The Development of active capacitive voltage divider based on current transformer with compensation circuit

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Abstract: In order to solve the test of the frequency response characteristics of the DC voltage divider, this paper proposed an active voltage divider based on an electronically compensated current transformer. By setting different current transformer primary and secondary turns ratios, the voltage divider ratio could be changed. Through the three-winding design on a single iron core, the active compensation of the current transformer is realized and the linearity of the current transformer is improved obviously. The notch circuit is used to improve the measurement accuracy of the secondary current sampling circuit of the current transformer. Tests indicates that the voltage divider ratio varies with frequency not more than 20ppm, and phase shift is not more than 200μrad within 2500Hz.

1. Introduction
In order to accurately measure the harmonic components in the DC line, the DC voltage divider should have a wide frequency bandwidth. However, in the actual test of the DC voltage divider for the frequency response, the test under the power frequency voltage is often used. In the high voltage wide frequency response test, a capacitive voltage divider composed of compressed gas capacitors is often used as a standard device. Compressed gas capacitors have the advantages of good frequency characteristics, low dielectric loss, and simple structure [1]. Using it as a high-voltage arm capacitor and connect it in series with a low-voltage arm capacitor to form a capacitive voltage divider. However, the voltage divider ratio will be affected when the secondary load is connected, in order to reduce this effect, one electronic unit is generally used to form an electronic voltage divider. For example, the high-voltage standard voltage divider 4860 produced by the Swiss HAFLEY company [2], the high and low voltage arms all use gas capacitors, with the electronic unit, which can realize the conversion of different voltage ratios. In order to obtain more transformation ratios, the 4860 electronic unit can directly input 1000V, and the input impedance can reach 10GΩ. In paper [3-4], a compressed gas standard capacitive voltage divider was designed in which the high and low voltage arm gas capacitors are designed in a shell. The follower circuit of the voltage divider has an input impedance above 5GΩ. The voltage divider has good frequency characteristics, and the measurement error is better than 0.1% in the range of 50 Hz to 2500 Hz. The 2502A electronic voltage divider produced by Canadian MI [5], based on the principle of zero magnetic flux current comparator, makes the ratio of the output voltage of the voltage divider to the primary high voltage and the capacitance ratio of the high and low voltage arm capacitors the same. Jiang Chunyang [6] designed a standard capacitor voltage divider based on a precision inverter. The high-voltage arm capacitance adopts compressed gas standard capacitors. The T-type equivalent circuit is used in the design to reduce the low-voltage arm parallel resistance to its voltage divider ratio. Under the influence of error, its measurement accuracy can meet 0.01% under power frequency conditions.
However, the voltage divider products of HAFLEY and MI are often used for calibration under power frequency errors. In order to obtain better measurement accuracy, internal circuits are often compensated under power frequency and are not suitable for high frequencies. Next test. The voltage divider in the literature [6] has good frequency characteristics, but its ratio is relatively fixed, and the high and low voltage arm capacitors are placed in a closed shell, which cannot achieve multi-ratio switching. In the literature [7], the primary high-voltage arm capacitor is not directly grounded, and there is a risk of float ground. At the same time, a large number of low-voltage arm capacitors are used in parallel when the multi-transformation ratio is switched.

This paper proposes an electronic voltage divider based on an electronic compensation current transformer, which can measure the frequency characteristics below 10kV. The high-voltage arm capacitor adopts compressed gas capacitors. The electronic compensation current transformer is used to achieve primary capacitance current conversion and improve current measurement accuracy. A 50Hz notch chip is used to greatly increase the loop gain of the sampling circuit, and improve the measurement accuracy under power frequency conditions.

2. Basic principles

Figure 1 shows the basic principle of the electronic voltage divider. In the figure, U1 is the input voltage of the voltage divider, the output of the voltage divider is U2, CH is the high-voltage compressed gas standard capacitor, and CL is the low-voltage arm capacitor of the sampling circuit. The low voltage electrode of the high voltage arm capacitor CH is connected to the input of the current transformer, and the other end of the current transformer is grounded. The current transformer adopts electronic compensation, and the detection winding voltage is amplified by G times and then connected to one end of the secondary winding of the current transformer, and the other end of the secondary winding is connected to the input end of the sampling circuit. The sampling circuit generates reverse current through OP1, and generates and output voltage at both ends of CL.

![Fig. 1 Schematic of active compensation voltage divider](image)

Suppose the transformation ratio of CT is $K$, the error is $\alpha$, the capacitance current is:

$$I_{C1} = U_i \omega C_H$$

(1)

According to the ratio of $K(1+\alpha)$, the current after conversion to the second winding is,

$$I_{C2} = U_i \omega C_H K (1 + \alpha)$$

(2)

Suppose the error caused by the sampling circuit is $\beta$, then the output voltage:

$$U_2 = K \frac{C_H}{C_L} U_i (1 + \alpha + \beta)$$

(3)

It can be found from formula (3) that different voltage division ratio outputs can be obtained by switching the transformation ratio of different current transformers. At the same time, it can be found
that the error sources that affect the voltage divider ratio of the voltage divider are the ratio error of the current transformer and the error of the sampling circuit. Two parts will be the key to ensuring the accuracy of the voltage divider measurement.

