Realization and Validation of the 10 mA–100 A Current Standard at CEM

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***Abstract*—Centro Español de Metrología (CEM) has developed a new ac–dc current standard to improve our measurement capabilities and extend the measurement range to 100 A and 100 kHz. The new standard is based on a step-up procedure using the combination of specially designed shunts and planar multijunction thermal converters. The new CEM ac–dc standard, the validation method, the uncertainty estimation, and the results are described.**

***Index Terms*—ac–dc comparators, ac–dc level dependence, ac–dc transfer measurements, current measurements, measurement uncertainty, precision measurements, thermal converters.**

I. INTRODUCTION

THE Centro Español de Metrología (CEM) calibration and measurement capabilities from ac–dc were previously based on the combination of commercial shunts and single-junction thermal converters. The measurement capabilities covered the range from 10 mA up to 2 A in frequencies from 10 Hz up to 100 kHz, and from 2 A up to 20 A in frequencies from 10 Hz up to 10 kHz. To improve the measurement uncertainties and extend the capabilities to 100 A at 100 kHz, a new standard was implemented.

This paper reflects the results obtained by CEM in the practical application and validation of the new current standard based on the work previously reported for some National Metrology Institutes [1]–[4].

The new standard is based on a step-up procedure from 10 mA to 100 A using a set of standards combining special squirrel-cage design shunts and planar multijunction thermal converters (PMJTCs) [5]. The shunts were manufactured by the Technical Research Institute of Sweden (SP) [4], based on a shunt design used at Dimitry Ivanovich Mendeleev All-Russian Institute for Metrology. The initial step in the chain is a 10 mA PMJTC calibrated at Physikalisch-Technische Bundesanstalt (PTB) as ac–dc current converter. From that, and up to 100 A 100 kHz, the standards, which consist of the set of shunts each with its dedicated PMJTC, are compared with the previous range in a build-up procedure. It was not useful to validate the system by the comparison with the previous CEM standard because the latter was current and frequency limited, the most challenged value is 100 A at 100 kHz, and mainly because of the considerable uncertainty improvement. The standard has been validated at two current levels in the build-up chain: at 100 mA, a middle point in the process, obtained after four steps, and at 100 A, the end of the chain after more than 10 steps. The verification has been made by means of two different combinations of shunt and PMJTC calibrated by SP at several frequencies. Finally, the complete set of current standards has also been checked by comparing the results obtained in each step by two different methods, in this way, some systematic differences, directly related with the measurements of the thermal converters output voltages, were detected. To evaluate the detected differences, a modified differential measurement system was implemented.

This paper describes the measurement systems, the influence of their different components, and the results obtained. The comparison of differential and two voltmeters measurement results as well as a theoretical and empirical justification of the differences founded between both systems are also detailed. In addition, some factors in the build-up chain are evaluated, such as level dependence at low frequencies, tee connectors influences, temperature influence, asymmetries, and so on. Finally, a detailed uncertainty budget is presented [6].

II. MEASUREMENT SYSTEM

In each step, the different combinations of shunts and PMJTCs are connected in series and their outputs are compared by two methods, by means of the two voltmeter method and by a differential measurement system.

In both methods, the standards are connected in series using a current tee connector. For high currents, the series connection was made using a high current tee connector designed and manufactured by Bundesamt für Eich-und Vermessungswesen BEV [7]. Up to 50 mA, two separate calibrators for ac and dc, working as voltage sources, provide the input current. For higher currents, an 8100 Clark Hess transconductance amplifier [8] sources the shunts. The calibrators for ac and dc provide the input voltage to the transconductance amplifier. Two Fluke 5700s are used to source the shunts or the transconductance amplifier. The low output of the sources and the transconductance amplifier are referred to ground. Vacuum relays were used to switch from ac and dc. In addition, a 1 μF capacitor filter was connected at the output of each thermal converter.

