

# On the calibration of direct-current current transformers

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## Abstract

Modern commercial direct-current current transformers (DCCT) can measure currents up to the kA range with accuracies better than  $1 \times 10^{-5}$ . We discuss here a DCCT calibration method and its implementation with commercial instruments typically employed in low resistance calibration laboratories. The primary current ranges up to 2 kA; in the current range below 100 A the calibration uncertainty is better than  $3 \times 10^{-7}$ . An example of calibration of a high-performance DCCT specified for primary currents measurement up to 900 A is discussed in detail.

## 1. INTRODUCTION

Direct-current current transformers (DCCT) are the most accurate dc high-current sensors commercially available [1], reaching specified relative accuracies in the  $10^{-5}$  range and integral nonlinearities below  $10^{-6}$ . The verification of such high performances and the calibration of the DCCT ratio require metrological facilities capable of handling high currents, with high accuracy and automated operability [2–5].

Ultimate current ratio accuracy is achieved in cryogenic current comparators (CCC) [6]. In a CCC, ratio accuracy is obtained by constraining the magnetic flux (generated by the current being compared) within superconducting shields. An extremely high sensitivity is achieved with a superconducting quantum interference device (SQUID) flux sensor. Even though CCCs capable of handling currents up to 100 A have been realized [7], these devices are research instruments not available in calibration laboratories. Ferromagnetic-core, room-temperature current comparators (CC) are current ratio devices which can achieve ratio errors lower than  $10^{-7}$  [8], and can be self-calibrated through step-up procedures [9, 10] with similar levels of uncertainty. Thus, a CC can be employed as current ratio standard in a DCCT calibration setup. Although complex and expensive instruments, high-current CC are common in electrical calibration laboratories, since they are part of commercial resistance ratio bridges employed for the measurement of low-value resistors. These instruments include also current sources, detectors, and firmware for automated operation.

The calibration of the DCCT ratio with a reference current ratio standard (possibly having a different nominal ratio) can be performed by different methods. Recent papers [11, 12] describe a method based on the comparison of the voltages developed by the secondary currents of the devices being compared on calibrated resistance standards.

Here we present a simple method that allows the calibration of the ratio of a DCCT by using commercial components, originally designed for the calibration of low-value resistors. This method does not require calibrated resistance standards; the accuracy, dependent on the primary current, is better than  $3 \times 10^{-7}$  for currents below 100 A. An example of calibration of a DCCT having a 1500 : 1 nominal ratio for currents up to 900 A is reported.

The implementation is being employed in the EURAMET.EM-S35 High DC current ratio supplementary comparison [13], in which INRIM acts as co-pilot laboratory.

## 2. CALIBRATION METHOD

Fig. 1 shows the schematic diagram of the calibration setup which includes three current ratio devices: the DCCT under calibration, an automated current range extender EXT and a current comparator ratio bridge CC.

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<sup>†</sup>In press on IEEE Trans. Instr. Meas.

