Using the binary inductive current divider to compare two shunt-TVC combinations at common ground

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Abstract. The paper describes a new measurement system to compare two shunt-TVC combinations with a testing current range of 10 mA to 1 A and frequency range up to 200 kHz. This new system is based on the use of Binary Inductive Current Divider (BICD) to provide two currents at common ground, and to eliminate the current leakage influence in series connection mode, especially at high frequency. With this system, ac-ac differences against 1 kHz between two shunt-TVC combinations have been determined, and show well agreement with the method by interchanging shunt-TVC at high and low terminal positions. The measurement results will be presented and the standard measurement uncertainties are below 3 μA/A at frequency ranges from 5 kHz to 200 kHz.

1. Introduction

Thermal converters are the most accurate standard for transfer of ac voltage or current to equivalent dc quantities [1]. Today, the thin-film or planar multi-junction thermal converters have been investigated and manufactured at PTB, to be used widely in the establishment of voltage or current standard in most national metrology institutes [2][3].

Two thermal voltage converters in parallel with coaxial shunts are usually compared in series connection by measuring the output response with ac and dc current applied [4]. During the inter-comparison of two shunt-TVC combinations, one of the dominant parts is the current leakage from the input terminal to the output and the housing of the TVC, especially at high frequencies [5]. Another part is caused by the admittance of the current tee [6]. In the step-up procedure for extension of the current and frequency ranges, those leakage influences will be accumulated gradually. Different methods for the connection and guarding of the TVC have been proposed. A high precision automated measuring system for ac-dc current transfer has been described by Rydler at RISE Research Institutes of Sweden, using a guarding to make the system work at symmetric state and to eliminate current leakage errors [7].

At NIM, a new measuring system has also been developed to compare two shunt-TVC combinations at common ground. This method is based on use of the BICD to provide two currents with known relationships, and keep the system symmetrical to compensate the leakage current through TVC. Meanwhile, with this system, two shunt-TVC combinations with identical value will be measured without the current tee.

2. Binary Inductive Current Divider

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The basic purpose of the BICD is to provide two currents with the low terminal connected at common ground, and the relationships between two currents can be self-calibrated [8]. The inner structure of the BICD is shown in figure 1. Twisted copper wires with 0.6 mm diameter are evenly and equally distributed around a high-permeability magnetic core. Considering the capacitive leakage between the magnetic core and the copper housing, a copper shielding is applied and connected to the input high terminal. The like terminals of two windings are inversely connected in series, and input and output taps of the BICD are mounted to coaxial connectors. The current shunts under test will be applied to the coaxial connector at I₁ and I₂ branches of the BICD respectively. Z₁S and Z₂S are the impedance of windings including wire resistance and leakage inductance.

![Figure 1. Basic structure of the BICD.](image)

The principle for the self-calibration of the relationship between two currents of the BICD has been described in [9]. To investigate the influence under different loads in two branches, two current shunts with the same resistance have been selected and compared. The relative difference between two current I₁ and I₂ has been measured with 1-Ω, 10-Ω and 90-Ω shunts in two branches of the BICD at frequencies from 5 kHz to 200 kHz respectively. The measurement results are shown in Table 1.

| shunt | 5   | 10  | 20  | 30  | 50  | 70  | 100 | 200 |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|
| 1 Ω   | 0.1 | -0.1| -0.2| -0.4| -1.3| -2.4| -4.6| -16.5|
| 10 Ω  | -0.1| -0.1| -0.2| -0.4| -1.3| -2.4| -4.6| -16.5|
| 90 Ω  | -0.1| -0.1| -0.2| -0.4| -1.3| -2.4| -4.6| -16.5|

As seen from Table 1, the relative errors between two currents of the BICD show to be below 5 μA/A at frequencies up to 100 kHz. The measurement difference with two 1 Ω, 10 Ω and 90 Ω shunts respectively in two branches of the BICD is determined to be less than 2 μA/A at frequencies up to 200 kHz.

