Research on Constant Current Technology of High Current Power Amplifier for Relay Protection Test Device

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Abstract. In order to provide more accurate and consistent reference current for power system under different loads, the constant current performance of the high-current power amplifier is studied. This paper presents a circuit topology suitable for high-current power amplifier circuits, and analyses the key factors that affect its constant current characteristics. It is found that resistance matching plays a decisive role in the constant current characteristics. Through quantitative analysis and verification, the boundary conditions of the output resistance of the high-current power amplifier under the specified resistance accuracy are also found. Then based on Monte Carlo analysis and worst-case analysis, the previous theoretical derivation afterwards is conducted. Finally, an effective method of resistance matching is brought forward, which is authenticated in the contrast test later.

1. Introduction

In electric power systems, power amplifier circuits are used to simulate and provide voltage or current signals under various applications such as comprehensive testing of relay protection systems, configuring and debugging of merging units, power quality analysis and outdoor installation protection detection [1].

As an important module for simulating and providing analog current signals in electric power system, the constant current performance of high-current power amplifier plays an important role in improving the efficiency of testing and debugging, the effectiveness of analysis and configuration, and the accuracy of detection and verification.

Literature [2] points out that in order to meet the basic requirements of high-current power amplifier circuits, the accuracy should not worsen than 0.2%, the ability of output current should be within 0 ~ 30A, and the load capacity should be within 0 ~ 0.5Ω. For the sake of ac current output, the high-current power amplifier circuit should be designed based on the current source circuit topology with bipolar output.

References [3] and [4] have conducted some studies on the high-current power amplifier circuit, and proposed feasible design ideas respectively. The designs are all based on the improved topology of Howland current source. However, due to the use of positive feedback, the circuit topology has a risk of self-excited oscillation. Meanwhile, the literatures above idealized the resistance of the key resistors without considering the effect of resistance-matching on the constant-current characteristics in the actual design. In addition, digital feedback control is used in literature [3], which increases the complexity of the system and reduces the stability of the system. In literature [4], the analog switch is
added to switch the feedback path, which may force the circuit to enter into the open-loop state due to the hysteresis effect caused by switching.

In order to study the constant-current characteristics of high-current power amplifier circuit, this paper firstly designs a general current source circuit topology based on the current parallel negative feedback, and then combines theoretical analysis and simulation analysis to find and quantify the influence of resistance matching on the output resistance and the constant current characteristic of the high-current power amplification circuit. Then Combined with the requirements for current accuracy in the range of load capacity in practical applications, a resistance trimming method is proposed and tested.

2. Topology of High-Current Power Amplifier Circuit

2.1. Howland Current Source Topology

Howland current source circuit topology includes the basic type shown in figure 1 and the improved type shown in figure 2.

![Fig.1 Topology of the basic Howland current source circuit](image)

The basic type was replaced by the improved type because of some defects in its input impedance, output current limitation, output swing limitation, efficiency and energy consumption.

![Fig.2 Improved Howland current source circuit topology](image)

2.2. General Current Source Circuit Topology based on the Current Parallel Negative Feedback

Aiming at solving the disadvantages of the two kinds of Howland current source circuit topology, this paper designs a general current source circuit based on the current parallel negative feedback by using negative feedback only, as shown in figure 3. U1 is the main amplifier, the resistor R1 and R2 are part of the main feedback network, U2 is a three op amp structure instrumentation amplifier with an amplification factor of AV, RL is the load, RS is the current sampling resistance, RP1, RP2, RN1 RN2 are the resistors in the voltage-divider. VI is input voltage of the current source, IL is output current, VL is the load voltage, VO is the output voltage of U1, VD is the differential input voltage of U2.
Fig. 3 General current source circuit topology of current parallel negative feedback

The open-loop gain of the op-amp is usually between 60db and 160db [8], and the input impedance of the FET op-amp is usually more than 100 GΩ [9], so the open-loop gain and input impedance of the op-amp can be regarded as infinite in theory analysis. According to Kirchhoff's current law and instrument amplifier characteristics, equation (1) can be derived.