A. Two Voltmeter Method

In the two voltmeter method, several cycles of ac, dc$^+$, ac, dc$^-$, and ac are then applied to the series connected shunts. During each cycle, the two outputs are directly measured using

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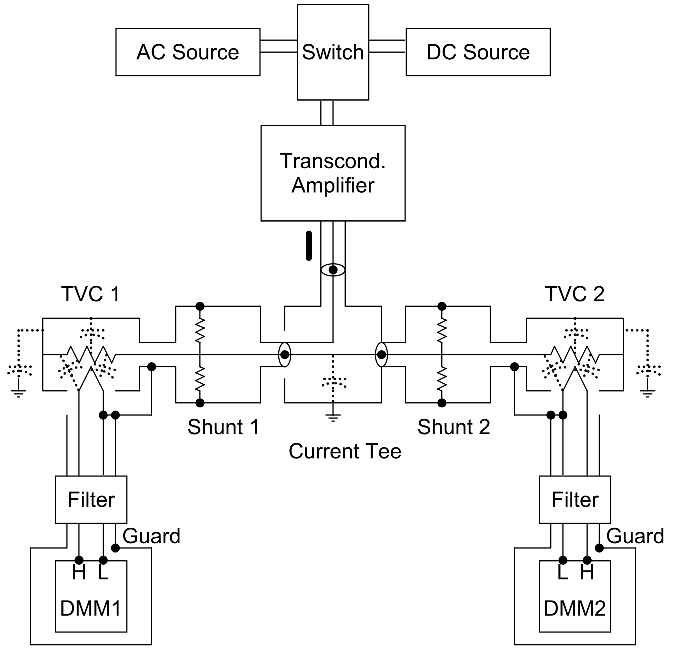

Fig. 1. Schematic diagram of the two voltmeter method.

digital voltmeters. In each cycle, the thermal converters' output drifts are assumed to be linear with time. In this way, the mean of the ac and the dc values are related to the same instance.

Fig. 1 shows a diagram of the two voltmeter method. Agilent 3458s are used to measure the output voltage.

According to [2] and [9], this connection minimizes the leakage current through the parasitic impedances, represented as capacitors in the diagram. In particular, the leakage current flowing through the heaters and the thermocouples wires is limited by connecting their cable shield and the voltmeter guard to the low or high of the current source for the standards connected in the low or high potential position, respectively [2]. Leakage current due to the higher potential of the connection point of the two standards can only be limited by the design of the tee connector [2]. According with the results obtained using this method and connections, there is no significant difference when the shunt positions are interchanged.

B. Differential Method

In the differential measurement system, the higher thermal converter output is divided using a resistive divider to be near equal to the lower output. The resistive divider is formed by the output resistance of the thermal converter and a variable resistor connected in parallel. The same cycles of ac, dc$^+$, ac, dc$^-$, and ac are applied to the series connected shunts. During each cycle, the lower output and the difference between the two outputs are measured by means of two nanovoltmeters. The drift influence has also been computed assuming that the drift variation is linear with time.

Fig. 2 shows a diagram of the differential method; Keithley 182 nanovoltmeters were used for the voltage measurements. These nanovoltmeters do not provide a separate guard isolated from the ground terminal.

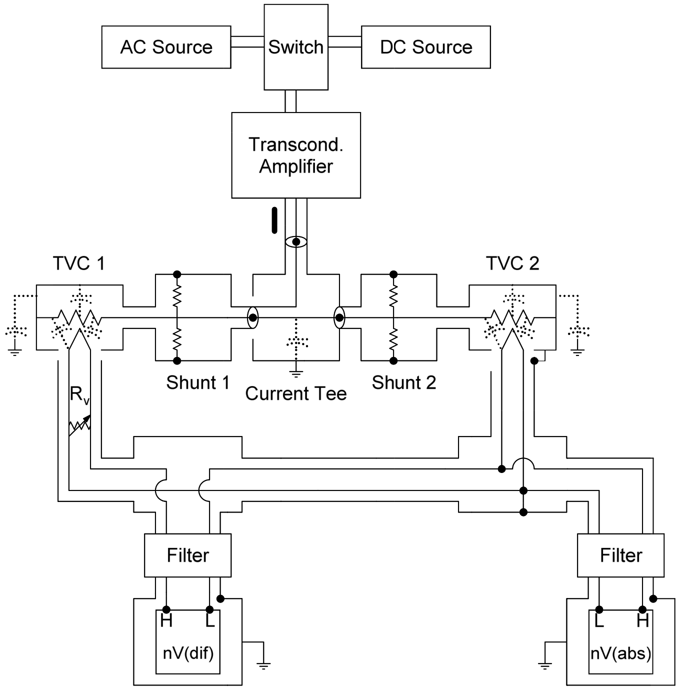

Fig. 2. Schematic diagram of the differential method.