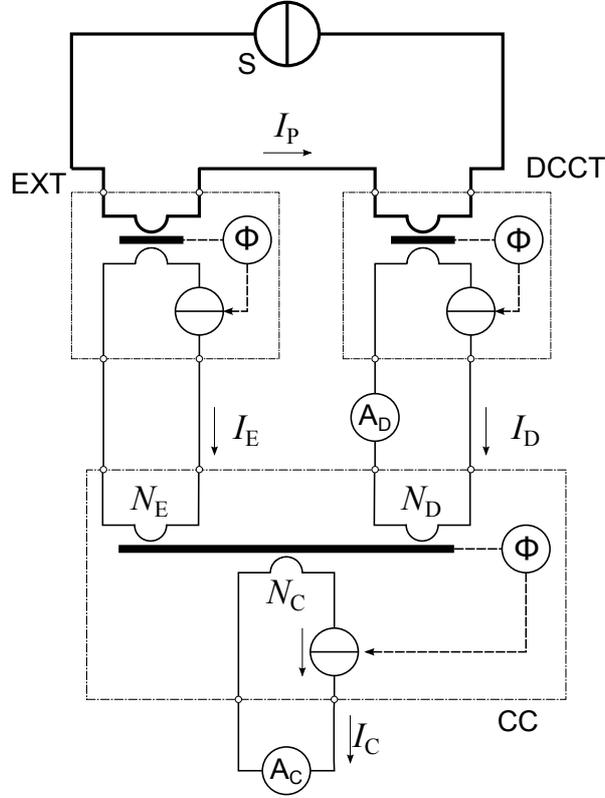


Figure 1: Schematic diagram of the DCCT calibration setup.  $S$  is a high-current source,  $EXT$  is an automated current range extender and  $CC$  is a dc current comparator. The ammeter  $A_D$  monitors the DCCT output  $I_D$ , while  $A_C$  measures the current  $I_C$  which is the input quantity of the measurement model (2).

## 2.1. OPERATION OF CURRENT RATIO DEVICES

The operation of the three current ratio devices, sketched in Fig. 2, is based on the same principle.

$m + 1$  windings are wound around a ferromagnetic core. Each winding  $k$  has  $N_k$  ( $k = 0 \dots m$ ) turns, and a current  $I_k$  flows through it. The magnetic flux  $\Phi$  in the core is given by  $\mathcal{R}\Phi = \sum_{k=0}^m N_k I_k$ , where  $\mathcal{R}$  is the core magnetic reluctance.  $\Phi$  is measured by a fluxgate detector [1, 14, 15] whose output constitutes the error signal of a feedback control. The output of the control drives current source  $I_0$ , connected to winding 0, to null the flux. The condition  $\Phi = 0$  yields the ampere-turns balance equation  $\sum_{k=0}^m N_k I_k = 0$ .

In normal operating conditions, DCCT and EXT have only two ( $m = 1$ ) active windings. The output  $I_0$  of the controlled current source constitutes the device output current; hence, the current  $I_1$  is scaled down with the turns ratio  $n_{1,0} = N_1/N_0$  as  $I_0 = n_{1,0}I_1$ .

In the CC, instead, more windings ( $m \geq 2$ ) are simultaneously active; the currents  $I_k$  ( $k = 0 \dots m$ ) are compared, weighted by their respective turn numbers  $N_k$ ; the measurement of  $I_0$  gives the CC reading, that is, the residual unbalance between the currents  $I_1 \dots I_m$  to be compared.

## 2.2. CIRCUIT DESCRIPTION

The input windings of both DCCT and EXT are connected in series and driven by the primary current  $I_P$  generated by the high-current dc source  $S$ . The DCCT and EXT output currents are respectively  $I_D = G_D I_P$  and  $I_E = G_E I_P$ , where  $G_D$  is the DCCT current gain (that is, the measurand) and  $G_E$  is the

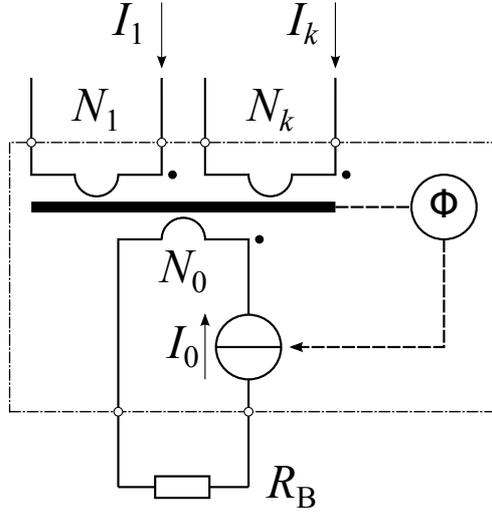


Figure 2: The operating principle of the instruments employed in the calibration setup.  $m + 1$  windings, with  $N_k$  ( $k = 0 \dots m$ ) turns each, are wound around a ferromagnetic core (black thick line). The flux detector  $\Phi$ , through an automatic control (not shown), steers the current source  $I_0$  until  $\Phi = 0$ ; a generic load  $R_L$  can be connected to the source.

EXT current gain.

