and proposes a high-precision current source design method supporting multi-channel expansion and isolated output.

2. Overall design

The expansion system diagram of the current source module is shown in Figure 1. The current source module is connected to the control board of the test current output system through a 6-seat connector, including +5V power supply, +3.3V power supply, ground, and four data cables for control. Electrical isolation is achieved between the current source modules and between the current source module and the MCU to avoid noise interference between the modules, thus improving the output accuracy and stability of the current source module. The upper computer is used to control the current output value of each module.
Figure 1. The expanded application diagram of the current source module

The circuit structure diagram of the current source module is shown in Figure 2, which consists of digital isolation, power isolation, D/A, linear current stabilizer, etc. The module implements digital isolation through the chip ISOW7841, and achieves the isolation and boost of the power supply through the power transformer driver. MCU controls the output voltage of DAC8830 through the data cable, outputs a stable current based on linear current stabilizer circuit.

Figure 2. Circuit structure diagram of current source module

3. Hardware design

3.1. Power circuit
Power circuit constitutes an important part of the current source module. Stable operation of the power module is an important guarantee for safe and stable operation of the test equipment and also a prerequisite for the normal operation of the current source module. The current source module needs a DC power supply to supply power for the operational amplifier, linear current stabilizer, reference source parts, etc. At the same time, to ensure that the operational amplifier can achieve 0V output, provision of a certain negative voltage is needed. A 3.3V DC power supply is required to supply power for the digital isolator and DA. It can be seen that the current source output system has complicated power supply. If the power supply is isolated on the control board, different power-consuming chips will cause certain voltage drop to the power supply. At the same time, there will be a certain degree of clutter, which will affect cleanliness degree of the power supply [8-10]. Therefore, each module has its own isolated power supply system to minimize the adverse effects between the modules. The schematic diagram regarding the power supply mode of the current source module is shown in Figure 3.
As shown in Figure 3, the current source module is connected to +3.3V DC power supply via the interface, and the +3.3V DC power supply is isolated and output by the digital isolator ISOW7841 to supply power to DA. The +5V DC power supply is connected through the interface, isolated and boosted by the low-noise transformer driver SN6505 to supply power to the operational amplifier, reference source and other chips. SN6505 is a push-pull transformer driver with low noise, low electromagnetic interference, which is specially designed for small isolated power supply. SN6505 can drive a center tap through DC power supply, which can achieve twice the turns ratio boost through full-wave rectifier circuit, that is, \( V_{OUT} = 2n \cdot V_{IN} \). Therefore, when SN6505 is used in conjunction with a transformer with a turns ratio of 1:3.1, +5V voltage of the main control board bus can be boosted to 31V. Considering that the operational amplifier OPA4188 needs to output 0V, the system needs to provide a certain amount of negative voltage. Using the chip alone to produce negative voltage wastes resources slightly, so two diodes are connected in series at the negative end of the full-wave rectifier, and the reference ground of the current source module is set at the positive end of the diode. In this way, a negative voltage of about 1.4V can be provided to meet the circuit needs. The isolated power circuit diagram of current source module SN6505 is shown in Figure 4.

Because the DC power supply output by the switching power supply has excessive noise, if no processing is provided, the power supply noise will be directly superimposed on the current output end, affecting the output accuracy of the current source [11-12]. To this end, a low-dropout linear regulator TPS7A39 from TI is selected as the current source module, whose schematic diagram is shown in Figure 4. The noise of TPS7A39 is 21\( \mu \)VRMS, and the noise rejection ratio is 52Db in the range between 10Hz and 2MHz. The output range of TPS7A39 is up to ±30V, and the output voltage can be independently adjusted to symmetrical or asymmetrical voltage externally. The positive and negative outputs of TPS7A39 are proportionally tracked during start-up, thereby alleviating common floating and other power sequencing problems in dual-rail systems. In this way, power noise such as switching power supply that can affect signal integrity is eliminated. Considering that the output voltage of TPS7A39 can be adjusted according to an external resistance and its function requires a certain voltage difference between the input voltage and the output voltage, the voltage output formula is shown in formula (1).
\[
\begin{align*}
V_{\text{OUTP}} &= V_{\text{REF}} \times (1 + R_{\mu} / R_{\mu}) = 1.2 \times (1 + 210 / 10) = 26.4V \\
V_{\text{OUTN}} &= V_{\text{REF}} \times (-R_{\nu} / R_{\nu}) = 1.2 \times (-8.1 / 10) = -0.972V
\end{align*}
\] (1)

3.2. DAC8830 circuit

In the circuit design, the digital-to-analog conversion chip is the 16-bit single-channel digital-to-analog converter DAC8830 launched by TI. For high-precision digital-to-analog conversion, the cleanliness of the reference voltage directly affects the chip performance, so the reference voltage is required to have extremely low noise and temperature drift. Here, 2.5V reference voltage generated by AD780 is selected as the reference voltage. Similarly, to prevent the reference power supply output load from affecting the reference power supply and reduce the plug-in output accuracy, the AD780 output end is driven by the operational amplifier, and then connected to DAC8830. The schematic diagram of the reference power supply is shown in Figure 5. The AD780 output reference voltage VREF is filtered by RC and then input to DAC8830 through a follower. Since the operational amplifier has strong output, adding a decoupling capacitor to the output end will cause fluctuations in the power supply, so the operational amplifier output is directly input to the reference voltage pin of DAC8830. To reduce the adverse effect of the operational amplifier on reference voltage accuracy, a high-precision, low-noise, rail-to-rail zero-drift operational amplifier OPA4188 from Texas Instruments (TI) is selected here. Its offset voltage is as low as 5µV and the drift is as low as 0.03µV/0C.