TABLE I

DIFFERENCES WHEN THE SHUNTS POSITIONS ARE INTERCHANGED FOR BOTH METHODS (VALUES IN µA/A)

Current	Differential method		Two multimeter method	
	70 kHz	100 kHz	70 kHz	100 kHz
0.02 A	4.0	5.6	0.5	0.8
0.5 A	3.3	6.0	0.3	0.6

When the outputs are compared by means of the differential measurement system, there is a difference at high frequencies when the shunt positions are interchanged.

Table I shows the differences between the values obtained when the positions of the shunts are interchanged, for both methods at 70 kHz and 100 kHz for 20 mA and 500 mA.

In the differential measurement system, due to the necessary connections to measure the output voltages, and that the nanovoltmeters do not have a guard separated from ground, it is only possible to connect the thermocouples wire shield and nanovoltmeter guard of the standard connected in the low position to the low of the current source. The different values obtained when the shunts positions are interchanged are due to the leakage current between the heater and the thermocouples wires of the standard connected in the high position.

This leakage current has been evaluated at frequencies higher than our present measurement capabilities. To make different configurations possible, the two nanovoltmeters have been replaced by an amplifier and a digital multimeter (DMM) for the measurement of the difference between the two outputs and a DMM for the lower output. The amplifier was an EM electronics A14 and the DMMs were Agilent 3458s. The 3458s provide a separate guard isolated from the ground terminal.

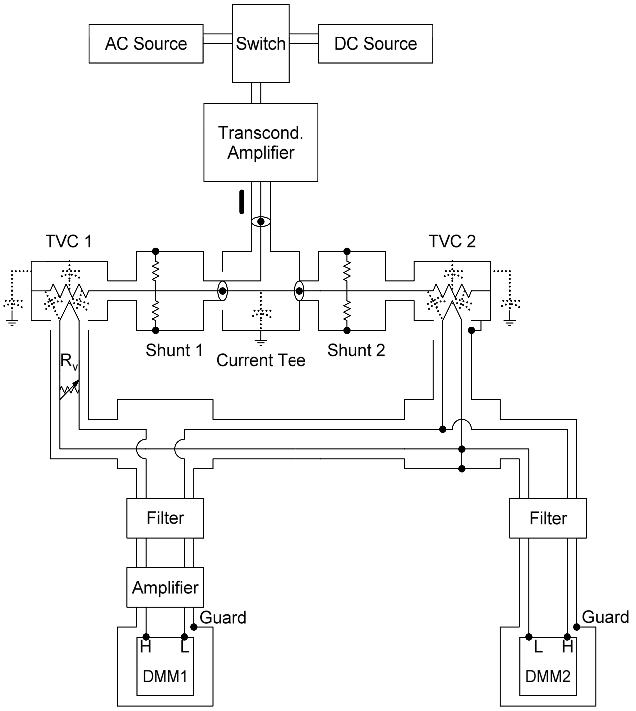

Fig. 3. Schematic diagram of the differential method using voltmeters with separate guard from ground.

This modification allows to connect the thermocouple wire shield and nanovoltmeter guard either to the standard connected in the low or high potential to the low or high input current wires, respectively. From this point on, this connection is called guard.

This new configuration will also remove the possible currents and their associate noise, induced in the shield due to the ground connection of the two nanovoltmeters. This influence has been found negligible at frequencies up to 100 kHz.