$I_D$  and  $I_E$  are connected to two input windings of CC, each having  $N_D$  and  $N_E$  turns.  $I_D$  is also measured by a high-accuracy ammeter  $A_D$ .

The CC compensation current  $I_C$ , linked to the CC winding with  $N_C$  turns, is measured by the ammeter  $A_C$ ; when operating properly, the CC balance equation is

$$N_E I_E + N_D I_D + N_C I_C = 0. \quad (1)$$

In (1), the sign of turn numbers  $N_x$  can be either positive or negative and is set by the winding direction. When in all current ratio devices each core flux is drawn to zero by the corresponding automated control, the balance equation of the whole circuit becomes

$$G_D = \frac{I_C}{I_P} \frac{N_C}{N_D} - G_E \frac{N_E}{N_D}. \quad (2)$$

### 2.3. MEASUREMENT MODEL

To derive an accurate measurement model, two major nonidealities of the devices employed should be considered:

#### **OFFSET**

All instruments based on the fluxgate technique suffer from a certain degree of dc offset, caused by the magnetization hysteresis and relaxation of the ferromagnetic core. This offset, of the order of  $10 \mu\text{A}$  per unit input turn [14], depends on temperature, measurement history and time drifts. To compensate this offset, the reading  $I_C$  in (2) is substituted with  $\Delta I_C = I_C - I_{C0}$ , where  $I_C$  is the reading taken at the nominal primary current  $I_P^{(n)}$  of interest, and  $I_{C0}$  is the reading with null primary current,  $I_P = 0$ .

#### **RATIO ERRORS**

The actual current ratios of CC can differ from the corresponding turn ratios. We call  $n_{CD}$  and  $n_{ED}$  the current ratios of which  $N_C/N_D$  and  $N_E/N_D$  are the corresponding nominal turn ratios.

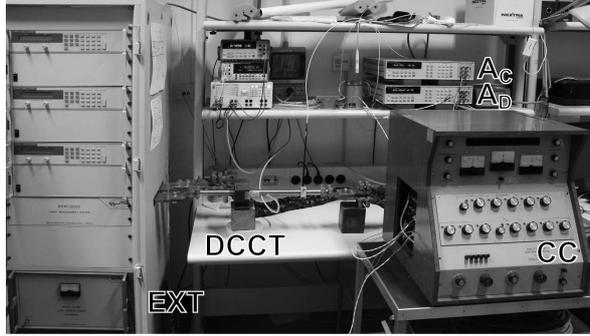


Figure 3: A photo of the implementation of the calibration method. See Sec. 3. and Fig. 1 for the identification of the labels.

Taking into account the above nonidealities, (2) can be rewritten as

$$G_D = \frac{\Delta I_C}{I_P} n_{CD} - G_E n_{ED}, \quad (3)$$

The relative gain error  $\delta G_D$  with respect to the nominal gain  $G_D^{(n)}$  is

$$\delta G_D = \frac{G_D - G_D^{(n)}}{G_D^{(n)}}. \quad (4)$$

### 3. IMPLEMENTATION

Fig. 3 shows an implementation of the schematic diagram of Fig. 1. It employs the following instrumentation:

**DCCT** The device under test, for which the results reported in Sec. 4. were obtained, is a LEM mod. ITN 900-S ULTRASTAB high-performance current transducer [16]. It handles primary currents  $|I_P| \leq 900$  A with a nominal current ratio  $G_D = 1/1500$ . The specified accuracy is better than  $2 \times 10^{-5}$  (including offset), the linearity better than  $1 \times 10^{-6}$ , maximum load resistance 2.5  $\Omega$ . Fig. 4 shows the DCCT mounted on the primary busbar.

**CC** Guildline mod. 9920 direct current comparator [14]. This instrument is particularly versatile since it provides several fixed windings having decadic (1 to 1000) number of turns and one winding with an adjustable number of turns through decade rotary switches; moreover, it allows a full reconfiguration of the connections between the windings and the internal electronics. The settings used in the calibration of the particular DCCT under test are:  $N_D = -100$  (fixed winding),  $N_E = 150$  (decade winding), and  $N_C = 1$  in order to achieve the highest sensitivity in the measurement of  $I_C$ .

