Design of high precision AC current power supply based on STM32F407

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Abstract. The design and implementation of high precision and stable AC current supply plays an important role in the use of various electronic devices. In order to achieve the design requirements of high output accuracy, good stability and low uncertainty, STM32F407 Microcontroller Unit is used as the control core in hardware, high-precision current is generated through digital-analog conversion circuit, and closed-loop adjustment control system is realized with I/V conversion and sampling circuit. Based on the fast Fourier transform theory, the device adopts the technology of surface-source integration and uses liquid crystal display configuration screen as the human-computer interaction medium. The experimental results show that its accuracy can reach 5/10,000, its stability can reach 5/100,000, and its uncertainty can reach 1/1,000. It is suitable for various high-precision occasions.

1. Introduction
The current source is a very important power supply unit. When the external impedance characteristic changes, it can still output a constant current, so it is widely used in modern scientific research and industrial production. Current output currents on the market are generally in a small range, low precision, and expensive. In response to market demand, this paper developed a new high-precision AC current source based on Cortex-M4 core. The main technical indicators are: current source operating voltage 5V; output current accuracy 0.05% RG, stability 0.005% RG / min, uncertainty 0.1% RG; output current range 0 ~ 5A adjustable; maximum output power is 20W; operating frequency 45~70Hz can be controlled.

2. Theory and algorithm of high precision current source
2.1. High-precision current source signal generation method
The fundamental signal output by the current source designed in this paper is synthesized by waveform and amplitude two-stage D/A. There are two ways to produce them: 1) generating a cosine table by programming; 2) importing a cosine table from the outside. Since the second method is better in real-time and reduces program memory consumption, this design uses the second method.

Because this design needs to perform FFT transform processing on the sampled signal, and in order to ensure synchronous sampling and no spectrum leakage and fence effect [1], this design adopts a cosine table method of importing 1024 points from the outside. The cosine table generation process is shown in Figure 1. Let a cosine function be as shown in Figure 1(a), and the corresponding formula is as follows:

\[ x_1(\theta) = \cos \theta, \theta \in [0,2\pi] \]  

(1)
The signal is a continuous signal. After it is subjected to phase 1024 aliquoting, it becomes Figure 1(b). The corresponding formula is as follows:

\[ x_1(n) = \cos \left( \frac{2\pi}{N} \times n \right), n = 0,1,2,\ldots,N-1 \]  

(2)

The peak-to-peak value of the signal is 2. Assuming that the peak-to-peak value of the actual application is A, the corresponding waveform is shown in Figure 1(c), and the formula is as follows:

\[ x_2(n) = \frac{A}{2} \cos \left( \frac{2\pi}{N} \times n \right), n = 0,1,2,\ldots,N-1 \]  

(3)

This design uses a 16-bit bipolar D/A chip with a digital input range of 0 to 65535. When the input digital quantity is 32768, the analog quantity of the D/A output is 0. Therefore, it is necessary to process the amplitudes of the waveform points of Figure 1(c) so that the analog quantities outputted by them are all actual effective values. The processed waveform is shown in Figure 1(d), and the corresponding formula is as follows:

\[ x_4(n) = \frac{A}{2} \cos \left( \frac{2\pi}{N} \times n \right) + C, n = 0,1,2,\ldots,N-1 \]  

(4)

\[ \text{Figure 1. Cosine table generation process.} \]

2.2. High-precision current source related algorithm

2.2.1. Fast Fourier Transform (FFT). Discrete Fourier transform can transform time domain analysis into frequency domain analysis, while frequency domain analysis makes it easier to obtain the amplitude of each harmonic. However, due to its computational complexity, it is rarely used in practical engineering [2]. On the basis of DFT (Discrete Fourier Transform), the FFT (Fast Fourier Transform) algorithm can greatly reduce the amount of computation. The essence of the FFT algorithm is to continuously decompose the long-order DFT into a short-order DFT, and reduce the computational complexity of the DFT according to the periodicity and symmetry of the twiddle factor [3]. Its periodicity and symmetry expression are as follows:

\[ W_N^{kn} = W_N^{(k+N)n} = W_N^{(k+N+n)} \]  

(5)

\[ W_N^{(k+N)/2n} = -W_N^{kn} \]  

(6)
2.2.2. **Base 4 FFT algorithm.** The radix-4 FFT algorithm divides the sequence of length N=4^l into four and the N-point DFT as a linear combination of 4 N/4 point DFT. Then use the symmetry and periodicity of the rotation factor to divide the N/4 point DFT into four, representing the DFT of four N/16 points, and repeat this until it is decomposed into a four-point DFT operation [4].

