

THE RESEARCH ON THE CALIBRATION OF DIRECT CURRENT-CURRENT TRANSFORMER*

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Abstract

The measurement accuracy of direct current-current transformer (DCCT) is one of the key factors influencing the output of high-precision direct current power supply. In this paper, a calibration system designed by measuring resistance principle with a high accuracy direct current comparator (DCC) was presented for DCCT whose measurement accuracy is better than 10^{-5} . The system can achieve high-precision calibration of DCCT within the measurement range of 0-400 A, and the uncertainty of the system calibration is better than 1.1×10^{-6} in the whole range. The accuracy and linearity of DCCT are tested to verify the accuracy of the whole calibration system, thereby the current accuracy of the magnet power supply can be further improved.

INTRODUCTION

As one of the core components of accelerator high-precision current power supply, Direct current-current transducer (DCCT) directly determines the current accuracy and stability. DCCT is the core component to ensure the stability, repeatability and accuracy of the power supply and it is also one of the key technologies for the development of future high-precision steady-current power supply. For the accuracy and repeatability of power supply (it can be regarded as the synthesis of short-term accuracy and long-term stability), it is necessary to establish a precision test and calibration system to realize the calibration of DCCT and improve the accuracy of power supply.

The accuracy test method based on current comparator (DCC) was first used to measure resistance, which is based on the principle of zero flux balance. With the maturity of current comparison technology, DCC is also used to measure the accuracy of DCCT. DCCT accuracy calibration is by comparing the output current of the measured DCCT and the standard range extender. This test method would not be affected by the current source accuracy, and the measurement uncertainty is as high as 0.3 PPM in the range of 100A. China has carried out the research on DCCT calibration technology [1-2], and the DCCT calibration is basically realized by comparison. In Beijing electron-positron collider renovation project, the calibration of DCCT is realized by comparing the standard DCCT (as a reference) with the measured DCCT [3].

Comparison method can achieve rapid calibration of multiple DCCTs, but for the whole calibration system, the main problems are as follow.

1. Calibration results are affected by the accuracy of the reference DCCT.

2. The data acquisitions of measured DCCT and standard reference DCCT are not conducted synchronously, and the measurement results are susceptible to power supply noise and current ripple. Considering the influence of these two factors, the calibration result of the system is only 100 PPM.

In this paper, a calibration method based on the DCC bridge is proposed, in which DCCT is equivalent to resistance to achieve high precision calibration.

DCC BRIDGE MEASUREMENT PRINCIPLE

The method based on the DCC bridge proposed in this paper will be used to calibrate and improve the test accuracy of DCCT. DCCT is used to measure current and convert large current to low voltage, which can be equivalent to one resistor. It is the theoretical basis of the calibration system that DCCT is equivalent to resistance. According to the principle of flux balance, the resistance is calibrated by adjusting the ratio of winding turns in the primary and secondary circuits of the bridge.

DCC is a kind of measuring instrument that can measure the ratio between two currents with high accuracy. Figure 1 shows the schematic diagram of DCC bridge measurement.

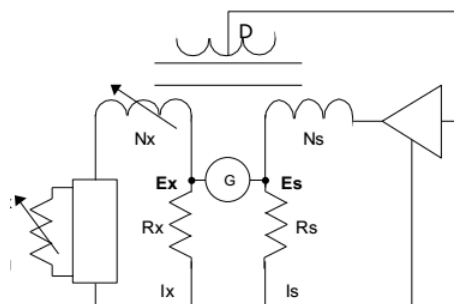


Figure 1: Schematic diagram of DCC bridge measurement.

$$I_s N_s = I_x N_x, I_x / I_s = N_x / N_s \quad (1)$$

$$R_x / R_s = I_s / I_x = N_x / N_s, R_x = (N_x / N_s) \times R_s \quad (2)$$

The output of the high-power current source is directly connected to the range expander. The purpose of the current reducer is to reduce the current in equal proportion to the coil turns. The measured current is scaled down to the optimal operating current of the DCC bridge. The reduced current is directly connected to the input port of bridge R_s as the reference while the DCCT output is connected to the bridge R_x as the measured signal. In the bridge, the current comparison coil is adjusted to achieve potential

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balance between the R_s and the R_x , at the same time the ratio of the measured end R_x to the reference end R_s is obtained, and then the equivalent resistance of the measured end is calculated. Figure 2 shows the principle of DCCT calibration system.