**EXT** Two different extenders were employed, depending on  $I_P$ :

- Measurement International mod. MI 6011B range extender. Primary current  $|I_P| \leq 100$  A, nominal ratio 1/1000, relative accuracy  $< 1 \times 10^{-7}$ .
- Measurement International mod. MI 6012M range extender.  $|I_P| \leq 2$  kA, nominal ratio 1/1000, relative accuracy  $< 2 \times 10^{-6}$ .

The above specifications were validated in the standard operating setup for low-valued resistor measurements [17].

**S** Two different sources were employed, depending on the primary current  $I_P$ :

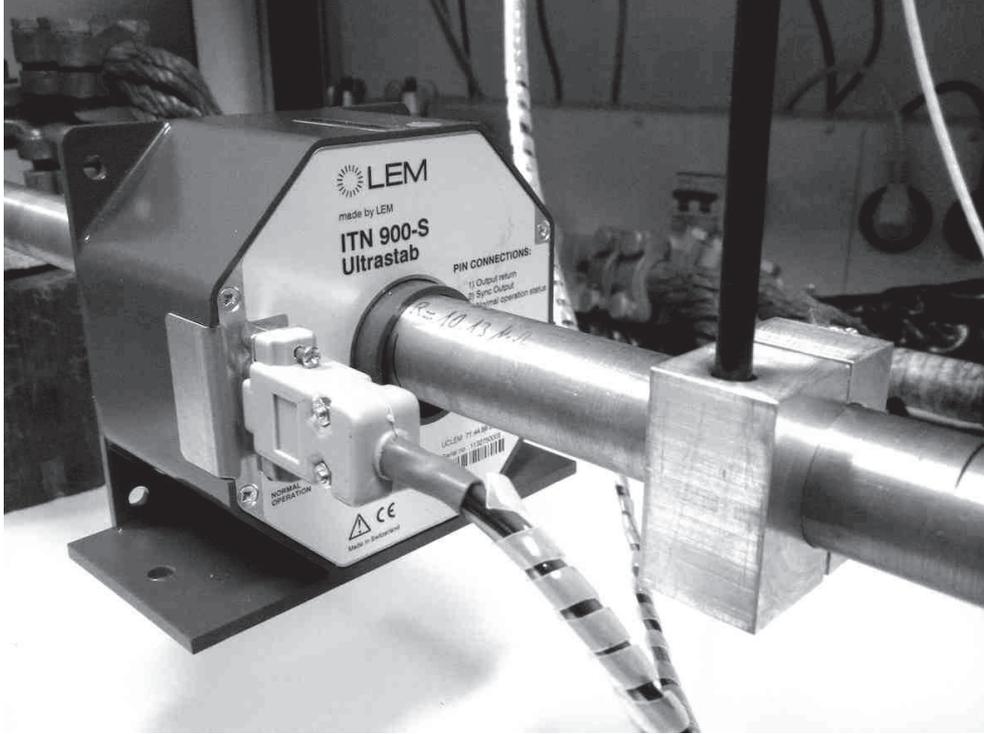


Figure 4: The DCCT under calibration mounted on the primary current busbar. The aluminum block in foreground embeds a Pt100 sensor to monitor the temperature of the primary current busbar.

- Measurement International MI 6100A linear dc power supply, for  $|I_P| < 100$  A. Current reversal is achieved with a switch internal to MI 6011B.
- Agilent mod. 6680 (two items in parallel) for  $|I_P| < 1750$  A. Current reversal is achieved with a Measurement International mod. 6025 pneumatic switch.

**A<sub>D</sub>** Agilent mod. 3458A multimeter in dc voltage mode, measuring the voltage drop on a Tinsley mod. 1659  $1\ \Omega$  standard resistor.

**A<sub>C</sub>** Agilent mod. 3458A multimeter in dc current mode, 100 mA range.

The DCCT and busbar temperatures are monitored with two Pt100 platinum temperature sensors (see Fig. 4) read by a Fluke mod. 1529 CHUB E-4 thermometer.