2.2.3. **Base 4 FFT algorithm complexity analysis.** When calculating DFT S(k) of length L with DFT S_l(k), l=0,1,2,3 of length L/4, the basic unit implements the following formula:

\[
S(k) = \sum_{l=0}^{3} W_L^{lk} S_l(k)
\]

\[
S(k + L/4) = \sum_{l=0}^{3} W_L^{l(k+L/4)} S_l(k) = \sum_{l=0}^{3} W_L^{ik} (-j)^l S_l(k)
\]

\[
S(k + 2L/4) = \sum_{l=0}^{3} W_L^{l(k+2L/4)} S_l(k) = \sum_{l=0}^{3} W_L^{ik} (-1)^l S_l(k)
\]

\[
S(k + 3L/4) = \sum_{l=0}^{3} W_L^{l(k+3L/4)} S_l(k) = \sum_{l=0}^{3} W_L^{ik} j^l S_l(k)
\]

Equation (7) is a formula for the 4 hour butterfly equation. It can be concluded that the base 4 operation requires 3 complex multiplications and 8 complex additions. Since there are a total of N/4 operation butterflies, the number of complex multiplications and complex additions required for the butterfly operation are 3N/4 times and 2N times, respectively.

In the case of N=4^l (l is a positive integer), the decomposition of the N-point sequence into a four-point sequence requires l=log_2 N decomposition [5]. Therefore, the complex multiplication number and the complex addition number required by the base 4 FFT algorithm are respectively

\[
M_c = \frac{3}{4} N \log_4 N = \frac{3}{8} N \log_2 N
\]

\[
A_c = 2N \log_4 N = N \log_2 N
\]

2.2.4. **Closed loop adjustment algorithm.** The PID (Proportion Integral Differential) control algorithm is a control method that performs correction based on the output feedback of the control object, and its expression is as follows

\[
U(t) = K_p e(t) + \frac{1}{T_i} \int_0^t e(t) dt + T_d \frac{de(t)}{dt} + u_0
\]

In the above formula, K_p is the proportional coefficient, T_i is the integral time constant, T_d is the differential time constant, e(t) is the error between the set value and the actual output value, and u_0 is the actual output value. The first three items represent the proportional, integral, and differential adjustments of the input signal [6]. However, in reality, the computer can only process discrete values and process them as follows.

\[
u(t) \approx u(k)
\]

\[
e(t) \approx e(k)
\]

\[
\int_0^t e(t) dt \approx \sum_{j=0}^{k} e(j) \Delta t = T \sum_{j=0}^{k} e(j)
\]

\[
\frac{de}{dt} \approx \frac{e(k) - e(k-1)}{\Delta t} = \frac{e(k) - e(k-1)}{T}
\]

Formula (10) can be converted to

\[
u(k) = K_p [e(k) + \frac{T}{T_i} \sum_{j=0}^{k} e(j) + \frac{T_d}{T} [e(k) - e(k-1)]] + u_0
\]

Where T is the sampling period and k is the sampling point number.

In this design, the closed-loop adjustment system is mainly to adjust the various disturbances of the output signal in the circuit and reduce the steady-state error. Therefore, the design only selects the proportional control link.
3. Hardware design of high precision current source

The high-precision current source developed in this paper adopts the technology of integration of meter and source. The STM32F407ZGT6 microprocessor with Cortex-M4 as its core is used as the operation unit. Its main frequency is up to 168MHz. It has 192KB SRAM and 1024KB FLASH, and it integrates FPU (Float Point Unit) and compatible DSP (Digital Signal Processing) library [7].

The overall structure of the system is shown in Figure 2. The user performs range conversion and labeling control operations on the LCD (Liquid Crystal Display) configuration screen; the MCU (Microcontroller Unit) adjusts the electrical parameters after receiving the relevant operations; using a 16-bit four-quadrant multiplying digital-to-analog converter chip DAC8822, through two levels of D/A turns the digital signal into an analog signal, the first stage output waveform, and the second stage output amplitude; the analog signal is output after power amplification.

![The hardware block diagram of high precision current source.](image)

In order to ensure the accuracy of the output analog signal, it is necessary to make a closed loop adjustment of the output analog signal. The output analog signal is converted into a low voltage and small current signal through the current transformer; its signal is converted into a voltage signal by the I/V conversion circuit; the MCU synchronously samples the voltage signal through the 16-bit high-speed high-precision A/D chip ADS8556 [8]. The sampled data is processed by a base 4 FFT algorithm to obtain an actual electrical parameter. The actual electrical parameters are displayed by the LCD configuration screen; the PID algorithm is used to fine tune the output waveform to achieve closed loop adjustment.

4. Software design of high precision current source

4.1. Software framework

The overall software design of the high-precision current source is matched with each module of the hardware block diagram.

In the main flow chart, the program first performs system initialization, including I/O initialization, variable initialization, timer initialization, etc.; then loads the waveform through the timer interrupt; waits for the LCD configuration screen data input. If there is data input, enter the timer interrupt function to load the output waveform amplitude, and finally output the valid waveform. In order to meet the accuracy requirements, the closed loop adjustment is performed after the waveform is output.