![Figure 5. Reference voltage circuit](image)

The schematic diagram of the DAC8830 circuit is shown in Figure 6. The data sheet shows that the output range of the DAC8830 output voltage VOUT is 0V ≤ VOUT ≤ VREF, that is, 0V ≤ VOUT ≤ 2.5V.

![Figure 6. Schematic diagram of DAC8830 circuit](image)

3.3. Linear current stabilizer circuit

In linear voltage stabilization and current stabilization, even though the linear adjustment power triode in the current stabilizer circuit works in the linear amplification region, the constant current circuit sends the output current signal to the differential comparator amplifier circuit, and the signal is amplified and sent to the inverting end of the first-stage operational amplifier in the form of negative feedback, which makes the power supply maintain a constant current state under the load change [13-15]. The linear current stabilizer circuit diagram is shown in Figure 7.
The voltage signal output by DAC8830 is amplified in the same direction by the operational amplifier OPA4188-B and then sent to the base stage of the triode to achieve power amplification. At the same time, the voltage signal at both ends of the sampling resistor R1 is sent to both ends of the differential amplifier INA34. After amplification, it is sent to the inverting end of OPA4188-C, so that the voltage value at both ends of the sampling resistor is stabilized at the voltage output value of DAC8830. That is, the sampling resistor current will not change with the load, but changes with the output voltage of DAC8830 to achieve the effect of current stabilization. The output current is shown in formula (2).

$$I_{OUT} = \frac{V_{OUT}}{RS \cdot n} \quad (2)$$

Where: $I_{OUT}$ is the output voltage value of DAC8830; $I_{OUT}$ is the output current value; $R_S$ is the resistance value of the sampling resistor; $n$ is the amplification factor of the differential amplifier. It can be seen from formula (2) that, sampling resistor accuracy exerts a great influence on the accuracy and stability of the output current, and sampling resistor also has certain power consumption. In view of this, the current source module uses a low temperature drift metal platinum chip resistor SMR3D. The temperature drift is lower than 2PPM/℃, and the rated power reaches 0.6W. The power consumption of the sampling resistor is $p = R_S \cdot I_{OUT}^2$. Hence, in a constant current circuit, lower resistor resistance means lower power consumption. According to formula (2), it can be known that when the DAC8830 output voltage and the module output current are constant, higher amplification factor of the differential amplifier means lower sampling resistance. However, while the differential amplifier amplifies the voltage signal on both ends of the sampling resistance, it will also increase noise. Based on comprehensive consideration, the sampling resistance of the current source module is determined to be 100Ω.

Although the output voltage range of DAC8830 is $0V \leq V_{OUT} \leq V_{REF}$, its output at zero point is very unstable, and zero setting of the system is inconvenient. If the output of the current source module can be output from a certain negative current, it is possible to avoid the unstable output area of DAC8830, so that the current source module can work stably at the zero point. Excessive output of negative current will waste the output range of the current source module. According to the principle of differential amplifier, if a certain reference voltage VREF2 can be provided to the differential amplifier, based on the feedback network formed by OPA4188-D, an addition circuit can be formed so that the current source module can output a certain negative current. At this time, accuracy of the reference voltage VREF2 will affect output accuracy of the current source module. For this reason, the reference voltage output by AD780 is selected and driven by a follower composed of OPA4188-A, so that low voltage reference voltage output is possible through the voltage divider formed by precision resistor network LT5400. Four-way precision matching resistor network is LT5400-3, that is, the resistance values of the four resistors are $R1 = 100k$, $R2 = 10k$, $R3 = 10k$, $R4 = 100k$. The matching error in the chip matching resistance is as low as 0.01%, and the matching temperature drift is as low as 0.2PPM/℃, which meets the accuracy requirements. The voltage value of the low voltage reference voltage is shown in formula (3).

$$V_{REF2} = \frac{V_{REF2}(10k/10k)(100k+100k+10k+10k)}{(100k+100k+10k+10k)} = 0.06V \quad (3)$$

From formula (3), it can be seen that the matching resistance accuracy of the differential amplifier also exerts a great influence on the accuracy and stability of the output current. To ensure
measurement accuracy, the precision operational amplifier INA134 composed of a differential amplifier produced by TI is selected here. Figure 8 is the internal schematic diagram of INA134. The working principle diagram of the differential operational amplifier is shown in Figure 9. It is an amplifier combining inverting input and non-inverting input. According to the superposition principle, there is:

\[ V_{\text{OUT}} = (1 + \frac{R_f}{R_1}) \left(\frac{R_2}{R_1 + R_f} V_2 - \frac{R_f}{R_1} V_f \right) \]  