#### 4. RESULTS

After a warming-up period of about 1 h at  $I_P = +I_P^{(n)}$ ,  $I_P$  is repeatedly cycled between values  $0, +I_P^{(n)}, 0, -I_P^{(n)}$  (ending the whole cycle sequence with  $I_P = 0$ ).<sup>1</sup> The reading  $I_C$  is continuously recorded. Fig. 5 shows a time series of  $I_C$  readings corresponding to an  $I_P$  cycle. For each value of  $I_P$ , after transients have died out, a time average  $\overline{I_C}(I_P)$  is computed (see gray bands in Fig. 5).

The quantity  $\Delta I_C$  to be employed in Eq. (2) is computed as  $\Delta I_C(I_P^{(n)}) = \overline{I_C}(I_P^{(n)}) - (\overline{I_C}^-(0) + \overline{I_C}^+(0))/2$ , where  $\overline{I_C}^-(0)$  and  $\overline{I_C}^+(0)$  are the zero readings respectively preceding and succeeding  $\overline{I_C}(I_P^{(n)})$  in the time series.

<sup>1</sup>It has been found that, for the particular DCCT being tested and for  $I_P$  near fullscale, the current must be ramped up smoothly to allow the DCCT automatic shutdown.

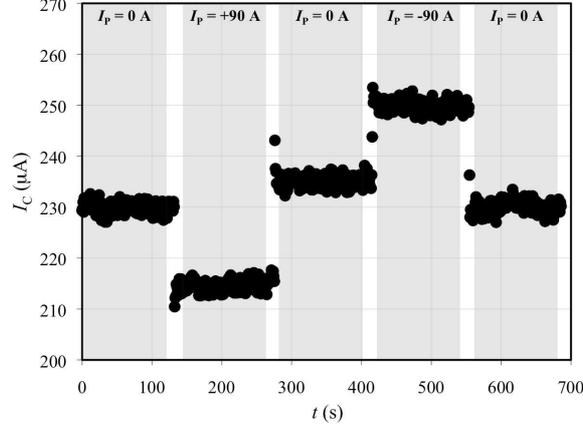


Figure 5: Time recording of the compensation current  $I_C$  for different primary currents  $I_P$ .

Table 1: DCCT gain  $G_D$  for different primary currents  $I_P$ . The relative deviation  $\delta G_D$  from nominal ratio is also reported.

$I_P^{(n)}$ A	Supply	EXT	$G_D$ $\times 10^{-4}$	$\delta G_D$ $\times 10^{-6}$	$U(\delta G_D)$ $\times 10^{-6}$
+90	6100A	6011B	6.666 653 9(16)	-1.92	0.24
-90	6100A	6011B	6.666 653 9(16)	-1.92	0.23
+300	6680A	6012M	6.666 682(16)	+2.3	2.3
-300	6680A	6012M	6.666 676(15)	+1.5	2.3
+600	6680A	6012M	6.666 677(15)	+1.6	2.3
-600	6680A	6012M	6.666 676(15)	+0.9	2.3
+900	6680A	6012M	6.666 672(15)	+0.9	2.3
-900	6680A	6012M	6.666 673(15)	+1.1	2.3

From each  $\Delta I_C(I_P^{(n)})$ , the absolute  $\Delta G_C(I_P^{(n)})$  and relative  $\delta G_C(I_P^{(n)})$  errors are computed. Fig. 6 graphically shows the values  $\delta G_D$  corresponding to each  $I_P^{(n)}$  measurement cycle.

Tab. 1 reports the estimates for  $G_D$  and  $\delta G_D$  of the DCCT under measurement, together with the corresponding 95 % expanded uncertainties, for several primary current  $I_P^{(n)}$  values.

As an example, the uncertainty budget for the calibration of  $G_D$  at  $I_P = +90$  A is given in Tab. 2, where it can be appreciated that the main contributions to the measurement uncertainty are due to the instability of  $I_C$  and the EXT and CC current ratios  $G_E$  and  $n_{ED}$ .

