Impedance measurement circuit based on improved voltage vector ratio method

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Abstract. China's inductance value is traced back to the national inductance working base. In addition, in China's electromagnetic metrology standard system, the inductance working standard can only be traced back to the source at 1kHz. The values at other frequencies are obtained after frequency conversion according to the distribution parameters of the inductance reference. The most accurate digital bridge is the 1689MRLC digital bridge, with impedance measurement accuracy of 0.02%, d and q measurement accuracy of 0.0001, and programmable test from 12Hz to 100kHz. Since the researchers need to work on the benchmark to ensure that the transmission capacity reaches 0.01% in the broadband (50 Hz-2.5 kHz), the measurement system needs to be redesigned.

1. Introduction

As a very important parameter of electromagnetic properties of materials, inductance parameter is an important part of measuring AC impedance. Different sizes and frequencies of inductors and coils are determined by different sizes and frequencies of inductors and inductors used in different industries [1-3].

With the inductance comparison values of 10mH and 100mH, China, the United States and Russia are the leading laboratories [4-6]. According to the needs of this international comparison, it is necessary to purchase equipment and improve the key components and transfer scheme of inductance working reference. Different from CCEM-k3, APMP inductor comparison standard is 10mH / 100mH two standard inductors. At present, only 100mH inductance transfer index in China has reached 5uH / h (k=1). In order to cope with international comparison, it is necessary to further review the index. In addition, it is urgent to increase the uncertainty index of 10 MH standard inductance [7].

2. High precision impedance measurement scheme

2.1. The measurement scheme adopted in this system

In today's society, the rapid development of digital technology makes the voltage vector ratio method more accurate and convenient for impedance measurement [8]. However, the voltage vector ratio method used before has some problems such as instability and imperfect virtual ground potential.
Therefore, some improvements are made in the conventional voltage vector ratio method to improve the accuracy and practicability of the measurement [9].

The system is based on the improved voltage vector ratio method and synchronous sampling method to improve the measurement accuracy. The synchronous sampling system is divided into analog part and digital part, as shown in Figure 1. The key technologies of the measurement system include virtual location acquisition, capacitance compensation and dual channel synchronous full cycle sampling.

The measured impedance \( Z_x \) is traced back to the standard resistance \( R_0 \). Point A needs to keep the ground potential, and its function is to prevent the current from leaking through stray capacitance. The voltages \( V_r \) and \( V_x \) at both ends of the standard resistor \( R_0 \) and the measured impedance \( Z_x \) are collected by the dual-channel synchronous data acquisition card PXI-5922. If \( \tau \) is the time constant of the standard resistance \( R_0 \). With \( Z_X = R_s + j \omega \tau \) and \( R_0 = R_0(1 + j \omega \tau) \), the calculation formula is as:

\[
\frac{Z_X}{R_0} = \frac{V_x}{V_r} = \frac{R_s + j \omega L_s}{R_0(1 + j \omega \tau)} = -(A + jB)
\]

Sort out

\[
R_s = -R_0(A - \omega B \tau) \quad (2)
\]

\[
L_s = -R_0(B \omega + A \tau) \quad (3)
\]

2.2. Amplitude and phase calculation method based on whole period sampling

In order to accurately obtain the voltage \( V_x \) across the standard device \( R_0 \) and the voltage \( V_x \) across the measured impedance \( Z_x \), it is necessary to perform digital signal processing on the collected signal to obtain the amplitude and phase of the signal. A certain number of data are collected by whole period sampling, and then the spectrum information of the signal is calculated by DFT transform. The basic principle of DFT is to transform time domain signals into discrete time signals. There is the following relationship among sampling frequency, signal frequency and sampling points: \( f = F_s/N \) (sampling frequency - \( F_s \), signal frequency - \( f \), sampling points - \( N \)) The value of each point after discrete Fourier transform (DFT) represents the amplitude information of the frequency point.

3. Hardware design of inductance measurement system based on synchronous sampling

3.1. Setting of virtual ground potential

If the virtual point is not used in the bridge, the point A in the circuit will leak to the ground potential, which is equivalent to incorporating a capacitor in the circuit, as shown in Figure 2. When the bridge is balanced, \( Z_3/Z_1 = Z_x/Z_2 \) cannot be guaranteed by \( I_1 = I_1^* \), \( I_2 = I_2^* \). If point A is directly grounded, other high potentials in the circuit will cause current leakage to point A, which makes \( Z_3/Z_1 = Z_x/Z_2 \) untenable.
Because the operational amplifier has the characteristics of high input impedance and low output impedance, the voltage vector ratio method uses its high open-loop gain to set the virtual location. In this way, $I_1 = I_2$ can be guaranteed, and then the measured impedance can be calculated by the proportional equation of the voltage vector ratio method.

The virtual point acquisition method used in this system is shown in Figure 3. The input end of the follower is connected to the point a between the standard impedance and the measured impedance, and the ground potential of the follower is connected to the end of the standard impedance near the power supply, so that the follower can follow the voltage $V_{ab}$ between a and b. The output terminal of the follower is connected with the ground through a 1:1 isolation transformer, and the potential at point A is taken as the ground potential. Because of the high input impedance of the follower, no extra current leakage will be introduced.

3.2. High precision voltage follower

Usually, the followers we use are mostly built by operational amplifiers. However, due to the performance differences of the operational amplifiers used, there are certain following errors. And the following error will increase with the increase of frequency. Because the impedance measurement accuracy of this system is high, the traditional follower cannot meet the requirements. Therefore, we need to design a follower with higher accuracy. The basic principle is to follow the following results of the traditional follower twice, so that the final following voltage is more accurate and the following error is smaller.