Fig. 3 shows the modified measurement system, when the thermocouples wire shield and the voltmeter guard are connected for the standard at low potential to the low input current terminal. In the other configuration (not shown in the figure), the thermocouples wire shield and the voltmeter guard are connected for the standard at high potential to the high input current terminal. It is only possible to do this connection for one of the standards, and there will be some leakage current from the heater to the thermocouple wires in the other standard.

The modified differential method has been used to compare two 10 mA current standards in four different combinations. For clarity, the standard with the lower thermocouple output is considered to be the test. The four possible combinations are: test in the low position and guard in the low position, test in the high position and guard in the high position, test in the low position and guard in the high position, and finally, test in the high position and guard in the low position. Obtained results for the four combinations, at 100 kHz, 300 kHz, and 500 kHz are summarized in Table II. As can be observed, for 100 kHz and 300 kHz, there is not significative position dependence (low or high) and the results only depend on the guard connection. Configuration 1 provides similar results to configuration 2, and configurations 3 and 4 are also analogous. It is due to the ac leakage through the unguarded standard that does not go through the other standard, increasing or decreasing their relative ac–dc difference depending on the position. At 500 kHz, there are some differences between configurations 1 and 2 and configurations 3 and 4, due to at this frequency, the influence of the asymmetry depends on the standards positions.

TABLE II

DIFFERENCES (TEST–STANDARD) IN AC–DC BETWEEN TWO 10 mA THERMAL CONVERTERS AT FOUR DIFFERENT COMBINATIONS (VALUES IN μA/A)

Configuration			Frequency (kHz)		
i	Test position	Guard connection	100	300	500
1	Low	Low	4.4	27	69
2	High	High	3.5	26	73
3	Low	High	-5.2	-32	-98
4	High	Low	-5.1	-32	-80

TABLE III

COMPARISON OF THE RESULTS OBTAINED WITH THE TWO VOLTMETER AND THE CORRECTED DIFFERENTIAL METHODS AT 10 mA (VALUES IN μA/A)

Frequency (kHz)	100	300	500
Differential method	4.4	27	69
Leakage current	5	30	80
Corrected differential method	-0.6	-3.0	-11
2 voltmeter method	-0.2	-0.7	-7

Theoretically, the measured values respond to the following equations:

$$M_1 = D + A + L_1 \tag{1}$$

$$M_2 = D + A + L_1 \tag{2}$$

$$M_3 = D + A - L_2 \tag{3}$$

$$M_4 = D + A - L_2 \tag{4}$$

where

M_i	measured difference between test and standard current converters in i configuration;
A	difference due to tee connector asymmetry;
D	difference between test and standard current converters;
L_1	ac–dc difference caused by the leakage current due to not "guarding" the known standard;
L_2	ac–dc difference caused by the leakage current due to not "guarding" the test standard.

Because the two current converters are similar (PMJTC), it can be assumed that the leakage currents L_1 and L_2 are the same and can be obtained from (1) or (2) and (3) or (4).

Table III contains the values obtained in the comparison of these standards by means of the differential method (configuration 1), the leakage current obtained from the above equations, the values obtained by the differential method after applying

TABLE IV
EVALUATION OF TEE CONNECTORS ASYMMETRY

Tee connector	Position	ac-dc difference (μA/A)				
		Frequency (kHz)				
		100	300	500	700	1000
T-1	High	-5	-12	-23	-91	-130
	Low	5	14	18	88	115
	Mean	0	1	-3	-2	-8
T-2	High	-18	-42	-73	-109	-144
	Low	16	42	71	113	154
	Mean	-1	0	-1	2	5
T-10	High	1	2	1	-55	-74
	Low	0	-1	-7	52	58
	Mean	0	0	-3	-2	-8

leakage current correction, and finally, the values obtained by the two voltmeter method. The leakage current values have been assigned from the mean of the values obtained by solving (1) and (3) and (2) and (4).

From the results, it can be concluded that the difference between the two methods, when the positions of the standards are not interchanged and the mean considered, is due to the leakage current from the unguarded standard. This error is mostly compensated when the mean of the measurements with the standards positions interchanged is considered and the difference is small compared with the measurement uncertainties.