## 5. CONCLUSIONS

The proposed setup allows the calibration of the ratio of a DCCT with accuracies in the  $10^{-6}$  range or better. The proposed implementation, suitable for primary currents up to 2 kA, is based on commercial instruments typically employed for the calibration of low-valued resistors, and therefore often available in calibration laboratories. The implementation is being employed for the participation to the EURAMET.EM-S35 comparison, which is co-piloted by INRIM and the Federal Institute of Metrology (METAS), Switzerland. The travelling standard of comparison is based on a LEM mod. IT 600-S ULTRASTAB transducer; the participants measure  $G_D$  at primary currents  $I_P = \pm 90$  A,  $\pm 300$  A and  $\pm 600$  A. The preliminary characterizations of the travelling standard performed by INRIM and METAS give results which are in agreement within a compound relative uncertainty better than  $5 \times 10^{-6}$ . At the present time the results of the comparison are confidential; a full validation of the INRIM method

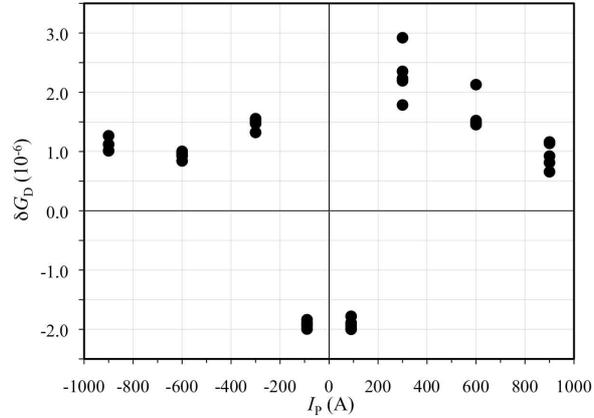


Figure 6: The relative gain error  $\delta G_D$  of the DCCT under calibration, for different nominal primary current values  $I_p^{(n)}$ . Each dot corresponds to half of the measurement cycle shown in Fig. 5. For each  $I_p^{(n)}$ , five measurement results are reported. The average value and its uncertainty are given in Tab. 1.

Table 2: Uncertainty budget for  $G_D$ , at  $I_p^{(n)} = +90$  A.

Quantity	$X$	$u(X)$	contrib. to $u(G_D)$	type	note
$\Delta I_C$	$-17.2 \mu\text{A}$	$0.36 \mu\text{A}$	$2.7 \times 10^{-11}$	A	Standard deviation of the mean, taken over 5 $I_p$ cycles
$I_P$	90 A	90 mA	$1.3 \times 10^{-12}$	B	$A_D$ readings (bound on maximum error)
$n_{CD}$	$-6.666\ 666\ 7 \times 10^{-3}$	$6.7 \times 10^{-10}$	$< 1 \times 10^{-13}$	B	CC manufacturer's specifications
$n_{ED}$	$-6.666\ 666\ 7 \times 10^{-1}$	$6.7 \times 10^{-8}$	$6.7 \times 10^{-11}$	B	CC manufacturer's specifications
$G_E$	$+1.000\ 000\ 0 \times 10^{-3}$	$5.8 \times 10^{-11}$	$3.8 \times 10^{-11}$	B	EXT (MI 6011B) manufacturer's specifications
$G_D$	$+6.666\ 653\ 9 \times 10^{-4}$	$8.1 \times 10^{-11}$			
$\delta G_D$	$-1.92 \times 10^{-6}$	$1.2 \times 10^{-7}$			
$U(\delta G_D)$		$2.4 \times 10^{-7}$			Expanded uncertainty, 95 % coverage probability

will become available after the publication of the comparison report, expected by the end of 2015.

#### ACKNOWLEDGMENTS

The authors are indebted with Alessandro Mortara, Federal Institute of Metrology (METAS), Switzerland, for fruitful discussions; and with their colleagues Fulvio Francone for help in the construction of the calibration facility, and Massimo Ortolano for having reviewed the manuscript.

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