The adoption of secondary follower will need to solve the problem of stability. When the follower load is a large capacitive load, incorrect compensation will bring some problems such as spike, oscillation, broadband reduction, output slew rate reduction and power consumption increase. In order to change the open-loop frequency response of the amplifier circuit, we can change the feedback network of the amplifier circuit. The feedback circuit is constructed by frequency compensation to ensure a larger loop gain with a certain gain margin or phase margin. By frequency compensation, the distance between poles can be widened, especially the distance between the main pole and adjacent poles, which can ensure the stability of the amplifier circuit and the loop gain. Next, we realize the stable operation of the amplifier circuit and ensure the loop gain by adding compensation poles. The transfer function of the amplifying circuit is shown as follows:

$$A_{V_1}(j\omega) = \frac{A_{V_0}}{(1 + j\omega/\omega_1)(1 + j\omega/\omega_2)(1 + j\omega/\omega_3)}$$  \hspace{1cm} (4)

As mentioned earlier, the phase of this three-pole transfer function reaches -180° between and. If a compensation pole is added to the transfer function of the amplification circuit, a binomial factor is added to the denominator to become

$$A_{V_2}(j\omega) = \frac{1}{(1 + j\omega/\omega_4)(1 + j\omega/\omega_5)(1 + j\omega/\omega_6)(1 + j\omega/\omega_c)}$$

If it is selected to be lower than before compensation, the loop gain will be less than 1 before the compensation pole contributes to the additional phase shift, thus making the circuit work stably and obtaining higher low-frequency loop gain.
We use dual-channel feedback to stabilize the capacitive load, as shown in Figure 4, where the load capacitance LC is 1000PF. The function of the feedback loop 1 is to ensure that the input and the input are equal through the feedback resistor. In the feedback loop 2, a feedback capacitor is added to the feedback loop so that the feedback loop can run stably at high frequency. Rx separates feedback loop 1 from feedback loop 2.

In order to ensure the stable operation of the circuit at different frequencies, we first analyze that the feedback loop 2 composed of capacitors is equivalent to short circuit at low frequency. Since the instability of the system mainly occurs at high frequency, we focus on analyzing the stability of the system at high frequency.

If we adopt two feedback channels, we need to face an important problem "BIGNOT". Because of the existence of complex conjugate zero and complex conjugate pole in the loop gain curve, the complex zero or complex pole will amplify the gain sharply when the closed-loop operational amplifier responds. Therefore, we need to ensure that the conjugate pole is lower than the conjugate zero in the 1/B curve, so as to eliminate the stability of the system.

The compensation loop constructed by CX and RF forms a new zero point to cancel the pole and eliminate the self-excitation to realize the stability of the system. When the new zero and the new pole are at the same frequency, they can cancel each other out

$$\frac{1}{2\pi R_F C_x} = \frac{1}{2\pi \left( \frac{R_0 + R_X}{R_0 + R_X + C_L} \right)}$$

3.3. Design of Lead Compensation Circuit

In the measurement loop, there will be a voltage drop between the standard resistor and the measured inductor, which makes the potential of the adjacent terminals A and B of the resistor and inductor not completely equal, resulting in measurement error.

Because the skins of the two channels have the same potential as A and B, and because of the lead voltage drop, there is a voltage drop in the skins of the two channels, which makes the measured reference potentials of the two channels different. Here, we can solve the problem of potential floating by connecting a 200 ohm resistor between the skins of the two channels and the ground. At the same time, the lead compensation circuit can be used to ensure that the adjacent potentials of the standard resistor and the inductor to be measured are equal to the ground potential to realize lead compensation. As shown in Figure 4, the design principle is to equalize the potentials of a and b through a follower, so as to make lead compensation.

In order to increase the precision of lead compensation circuit, a designed high-accuracy follower is adopted, which has low output impedance, and the voltage output and current output are connected into the circuit separately to reduce the influence of lead voltage drop.

3.4. Capacitance compensation

It can be seen from the schematic diagram of the measurement system that the input capacitance of the follower in the added virtual location acquisition circuit is equivalent to being connected in parallel...
with both ends of the resistor, so the parallel capacitance should be compensated when calculating the standard resistance. The actual measured capacitance at the input end of the follower is 8.33pF. In addition, it is necessary to measure the influence of the standard resistance time constant. The q value of the resistance at 100KHz can be measured by the 1689M digital bridge, and the influence of the time constant τ can be calculated by τ=L/R+RC, which can be compensated in impedance calculation. By analyzing the schematic diagram of the measurement system, it can be seen that the introduced capacitance mainly includes two parts: first, the follower input capacitance in the virtual location acquisition circuit is connected in parallel with both ends of the resistance, so the parallel capacitance should be compensated when calculating the standard resistance, and the actual measured follower input capacitance C1=8.33pF. Second, the capacitance C2 introduced by AC resistance can be compensated by measuring the standard resistance time constant. From the calculation formula of standard resistance

$$R(1+j\omega\tau) = R[1+j\omega(L/R-RC)]$$  \quad (7)

The time constant to be compensated is obtained $\tau = L/R - R(C_1 + C_2)$.

$$L_s = -\frac{B}{\omega} + A\tau = -\frac{B}{\omega} + A(L/R - R_1 C_2 - R_1 C_1)$$  \quad (8)

4. Conclusion

The inductance measurement range of the impedance synchronous sampling measurement system proposed in this paper is 100 h-1 h, the inductance measurement accuracy is better than 0.01% at 1kHz, and the measurement frequency range is 100Hz-20kHz. Another advantage of this measuring system is its flexibility, which can be used not only for comparison of inductance and resistance, but also for comparative measurement of R-R, R-C, L-L and C-C, and can be further developed into a high-precision LCR measuring system with accuracy better than 0.01%, which is used in the field of AC impedance measurement traceability.

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