4.2. Waveform output

Timing time interval is the key to ensure the accuracy of the output waveform. Therefore, the waveform output part adopts an advanced timer with a clock frequency of 168MHz and 32 bits.
When the time is up, the waveform timer is interrupted. First, the MCU writes the waveform data to D/A, and loads the output waveform by querying the cosine table; after waiting for the output waveform point to be full, the timer is turned off. When the user inputs the amplitude through the LCD configuration screen, the amplitude electric parameter processed by the MCU is written to the D/A, and the waveform with the amplitude is output, and the current signal with the actual effect is outputted at this time. When the timer frequency changes, it is only necessary to modify the timing interval when the next timer is interrupted.

4.3. Data processing
When the time is up, the sampling timer is interrupted. First, start A/D conversion, sample the voltage signal after I/V conversion; wait for the data in a cycle to be processed, and then perform the base 4 FFT operation; when the sampling period is over N cycles The moving average of the electrical parameters obtained in N sampling periods is used to make the parameters such as the amplitude of the signal more accurate. To do the moving average, you need to sort the electrical parameters obtained by the base 4 FFT operation. Here, the time complexity is used as the quick sorting method. In order to reduce the system error, the middle part of the data is accumulated and then averaged after sorting; finally, it is passed to the MCU for PID closed-loop control adjustment.

4.4. Data display
The touch screen used in the high-precision current source designed in this paper is the SDWe043C06T configuration screen of Zhongxian Technology. The configuration screen is driven by variables. All displayed characters and icons are defined as a variable, and the variable storage address is assigned, the display format is defined, and the configuration file is generated and downloaded to the display terminal. When the display needs to be refreshed, the user only needs to send the variable content and the variable storage address to the display terminal through the serial port, and the display terminal will automatically display according to the defined display format [9].

The interface production process is as follows: firstly, the border text of the interface is drawn according to the designed template in the Visio drawing software; then the corresponding control is dragged to the corresponding position by the VGUS4.3 interface development tool software; then the properties of the control are set; Finally, the generated configuration file is downloaded to the configuration screen.

5. Experimental results and analysis
Due to the high accuracy of the output current of the device, the ordinary multimeter cannot be used as its testing tool. Therefore, the data measured by the RD-33 three-phase standard meter with an accuracy of 0.01 is used as the measured value.

Accuracy test: The output current is measured in each range, and the actual output current value is measured, thereby obtaining the accuracy of the output current. It can be seen from Table 1 that the maximum error of the output current is 0.0339%, which is less than 0.05% of the design requirement and meets the design requirements.

| Range  | Set value I/A | Measured value I/A | Output current accuracy % |
|--------|---------------|--------------------|--------------------------|
| 0.5    | 0.50017       | 0.500024           | 0.0292                   |
| 1.0    | 1.00035       | 1.000011           | 0.0339                   |
| 2.5    | 2.00061       | 2.000032           | 0.0289                   |
| 5.0    | 3.00087       | 3.000013           | 0.0286                   |
| 5.0    | 4.00073       | 4.000026           | 0.0176                   |
| 5.0    | 5.00098       | 5.000019           | 0.0192                   |
Stability test: The maximum current in the range is output under each range, and the maximum current and minimum current at full scale are measured within 1 minute, thereby determining the stability of the output current. It can be seen from Table 2 that the output current stability is less than 0.005%, which meets the design requirements.

| Range | Set value I/A | Measured value $I_{max}$/A | Measured value $I_{min}$/A | Stability % |
|-------|---------------|----------------------------|---------------------------|-------------|
| 0.5   | 0.50009       | 0.500014                   | 0.499993                  | 0.0042      |
| 1.0   | 1.00021       | 1.000011                   | 0.999972                  | 0.0039      |
| 2.5   | 2.50047       | 2.500052                   | 2.499965                  | 0.0035      |
| 5.0   | 5.00063       | 5.000093                   | 4.999934                  | 0.0032      |

Uncertainty test: According to the evaluation standard of GB/T 27418-2017 Measurement Uncertainty Evaluation and Representation, the Class A standard uncertainty of current input quantity $x_i$ is:

$$u(x_i) = s(X)$$  \hspace{2cm} (12)

Where $\bar{X}$ is the sample mean and $s$ is the experimental standard deviation of the sample mean. The test randomly selects 20 measurements at a certain current set value (due to the large number of data, not listed here), thereby determining the uncertainty of the output current. It can be seen from Table 3 that the uncertainty of the output current under different ranges is very small, indicating that the measured data is very close to the measured true value.

| Range | Set value I/A | Uncertainty % |
|-------|---------------|---------------|
| 0.5   | 0.50004       | 0.0911        |
| 1.0   | 1.00015       | 0.0821        |
| 2.5   | 2.50029       | 0.0769        |
| 5.0   | 5.00057       | 0.0715        |

6. Conclusions

A high precision AC current source device was designed and implemented. The STM32F407 single-chip microcomputer is used as the main control core, and interacts with the user through the LCD configuration screen to realize the output and adjustment of the high-precision AC current source. Through the joint debugging of hardware modules and software modules, the design requirements are met. The look-up table method, base 4 FFT algorithm and PID adjustment algorithm applied in this paper are the key to realize the design requirements, and overcome the characteristics of low output current precision, poor stability and large uncertainty.

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