3. Electronic compensation current transformer

The schematic diagram of the electronic compensation current transformer is shown in Figure 2. W₁ is the primary winding of the current transformer, W₂ is the secondary winding of the current transformer, and W₃ is the detection winding of the current transformer. The detection winding is connected to a non-inverting amplifier with a gain multiple of G, the amplifier output is connected to one end of W₂, and the other end of W₂ is grounded. The primary capacitor current I₁ flows into the primary winding W₁, and W₂ forms a loop through the amplifier output and ground to generate secondary current. Due to the excitation error, there will be magnetic flux in the iron core. The voltage U₀ is detected by W₃, which is amplified by the amplifier G, a compensation current is generated on W₂ until the entire system is in a stable state [7].

![Fig 2 schematic of active compensation current transformer](image)

The equivalent circuit diagram of the electronic compensation current transformer shown in Figure 2 can be shown in Figure 3. Where, Z₃ is the output impedance of W₃, Z₅ is the input impedance of the electronic circuit, U₀ is the output of the detection winding, G is the gain of the electronic circuit, and K₂₃ is the turns ratio of W₂ and W₃. All impedances are converted to secondary.

![Fig. 3 equitation circuit of active compensation current transformer](image)

Suppose the current transformer error is εₑ, then the error formula using ampere-turns is:

\[
ε_e = \frac{I_1 W_2 - I_1 W_1}{I_1 W_1} = \frac{W_2 \frac{U_2}{Z_m} + W_2 \frac{U_2}{Z_5}}{I_1 W_1}
\]  

(4)
It can be obtained from Figure 4:
\[-G \frac{W_2}{W_2} U_2 = I_2 (Z_2 + Z_b) \quad (5)\]

Then:
\[U_2 = \frac{I_1 Z_2 + Z_b}{G \frac{W_2}{W_2} + 1} \approx \frac{I_2 W_2 (Z_2 + Z_b)}{G W_3} \quad (6)\]

Incorporating formula (6) into formula (4), we can get:
\[\varepsilon_n = \frac{I_2 W_2}{I_1 W_1 V W_3} \left( \frac{1}{Z_m} + \frac{1}{Z_5} \right) (Z_2 + Z_b) \]
\[\approx \frac{W_2}{G W_3} \left( \frac{1}{Z_m} + \frac{1}{Z_5} \right) (Z_2 + Z_b) \]
\[= \frac{Z_2 + Z_b}{Z_m Z_5} \frac{G}{Z_m + Z_5} \frac{k_{23}}{k_{23}} \quad (7)\]

It can be found from equation (7) that when Z5 tends to infinity, the final error of the current transformer can be obtained as:
\[\alpha = \frac{k_{23} \alpha_0}{G} \quad (8)\]

Among them \(\alpha_0\) is the error when the current transformer is not compensated.

The error of the current transformer after the electronic compensation depends on the gain G of the electronic circuit, and the gain G of the electronic circuit cannot be infinite, which is mainly limited by the stability of the feedback system. But compared with a single-stage current transformer, its error can be significantly reduced.

The designed current transformer has 1000 turns for the primary winding and 1000 turns for the secondary winding. The taps of 200, 500, 800 and 1000 are designed of primary winding. The high-voltage arm capacitor is 100pF, and the low-voltage arm sampling capacitor could be 100nF. The ratio would be 5000, 2000, 1250 and 1000. The main iron core material of the current transformer is made of nanocrystalline material, and the initial permeability can reach 110,000. The main structure of the current transformer is shown in Figure 4, in which the detection winding and the iron core are placed in a magnetic shielding box made of permalloy. The primary winding and the secondary winding are respectively wound outside the magnetic shielding box.

The detection winding is designed to be 500 turns, according to the sensitivity calculation formula of the current comparator [8]:

![Fig.4 main structure of current transformer](image-url)
Where, \(E\) is the induced voltage (V), \(S\) is the core cross area (cm\(^2\)), \(\mu\) is the initial permeability of the core (T/Oe), \(N_D\) is the number of turns of the detection winding, and \(l\) is the average magnetic path length of the core (cm). According to the core size, the inner diameter is 110mm, the outer diameter is 150mm, and the height is 70mm. The detection winding is 1000 turns. When the power frequency is 10kHz, if the error is 0.005%, the output voltage of the detection winding is calculated to be about 250\(\mu\)V.