III. LEVEL DEPENDENCE EVALUATION

The step-up procedure is based on the assumption that the ac–dc difference of a shunt and thermal converter combination is the same at the two current levels used in the step-up procedure. Level dependence can produce systematic errors that are added in each step and can be considerable at the end of the chain, after more than 10 steps. Because of their design, it was not expected to find an appreciable low frequency level dependence on the shunts. It was likely to find a level dependence behavior of the PMJTC at low frequency.

According to [10], the variation of the transfer difference for the thermal converters at low frequency is proportional to the input power. To evaluate the power dependence, two thermal converters calibrated by PTB as ac–dc voltage transfer difference at two different voltages, 1 V and 1.5 V, respectively, were used. By comparing these standards at 1 V, a thermal converter calibrated at two different voltages (1 V and 1.5 V) was obtained. These standards were calibrated in the same period with the same system. The uncertainty associated to the difference between the values at 1 V and 1.5 V is small. The ac–dc transfer difference variation between applying 1 V and 1.5 V was about 0.9 μV/V at 10 Hz. Using these two values and assuming linear variation with power, the ac–dc transfer difference at 0.5 V was assigned. This standard was later employed to calibrate every thermal converter used in the chain at 0.5 V and 1 V and from that, the low frequency level dependence obtained. The differences at these two levels found in the set of thermal converters vary from 2 μV/V to 3.6 μV/V.

TABLE V
COMPARISON OF THE RESULTS OBTAINED AT 5 A WITH BOTH METHODS
(VALUES IN μA/A)

Frequency (kHz)	0.01	0.02	1	10	70	100
Differential method	-1.8	-0.3	0.0	-0.7	-13.4	-22.7
2 voltmeter method	-1.5	0.0	0.5	-0.9	-12.5	-21.3
Difference between both methods	0.3	0.3	0.5	-0.2	0.9	1.4

TABLE VI
COMPARISON OF THE CEM NEW STANDARD VALUE AT 100 A AND THE SP CALIBRATION CERTIFICATE VALUES

Frequency (kHz)	0.01	1	10	100
CEM values (μA/A)	-11	-1	2.2	-30.8
SP values (μA/A)	-11	-1	2	-34
Difference SP – CEM (μA/A)	0	0	-0.2	-3.2
SP certified uncertainty, $k = 2$ (μA/A)	45	40	70	200

These power coefficients were later used to correct the ac–dc differences, according to the current level corresponding to each step of the build-up process.

Finally, the corrections at 10 Hz were in the order of 4 μA/A at 100 mA, after four steps, and about 15 μA/A at 100 A, after more than 10 steps.

A sampling measurement system to obtain the ac–dc differences at low frequencies is under development at the laboratory. This measurement system will permit a better determination of the low-frequency level dependence of the thermal converters. This system will also provide an absolute value of the ac–dc difference of the thermal converters.

IV. TEE CONNECTOR INFLUENCE EVALUATION

For each step in the build-up chain, the difference between the two standards is measured two times interchanging their position; the mean of these two values is assigned. Different tee connectors have been evaluated by comparing two standards using the two voltmeter method. Some of these tee connectors have been made intentionally asymmetric, increasing the length of one side, to check the correction efficiency when the mean is assigned. It was also used to select the most adequate tee connector for the build-up.

Table IV includes the values obtained in high and low positions and the mean of the two values obtained in each position, for three different tee connectors. As can be observed from this table, when comparing two similar standards, the tee connector asymmetry can be almost compensated taking the mean of the values obtained in both positions.

V. RESULTS

Table V shows the comparison of the results obtained at the 5 A step with both methods (the values are the mean of the two measurements when the shunts positions are interchanged). The values shown in this table for the differential method were not corrected for the leakage term.

Table VI shows, at 100 A, the CEM values obtained by means of the two voltmeter method, the SP certified values,

TABLE VII

COMPARISON OF 50 A AND 100 A SHUNTS (VALUES IN μA/A)

Frequency (kHz)	0.01	1	10	50	100
Measured difference	-5.5	-0.4	0	3	-1
Difference obtained from the certified values	-5	2	1	-1	-1

and uncertainties. At 100 A and 100 kHz, the difference between the SP values and CEM values was in the order of 17 μA/A when the differential method is used. This difference is consistent with the measurement uncertainty.