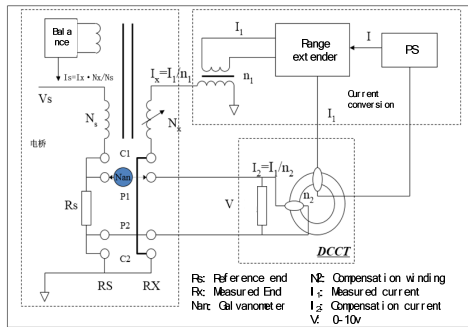


Figure 2: DCCT calibration system principle.

The calibration system uses commercial standard bridges that the accuracy of the ratio range can be better than 0.05 PPM. The output of the power supply is proportionally reduced by the fixed turn ratio of the range extender, as shown in Figure 2. Considering the key parts of the whole system, the uncertainty of system measurement is better than 1.1 PPM.

ACCURACY TEST

The calibration system is composed of high precision bridge, two stage range extender, precision current source and commutator switch.

System measurement is carried out by setting different current values. The number of repeated test data at each point can be set through the program, and the test balance time should be the shortest while ensuring the accuracy. Take HITEC TOPACC 300A as an example (the output voltage is 0~10v, and the equivalent resistance is 1/30Ω), the sampling number at each point is set as 30 and the equilibrium time is set as 12 seconds, so DCCT equivalent resistance value is the average value of 30 samples. Figure 3 shows the test dispersion at 25A current.

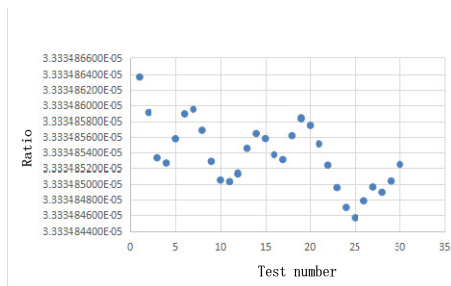


Figure 3: Test data dispersion at 25 A current.

The reference resistance in the test is 1000Ω as the comparison standard. The calculation result of the average test ratio under 25A current is $3.333485299 \times 10^{-5}$ (ratio= R_x/R_s), the test uncertainty is better than 2.14×10^{-7} , and the equivalent resistance of DCCT is 0.0333348529Ω.

Figure 4 shows the dispersion of tested data at 250Acurrent. The result shows that the average equivalent resistance ratio at 250A current is $3.3334739971 \times 10^{-5}$, the test uncertainty is better than 2.11×10^{-7} , and the equivalent resistance of DCCT is 0.0333347399705128Ω.

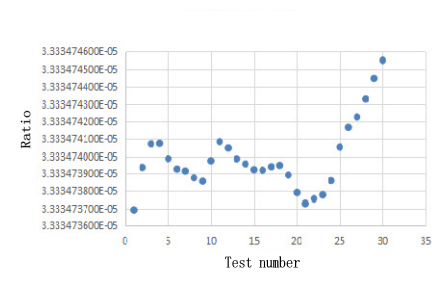


Figure 4: Test data dispersion at 250 A current.

LINEARITY TEST

DCCT linearity can be calibrated according to the test equivalent resistance at each point. Table 1 shows the linearity test results of HITEC TOPACC 600A (output voltage 0~10v, equivalent resistance 1/60 ohm, test range 0~ 400A) before calibration.

Table 1: DCCT Linearity Before Calibration

Current(A)	Reference voltage(V)	Test voltage(V)	Linearity (PPM)
50	0.833333 333	0.833338941	0.56076
100	1.666666 667	1.666675814	0.914728
150	2.5	2.500013541	1.35406
200	3.333333 333	3.333349093	1.57602
250	4.166666 667	4.166682888	1.62208
300	5	5.000014644	1.46436
350	5.833333 333	5.833344 224	1.08905
400	6.666666 667	6.666680697	1.40302

Table 1 shows the comparison between the calculated voltage according to the equivalent resistance and the ideal voltage. The maximum linearity of the DCCT before calibration is 1.62208 PPM.