The feedback amplifier adopts a non-inverting amplifier structure. The schematic diagram is shown in Figure 5. In order to increase the output capacity of the circuit, an AC buffer with high power output capability is added to the loop, and the gain is 1. The circuit design gain is 500 and the output current is 250mA.

The measurement error of the current transformer will be tested together with the sampling circuit.

4. Sampling circuit
Since a compressed gas capacitor is used as the input high-voltage arm, there will be a 90\(^\circ\) phase difference between the primary current and the primary voltage, if a resistor is used for sampling, it will produce an output signal with the same 90\(^\circ\) phase as the primary voltage. In order to obtain a better output, this part will use low-voltage solid capacitors as the secondary sampling element of the current transformer, and cooperate with the active circuit to achieve accurate secondary current acquisition.

Figure 6 shows the schematic diagram of the secondary sampling current. The secondary current of the current transformer flows into the input terminal of the sampling circuit, and the circuit will generate a current opposite to the current direction and equal in magnitude to flow through \(C_1\) and generate output voltage at the end of \(C_1\).

In order to ensure the circuit work, a resistor needs to be connected in parallel with \(C_1\). The treatment of this resistor refers to the double T-type circuit proposed in the literature [6] to reduce the impact of the resistor in AC conditions.
A 50Hz notch chip circuit is added to the feedback loop of OP2. This chip can produce excellent notch effects on 50Hz signals. In this way, at 50Hz, the circuit composed of OP2, R2, and R3 will appear approximately open circuit, to increase the open loop gain of the whole circuit, thereby reducing the influence of the circuit on the measurement output. Figure 7 shows the simulation curve of the open loop gain of the above circuit. It can be seen that at 50Hz, the open loop gain of the circuit increases from $5 \times 10^6$ to $80 \times 10^6$, and the rated output of the sampling circuit is 5V. The voltage arm capacitor C1 uses solid ceramic capacitors.

![Fig.7 open loop gain curve of I/V converter circuit](image)

5. Current transformer and sampling circuit test
In the test, the high-voltage arm capacitance in Figure 1 is changed to a low-voltage gas capacitor, the capacitance value is 10nF, the input voltage is selected as 50V, the current transformer is selected as 1000:1000 turns ratio according to the design, and the sampling capacitor of the low-voltage circuit is 100nF, then the second output voltage is 5V. The input side voltage is measured by a multi-induction voltage divider. The secondary output is 5V. The error of the induction voltage divider is no more than 2ppm and 2μrad at power frequency, and the maximum error is no more than 200ppm and 10μrad at 2500Hz. The NI digitizer 5922 was used to measure the errors, and the additional error of the two channels of 5922 is not more than 0.005% and 10μrad. In order to obtain better linearity, the method of dual channel switching in literature [9] is used manually, the calculation eliminates the additional error caused by the difference between two channels.

![Fig.8 test circuit of divider](image)

Figure 9 shows the error curve of the voltage divider from 10% voltage point to 120% voltage point under 50Hz. The ratio difference is calculated with the voltage divider ratio calculated at 10% voltage point as the rated value, and the ratio difference and phase shift can be found there is a change process. The reason is that the electronic compensation effect is poor at the 10% voltage point due to the small error ampere-turn. At each point above 20%, the error change is not more than 10ppm and 5μad.
According to the test principle in Figure 8, the voltage divider error was tested in the range of 2500Hz and the output voltage was 5V. The test result is shown in Figure 10. The voltage divider error maintains good linearity before 1500Hz, and the error begins to increase after 1500Hz. The main reason is that the feedback loop formed by the electronic compensation circuit of the current transformer is compensated after the frequency increases. The effect becomes worse. With the frequency increasing, the error will return to the level before compensation. The change of the phase shift is much more due to the solid capacitor used in the sampling circuit, and the equivalent dielectric loss becomes larger with the frequency increasing. But overall, the divider ratio of the voltage divider within the range of 2500 Hz does not vary more than 20 ppm with frequency, and the phase shift does not vary more than 200 μrad.

Fig.9 error curve of divider under different voltage

In order to test the output stability of the voltage divider, the stability of the voltage divider under the power frequency was measured within 2 hours. The error curve is shown in Figure 11. The maximum change of the ratio difference is about 20 ppm, and the phase shift about 10 μrad. The period stability can be calculated as 0.17ppm/min and 0.08 μrad/min.