(4)

When \( R_2 = R_f \) and \( R_f = R_1 \), there is

\[ V_{\text{OUT}} = \frac{R_f}{R_1} (V_2 - V_f) \] \( \Rightarrow \) \( V_{\text{OUT}} = \frac{V_{\text{REF}}}{V_2} = \frac{R_f}{R_1} \)

(5)

As shown in Figure 8, INA134 internally integrates a precision resistance network, which effectively solves the problem that temperature drift of the resistance affects the measurement accuracy. When the Sense pin of INA134 is connected to the Output pin to form a negative feedback circuit, its gain is:

\[ A_{\text{Vf}} = \frac{R_f}{R_1} = \frac{25k\Omega}{25k\Omega} = 1 \]

(6)

In summary, the output range of the current source module is shown in formula (7).

\[ -\frac{V_{\text{REF}}}{R_3 \cdot n} \leq I_{\text{OUT}} \leq \frac{V_{\text{REF}}}{R_3 \cdot n} \Rightarrow -0.6mA \leq I_{\text{OUT}} \leq 24.4mA \]

(7)

3.4. Digital isolation circuit
The current source is isolated and output, so digital signal isolation is necessary. In the current source module design, ISOW7841 produced by TI, a low radiation, reinforced digital isolator with integrated power supply, is used. The schematic diagram of ISOW7841 is shown in Figure 10. The advantage of ISOW7841 is that it has interior power isolation, and the isolated 3.3V power source can be used as the power source for chips such as DA. Single power supply alone can achieve the digital isolation effect and provide power, thus simplifying the circuit.

4. DAC8830 programming
The data of DAC8830 is controlled and transmitted by the transmission chip select line (CS). When CS is at high level, the MCU cannot access DAC. MCU accesses DAC by pulling the CS line low, and
latches the serial data on the data line (SDI) to the input shift register at the rising edge of the clock signal line (SCLK). The data latch sequence is from low to high. All data registers have 16 bits, and CS must be pulled high after 16 SCLK inputs are completed. The timing diagram of DAC8830 is shown in Figure 11. According to the DAC8830 data manual, when the chip is powered by 3.3V, the minimum clock cycle tsck is 20ns, and the minimum DAC data update time ttd is 30ns.

![Figure 11 DAC8830 timing diagram](image)

DAC8830 can output a unipolar voltage from 0V to V_{REF}. The reference voltage of the test system is 2.5V. The relationship between DAC8830 input code and output voltage is shown in Table 1.

| Input code | Output voltage |
|------------|----------------|
| 1111 1111 1111 1111 | \( V_{REF} \times (65535/65536) \) |
| 1000 0000 0000 0000 | \( V_{REF} \times (32768/65536) = V_{REF}/2 \) |
| 0000 0000 0000 0001 | \( V_{REF} \times (1/65536) \) |
| 0000 0000 0000 0000 | 0V |

5. Main performance test

5.1. Output accuracy test

After the upper computer calibration, to verify the output accuracy of the current source, the output interface is connected with a precision load resistance of 1000Ω (the actual resistance value is 999.78Ω). The current source module outputs a set of current data from 0mA to 20mA. The voltage value at both ends of the corresponding load resistance is measured by a six-and-a-half-digit digital multimeter, and the actual current value is calculated based on Ohm's law. A set of tested data is shown in Table 2. It can be seen from the table that the setting accuracy of the current source module can reach a level of 0.005mA, which has a strong load output capacity to drive 1k, so the set indexes are met.

| Serial number | Setting value /mA | Measured value /mA | Error /FS |
|---------------|------------------|--------------------|-----------|
| 1             | 0                | 0                  | 0         |
| 2             | 5                | 4.997              | 0.0015    |
| 3             | 10               | 9.999              | 0.0005    |
| 4             | 15               | 15.005             | 0.0025    |
| 5             | 20               | 20                 | 0         |
5.2. Sensitivity test
To test sensitivity of the current source module, that is, the response time, the oscilloscope is set to the automatic measurement mode, and the oscilloscope probe end is connected to both ends of the output end-terminated resistor. After the power is turned on, this experiment controls the current source in the 0 output state to output the full scale, and measure the time it takes. The test result is shown in Figure 12, and its response time is 500ms.

6. Conclusion
Based on the design concepts of miniaturization, multi-channel expansion, and integration, a high-precision isolated current source module for multi-channel expansion is designed. The current source module consists of isolated power supply circuit, A/D, D/A conversion circuit, linear current stabilizer circuit and digital isolation circuit, etc., which is connected to the main control board through a six-wire interface. MCU only needs three data lines to complete control of the current source module. In the system hardware design, based on the principle of linear current stabilization, through the application of advanced chips such as high-performance analog-to-digital converter DAC8830, high-precision low-noise operational amplifier OPA4188, the technological advancement and integration level of the current source module is improved. The module output accuracy was tested using a six-and-a-half-digit digital multimeter. Experiments have proved that the current source works stably and has high accuracy, which meets engineering needs.

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