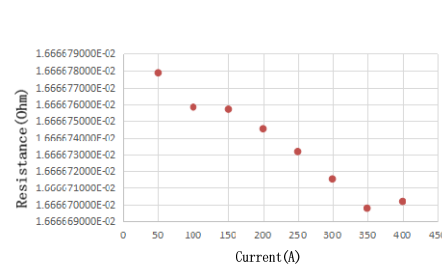


Figure 5: Equivalent resistance of DCCT at different currents.

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Figure 5 shows the equivalent resistance of DCCT obtained in the range of 400A under different current tests. The equivalent resistance corresponding to each current is obtained by taking the average value through multiple measurements. The uncertainty of equivalent resistance measurement at each point is better than 0.25 PPM, which ensures the accuracy of measurement. Figure 6 shows the error distribution between the voltage calculated by DCCT test and the ideal voltage. In order to achieve the calibration of DCCT, the test voltage fitting line should be compensated to obtain the optimal linearity.

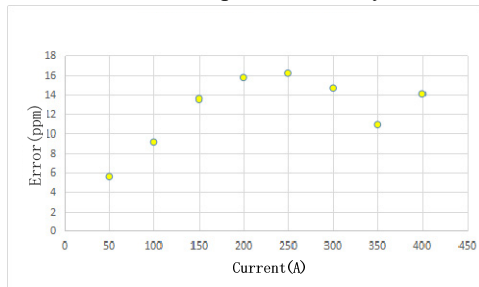


Figure 6: Error of calibration voltage and ideal voltage before calibration.

The slope and intercept of the fitting line of the regression line can be calculated according to the test voltage. The calculation method is as follows.

The intercept a and the slope b of the regression line are:

$$a = \bar{y} - \frac{\sum(x - \bar{x})(y - \bar{y})}{\sum(x - \bar{x})^2} \bar{x}, \quad b = \frac{\sum(x - \bar{x})(y - \bar{y})}{\sum(x - \bar{x})^2} \quad (3)$$

x is the test voltage value and y is the ideal voltage value.

The slope and intercept of the test data regression line can be calculated by formula (3), and then the compensation voltage can be calculated to achieve the measurement voltage calibration. The slope and the intercept were 0.999998979 and 8.65273×10^{-6} . The DCCT linearity after calibration is better than 0.6 PPM in 400A test range. Table 2 shows the equivalent output voltage and the linearity of the calibrated DCCT.

Table 2: DCCT Linearity After Calibration

Current(A)	Reference voltage(V)	Calibration voltage(V)	Linearity (PPM)
50	0.833333333	0.833330001	-0.333197
100	1.666666667	1.66666315	-0.035153
150	2.5	2.500003483	0.348255
200	3.333333333	3.333338476	0.514286
250	4.166666667	4.166671711	0.504432
300	5	5.000002908	0.290782
350	5.833333333	5.833331929	-0.14045
400	6.666666667	6.666667843	0.117596

Figure 7 shows the error distribution between the equivalent voltage of the calibrated DCCT and the ideal voltage. The error after calibration is obviously smaller than before calibration, and the linearity is better than 0.6ppm, which is 1 order of magnitude higher than before calibration. Therefore, DCCT calibration can better improve the accuracy of measurement, and lay a foundation for improving the power supply accuracy and beam quality.

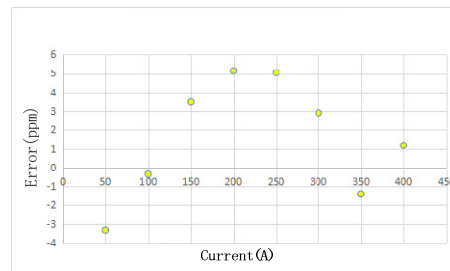


Figure 7: Error of calibration voltage and ideal voltage after calibration.

CONCLUSION

Based on the principle of DCC bridge resistance measurement, The DCCT calibration system can realize a rapid and high-precision calibration of DCCT. The system adopts the method of high-precision bridge and range extender to realize the calibration of DCCT accuracy and linearity through the comparison the measured DCCT and traceable standard resistance. The calibration uncertainty is better than 1.1 PPM in the range of 0-400 A, and the calibration accuracy of the system is verified by the experimental test of HITEC Topacc 300A and Topacc 600A. The linearity of DCCT (after calibration) can be better than 0.6 PPM within 400 A. The research of DCCT calibration system lays a foundation for the improvement of power supply accuracy and accelerator beam quality.

ACKNOWLEDGEMENT

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