Fig.10 error curve of divider under different frequencies

Fig.11 error curve of long time test
6. Integrated error test

The integrated error measurement of the voltage divider is the same as the test circuit shown in Figure 9. The schematic diagram of the circuit is shown in Figure 12. The laboratory high-voltage standard gas capacitor’s rated voltage is 200kV and the rated capacitance is 100pF. 10kV high voltage instrument voltage transformer is selected here as the standard device and cooperates with the secondary induction voltage divider to obtain the secondary signal matching the output of the voltage divider. The current transformer turns ratio is 500:1000, and the voltage division ratio is 2000. In the test, the ratio of the 10% of primary voltage is used as the standard ratio, and the change of the ratio is measured. It can be seen from the integrated measurement result that the ratio of voltage divider does not change more than 15 ppm, and the phase shift is about 25 μrad. This test result is very close to the 50Hz test result in section 3.

![Fig.12 test circuit of entire error of voltage divider](image)

![Fig.13 entire error curve of divider](image)

7. Measurement uncertainty analysis

The GUM method [10] was used to analyze the measurement uncertainty of the active compensating capacitive voltage divider. When the voltage divider is used as a standard device in the test, the main influencing factors are as follows:

1) Stability of high voltage arm capacitor. In the range of power frequency to 2500Hz, compressed gas capacitors have excellent short-term stability. In the short time used as a standard device, the uncertainty introduced by the influence of temperature and voltage is not more than 1ppm and 1μrad.

2) Short-term stability of low-voltage capacitors. Low-voltage capacitors are made of double-layer ceramic capacitors, with a nominal temperature coefficient of ±30ppm/℃, and their actual temperature coefficient is generally within ±20ppm/℃. During the test, in a short time (e.g. 5min), the temperature change is 1℃, which is equivalent to the error and then calculated according to the uniform distribution (divided by 1.732), then the measurement uncertainty introduced by it is about 12ppm, the uncertainty component is about 12ppm and 12μrad. After the frequency increases, the influence of the dielectric loss on the angular difference will increase accordingly. From the test results in Figure 11, the ratio difference changes at 25ppm, and the phase shift changes around 160μrad. Calculated according to the uniform distribution, the ratio uncertainty is about 15ppm, the phase shift is about 100μrad.
(3) Op-amp circuit interference. The impact of the operational amplifier circuit on the measurement results mainly comes from the noise of the electronic circuit itself and the fluctuation of the circuit. This part of the influence cannot be eliminated, but the average value can be calculated through multiple measurements to reduce this type of influence. The reason is that noise and fluctuations have a lot of randomness, most of the influence will be reduced in the calculation of multiple measurements [11], the maximum value of the fluctuation in the multiple measurements in Figure 12 is about 20ppm and 10μrad. After the average algorithm is used, the influence will be reduced to about 2ppm and 2μrad. When the frequency increases, the influence will increase, but at the highest 2500Hz, this part of the influence can be amplified to about 10ppm and 10μrad.

(4) Electronic compensation current transformer. The influence of the electronic compensation current transformer mainly comes from the electronic circuit part, and the gain of the circuit is in the denominator part of the error calculation, and the influence of the gain on the current transformer is very limited. From the test results of the third part, it can be known that from 20% to 120%, the error change is no more than 10ppm and 5μrad, the measurement error change introduced by the electronic compensation current transformer should be no more than 3ppm and 2μrad. Calculated according to uniform distribution, the introduced measurement uncertainty is 2ppm and 1.5μrad. As the frequency increases, the electronic compensation effect will become worse, and the current transformer error will also become larger. For the highest of 2500Hz, the uncertainty introduced after the transformer compensation is magnified 10 times to about 20ppm and 15μrad.

(5) Environmental electromagnetic field. Since the high-voltage arm is a capacitor, it has good environmental electromagnetic field "immunity". The low-voltage belt unit is installed in a metal shell and is far away from the interference electromagnetic field of the booster, reactor, etc. under test. The influence of this part can be ignored.

Therefore, when the voltage divider is used as a standard device, the class B synthetic expanded uncertainty introduced by it under the power frequency is about 25ppm (k=2) and 25μrad (k=2). When used under non-power frequency, the dielectric loss of the low-voltage capacitor will increase the influence of the phase shift. The range of 50Hz to the highest 2500Hz is evaluated for Type B synthetic expansion uncertainty of about 50ppm (k=2) and 200μrad (k=2).

8. Conclusion
In this paper, a voltage divider for electronically compensated current transformers was proposed. The composition of each part and the corresponding detection methods and results in detail were introduced, and finally the type B uncertainty when the voltage divider is used as a standard device was introduced.

(1) The use of electronically compensated current transformers can achieve multi-transformation ratio switching, and has good linearity, and the error change at power frequency is not more than 10ppm and 5μad.

(2) The error of the voltage divider under different voltages and the error under different frequencies was tested. The measurement results show that the voltage divider ratio within the range of 2500Hz varies with frequency not more than 20ppm, and the phase shift change not more than 200μrad.

(3) The evaluation of the type B extended uncertainty of the voltage divider in the range from 50Hz to the highest 2500Hz was introduced ,it is about 50ppm (k=2) and 200μrad (k=2).

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