3. Measurement Setup

To eliminate the current leakage influence through the TVC, a new measurement setup has been proposed to compare two shunt-TVC combinations at common ground with the use of the BICD, and shown in figure 2. As seen from this setup, two ac voltage signals are applied at regular intervals to the input of the transconductance amplifier through a computer control switch, and output currents ranging from 10 mA to 1 A at frequencies from 1 kHz to 200 kHz. The measuring current generated at the output of the amplifier is flowed into the input terminal of the BICD to produce two identical current branches, and marked as I₁ and I₂. Two current shunts Rₓ and Rₛ are connected in the I₁ and I₂ branches, and the test and reference TVCₓ and TVCₛ sense the voltage drop on the shunt Rₓ and Rₛ respectively. The output voltages of TVCₓ and TVCₛ are measured by two dedicated nanovoltmeters at different frequencies.

To reduce the shift influence from the TVC during the measurement, ac current is applied sequentially to the shunts under f₁, f₀, f₀, f₁ four frequencies steps in one comparison cycle. The ac-ac
difference between two shunt-TVC combinations at different measuring frequencies can be known from:

\[
\Delta \delta_{ac\rightarrow ac}^{X-Y} = \delta^{S}_{ac\rightarrow ac} - \delta^{X}_{ac\rightarrow ac} = \frac{e^{S}_{f} - e^{S}_{f_0} - e^{X}_{f} - e^{X}_{f_0}}{n_{X} e^{S}_{f} - n_{S} e^{X}_{f_0}}
\]

(1)

where \( \delta^{S}_{ac\rightarrow ac} \) is the ac-ac difference of the \( R_{S}\)-TVC\( S \) combination, and \( \delta^{X}_{ac\rightarrow ac} \) is the ac-ac difference of the \( R_{X}\)-TVC\( X \) combination, \( e^{S}_{f} \) and \( e^{S}_{f_0} \) are the average of output voltage of the TVC\( S \) and TVC\( S \) respectively at frequency \( f_0 \), \( e^{X}_{f} \) and \( e^{X}_{f_0} \) are the average of output voltage of the TVC\( X \) and TVC\( S \) at frequency \( f_1 \). It is assumed that the output voltage of the TVC is proportional to the \( n \)-th power of the input voltage drop on the shunt, and the \( n_{X} \) and \( n_{S} \) also can be determined.

Figure 2. Measurement system with BICD to compare two shunt-TVC combinations at common ground.

4. Measurement Results

Considering the current leakage influence in series connection, the measurement setup based on the use of BICD, marked as method 1, has been developed to compare two shunt-TVC combinations at common ground. Meanwhile, another method by interchanging the position, marked as method 2, has also been applied to reduce this leakage influence. The ac-ac difference against 1 kHz between the directly comparison of two TVCs with the 90 Ω PMJTC manufactured by PTB/IPHT has been measured by means of the two different methods above at 10 mA, and the results are shown in figure 3 at frequencies from 5 kHz to 200 kHz.

Figure 3. Measurement results for comparing two TVCs directly with two methods respectively.

Seen from figure 3, the influence from current leakage has been well eliminated, and the ac-ac difference between two TVCs has been determined at measuring frequencies. The difference between two different methods is measured with well agreement to be less than 2 μA/A from 5 kHz to 200 kHz.

Meanwhile, two 1-Ω shunt-TVC combinations and two 10-Ω shunt-TVC combinations have also been compared and measured respectively using the both methods. The measurements of two 1-Ω shunt-
TVC combinations have been done at 100 mA and two 10-Ω shunt-TVC combinations at 1 A with the frequency ranges from 5 kHz to 200 kHz. The comparison results are given in figure 4. The figure shows that the difference between two 1-Ω shunt-TVC combinations is measured to be less than 5 μA/A, and between two 10-Ω shunt-TVC combinations also below 5 μA/A at frequencies up to 200 kHz. The difference between two methods for comparing two shunt-TVC combinations with 1-Ω and 10-Ω shunt severally has also been measured with the range below 3 μA/A from 5 kHz to 200 kHz.

5. Conclusion

A measurement system for measuring the ac-ac transfer difference between two shunt-TVC combinations with identical value has been proposed. This setup is based on the use of a self-calibrated BICD to compare two shunt-TVC combinations at common ground, and is applied to measure at 10 mA, 100 mA and 1 A in this paper. The measurement results show well agreement to be less than 3 μA/A, by comparing with the interchanging the position method, and with expanding uncertainties being below 5 μA/A at frequencies up to 200 kHz. In future work, another measurement setup based on cascaded BICD with current ratio of 10:1 will be designed, and to compare 1-Ω and 10-Ω shunt-TVC combinations directly at common ground only in one step.

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