\[
\begin{align*}
V_L + A_v V_D &= 0 \\
V_D &= \frac{R_{P1}}{R_{P1} + R_{P2}} V_o + \frac{R_{N1}}{R_{N1} + R_{N2}} V_L \\
V_o - V_L &= \frac{R_L}{R_S} V_{R1} + \frac{V_L}{R_{N1} + R_{N2}} \\
V_L &= R_L I_L
\end{align*}
\]

(1)

According to equation (1), the output current \( I_L \) of the current source is shown in equation (2).

\[
I_L = -\frac{R_L (R_{P1} + R_{P2}) (R_{N1} + R_{N2}) V_I}{R_S A_v R_{P1} R_L (R_{N1} + R_{N2}) + K R_L}
\]

(2)

It can be seen from equation (2) that the output current \( I_L \) of the current source is affected by the load \( R_L \), and \( K \) is used to express the impact, as shown in equation (3).

\[
K = R_{P2} (R_{N2} + R_S) - R_{N1} R_{P2}
\]

(3)

The smaller the \( K \) is, the better the constant current characteristics of the current source is. When \( K=0 \), the output current of the current source is shown in equation (4).

\[
I_L = -\frac{R_L (R_{P1} + R_{P2}) V_I}{A_v R_{P1} R_L R_S}
\]

(4)

At this point, the output current is not affected by the load. In an ideal situation, the output resistance of the current source is infinite.

3. Analysis of Output Resistance

According to equation (2), the output resistance is shown in equation (5).

\[
R_o = \frac{R_{P1} R_S (R_{N1} + R_{N2})}{K}
\]

(5)

According to equation (5), the smaller the \( K \), the greater the output resistance is and the better the constant-current characteristics of the current source can have.

Equation (3) defines the degree of resistance matching. The smaller the value of \( K \), the better the resistance matching of \( R_S, R_{P1}, R_{P2}, R_{N1} \) and \( R_{N2} \) can be obtained.
Considering the sampling precision and thermal effect, the resistance of RS between 10 mΩ and 30 mΩ is a good choice.

The higher the resistance value, the higher the resistance noise is; the smaller the resistance value, the higher the power. Therefore, considering the power consumption and the resistance noise, the values of RP1, RP2, RN1 and RN2 are usually between 10k and 20k.

For the sake of analysis, the median of 15 k and the relatively high resistance accuracy of 0.1% are taken for RP1, RP2, RN1 and RN2, so the actual resistance of RP1, RP2, RN1 and RN2 is between 15015Ω and 17985Ω which means a 15 Ω offset. The offset is nearly 3 orders of magnitude higher than the sampling resistor RS, so equation (5) can approximate can be approximated as equation (6):

$$R_O \approx \frac{R_{p1}R_{n1}(R_{n1} + R_{n2})}{R_{p1}R_{n2} - R_{p2}R_{n1}}$$

There, therefore, only the resistance matching of RP1, RP2, RN1 and RN2 should be considered when analyzing the output resistance of the current source.

Assuming that the nominal values of RP1, RP2, RN1, and RN2 are all R, and the resistance accuracy is δ, so the resistance are within the range of $$[\left(1-\delta\right)R, \left(1+\delta\right)R]$$.

When the resistances of RP1, RP2, RN1, and RN2 are shown in equation (7), the output resistance R0 is the minimum positive resistance, and the resistance is shown in equation (8).

$$\begin{cases} R_{p1} = R_{n2} = (1 + \delta)R \\ R_{p2} = R_{n1} = (1 - \delta)R \end{cases}$$

$$R_O \approx \frac{R_S}{2\delta}$$

When the resistances of RP1, RP2, RN1, and RN2 are shown in equation (9), the output resistance R0 is the minimum negative resistance, and the resistance is shown in equation (10).

$$\begin{cases} R_{p1} = R_{n2} = (1 - \delta)R \\ R_{p2} = R_{n1} = (1 + \delta)R \end{cases}$$

$$R_O \approx -\frac{R_S}{2\delta}$$

According to equations (8) and (10), it can be seen that when the resistance of RP1, RP2, RN1, and RN2 are randomly selected within the tolerance range, the value range of the output resistance is shown in equations (11):

$$R_O \in \left(-\infty, -\frac{R_S}{2\delta}\right) \cup \left[\frac{R_S}{2\delta}, +\infty\right)$$

Therefore, the resistance matching of RP1, RP2, RN1 and RN2 can significantly affect the output resistance of the current source, thus affecting its constant current performance.

4. Simulation Analysis of the Effect of Resistance Matching on Constant Current Characteristics

For further verification, a high-current power amplifier circuit is designed by using PSPICE based on the circuit topology above, and the study of the effect of resistance matching on the constant current characteristics is carried out based on the circuit simulation.

4.1. Circuit Modeling

A circuit molding of the high-current power amplifier circuit is brought up as shown in figure 4.

In Figure 4, the resistance of R1 and R2 is 3K, the resistance of RS is 0.03Ω, the resistance of RL is 0.5Ω, the nominal value of RN1, RN2, RP1, RP2 is 15K, and the signal source is 1V, 50Hz sine wave.
4.2. Monte Carlo Analysis

Monte Carlo Analysis is essentially a mathematical statistical analysis. According to specific statistical distribution, the component model parameters are randomly changed according to the set tolerance limit, and the parameters and response of the circuit are calculated [10].

When using Monte Carlo Analysis to study the effect of resistance matching of RP1, RP2, RN1 and RN2 on the constant current characteristic of the current source, the maximum tolerance must be specified. It is assumed that all resistors with a precision of 1% are adopted, and all samples are subject to independent normal distribution, so the actual tolerances of RP1, RP2, RN1 and RN2 are independent of each other, and are randomly assigned according to the normal distribution within the range of -1% to +1%.

The number of random seeds is 17533, and 400 trials are conducted. In order to avoid the influence of the transient response of the circuit, the time domain sampling is performed in the time interval of 50ms ~ 100ms after the circuit enters the steady state. The simulation waveform of the output current under time domain is shown in figure 5.

![Fig.5 Monte Carlo time domain simulation waveform](image)

According to figure 5, the minimum value of the steady-state current output amplitude is 2.8A, and the maximum value is 7.7A.

In order to further analyze the distribution law of output current amplitude, the time-domain waveform of the output current is statistically analyzed, and a statistical histogram of the output current amplitude is drawn, as shown in figure 6. The relevant data of the output current amplitude statistical histogram is shown in table 1.
The histogram and its data analysis show that when we choose resistors with 1% accuracy, the output of the current source has a large deviation under the excitation of the same signal source.

### Tab.1 Histogram data analysis

| Categories | Mean (A) | Sigma (A) | 3*sigma (A) | Minimum (A) | Maximum (A) | median (A) | 10th % ile (A) | 90th % ile (A) |
|------------|----------|-----------|-------------|-------------|-------------|------------|----------------|----------------|
| n samples  | 4.43241  | 0.788932  | 2.3668      | 2.80905     | 7.7301      | 4.2704     | 3.57846        | 5.4835         |

### 4.3. Worst Case Analysis

Worst-case analysis can find out the maximum degree of deviation from the design value of the technical indicator concerned under the given maximum tolerance of the specified device parameter, and give the specific tolerance of the specified device parameter in detail [11].

The worst case is when the current output amplitude has the largest deviation from the nominal value. In this case, the current output amplitude has a maximum value and a minimum value.

When the accuracy of RP1, RP2, RN1 and RN2 is 1% and 0.1%, the amplitude of the output current and its corresponding resistance mismatch in the nominal and worst case are shown in Table 2 and Table 3 respectively.

#### Tab.2 Resistance tolerance and output in the worst case (1% accuracy)

| Categories          | Nominal Current Output | Maximum Current Output | Minimum Current output |
|---------------------|------------------------|------------------------|------------------------|
| Deviation of RP1    | 0%                     | -1%                    | 1%                     |
| Deviation of RP2    | 0%                     | 1%                     | -1%                    |
| Deviation of RN1    | 0%                     | 1%                     | -1%                    |
| Deviation of RN2    | 0%                     | -1%                    | +1%                    |
| Normalization of the output current | 100% | 150.81% | 75.527% |

#### Tab.3 Resistance tolerance and output in the worst case (0.1% accuracy)

| Categories | Nominal Current Output | Maximum Current Output | Minimum Current output |
|------------|------------------------|------------------------|------------------------|
| Deviation of RP1 | 0%                     | -0.1%                  | 0.1%                   |
| Deviation of $R_{P2}$ | 0%  | 0.1% | -0.1% |
| Deviation of $R_{N1}$ | 0%  | 0.1% | -0.1% |
| Deviation of $R_{N2}$ | 0%  | -0.1% | +0.1% |
| Normalization of the output current | 100% | 103.49% | 97.71% |

The constant current performance of the current source has been greatly improved due to an order of magnitude improvement in the resistance mismatch.

In order to make sure that all of the samples meet the above requirements and keep a 20% margin, it is easy to find that the range of output resistance is as follows

$$R_o \in (-\infty, -300\Omega] \cup [+300\Omega, +\infty)$$

At this point, according to the equation (8) and (10), the necessary resistor precision is as follows

$$\delta \approx \frac{R_o}{2R_o} = 0.03 = 0.005\%$$

High-precision resistors greatly increase the manufacturing cost of current amplifiers and are not suitable for actual production.

5. The Method of Resistance Trimming and Its Application

In order to satisfy the constant current characteristics norm of the high-current power amplifier in power system, this paper designs a resistor trimming circuit, as shown in figure 7.

When resistors are chosen for $R_{N1}, R_{N2}, R_{P1}$ and $R_{P2}$ with nominal resistance of $R$ and accuracy of $\delta$, the resistance of the potentiometer should be larger than $2\delta R$ slightly.

![Fig.7 Current source output resistance fine tuning circuit](image)

In order to evaluate the effect of the method, we conducted a comparative test on a test board designed based on figure 4 in a constant temperature room with a temperature of 27°C.

Resistors listed in table 4 are intentionally picked from the series of E96 with nominal value of 15k and 1% accuracy by using the 6½-digit resolution DMMs

| Designator | Resistance measured (kΩ) |
|------------|--------------------------|
| $R_{P1}$  | 14.857                   |
| $R_{P2}$  | 15.146                   |
| $R_{N1}$  | 15.143                   |
| $R_{N2}$  | 14.862                   |

The experiment is conducted based on the control variable method, under the same signal source and loads.

The output current before and after using the resistance trimming method under different load resistance values is shown in table 5.
Tab.5 Measured output

| Resistance of the load (Ω) | Output current measured (A) | After Using resistance trimming method |
|---------------------------|-----------------------------|----------------------------------------|
| 0.0002                    | 4.3999                      | 4.3570                                  |
| 0.1003                    | 4.7008                      | 4.3570                                  |
| 0.1999                    | 5.0438                      | 4.3575                                  |
| 0.2997                    | 5.4419                      | 4.3579                                  |
| 0.4002                    | 5.9124                      | 4.3583                                  |
| 0.4996                    | 6.4637                      | 4.3587                                  |

Curve fitting is performed in figure 8 based on the data of table 5.

It can be seen clearly that by using the method, the levelness of output current improved obviously. According to the calculation based on the data in table 5, the precision of the output current is better than 0.04% in the full load range after using the method. The effect of the load resistance on the current output precision of the high-current power amplifier is significantly reduced by the resistance trimming method, which verifies its effectiveness.

6. Conclusion

The applications and the importance of the constant current performance of the high-current power amplifier circuit in the electric power system are introduced in this paper.

The topology of the current source circuit is designed based on the general current source of current parallel negative feedback. Theoretical analysis and computer simulation show that resistance matching is the key factor affecting the constant current characteristics of the current source. Based on the theoretical analysis, the resistor trimming method is proposed and experimentally verified. The results show that the method can effectively improve the constant current precision of the high-current power amplifier, which is of great significance to the power system.

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