Finally, a verification of the two voltmeter measurement system at the highest currents has been performed. There were available SP calibration certificates for the 50 A and 100 A current shunts and PMJTC combination, and from these certificates, the difference between the two standards can be obtained. This difference has been compared with the one obtained in the 50 A to 100 A step-up procedure. Table VII shows, at several frequencies, the difference obtained with the measurement systems and that obtained from the SP certificates.

VI. UNCERTAINTY BUDGET

For each step, the ac–dc difference is obtained by the comparison with the previous reference. For the case of the two voltmeter method, the new value is obtained according to the following equation:

$$\delta_t = \delta_s + \mathrm{dif} + C_{\mathrm{LF}} + C_{\mathrm{LEV}} + C_{\mathrm{DMM1}} + C_{\mathrm{DMM2}} + C_n + C_M + C_f + C_T + C_{\mathrm{con}} + C_{\mathrm{asym}} + C_{\mathrm{drift}} + C_{\mathrm{guard}} \qquad (5)$$

where

δ_t	ac–dc difference of the thermal converter under test;
δ_s	ac–dc difference of the reference thermal converter;
dif	measured difference between standard and test;
C_{LF}	low frequency correction of the thermal converter level dependence;
C_{LEV}	level dependence correction of the shunt;
C_{DMM1}	linearity correction of $\mathrm{D_{MM1}}$;
C_{DMM1}	linearity correction of $\mathrm{D_{MM2}}$;
C_n	correction of the sensitivity of the thermal converters;
C_M	reproducibility correction;
C_f	correction for frequency variation;
C_T	correction for temperature influence;
C_{con}	correction due to the connectors;
C_{asym}	correction due to uncompensated tee connector asymmetry;
C_{guard}	correction due to not perfect guarding;
C_{drift}	correction due to the long term standard drift.

TABLE VIII

COMPARISON OF TWO PMTCS AT DIFFERENT TEMPERATURES (VALUES IN μA/A)

Temperature (ºC)	Frequency (kHz)		
	0.01	10	100
26	0.1	-0.1	-0.3
23	-0.1	-0.7	1.7
21	-0.3	0.1	-0.5

Furthermore, the uncertainty estimation for the two voltmeter method is obtained from the following equation (sensitivity coefficients for each uncertainty component are one, as model (5) is linear):

$$u_{\delta t}^2 = u_{\delta s}^2 + u_{\mathrm{dif}}^2 + u_{\mathrm{CLF}}^2 + u_{\mathrm{CLEV}}^2 + u_{\mathrm{CDMM1}}^2 + u_{\mathrm{CDMM2}}^2 + u_{\mathrm{Cn}}^2 + u_{\mathrm{CM}}^2 + u_{\mathrm{Cf}}^2 + u_{\mathrm{CT}}^2 + u_{\mathrm{Ccon}}^2 + u_{\mathrm{Casym}}^2 + u_{\mathrm{Cguard}}^2 + u_{\mathrm{Cdrift}}^2 \qquad (6)$$

Thus, the different uncertainty components have been evaluated. They are due to the uncertainty of the initial thermal converter calibration at 10 mA, and the uncertainty of each step comparison from 10 mA to 100 A.

The uncertainty of the 10 mA is obtained from the PTB certificate. A long-term drift uncertainty component (u_{Cdrift}) has also been considered to cover the possible drift variations.

In each step, the uncertainty of the measured values (u_{dif}) is evaluated by statistical methods. The uncertainty due to the sensitivity correction of each thermal converter (u_{Cn}) has been statistically evaluated from several determinations, measuring the output from a known input variation.

The influence of the temperature on the PMTCs has been evaluated doing the same comparison at three different temperatures. As can be observed in Table VIII, there is no appreciable variation with the temperature. The shunts temperature dependence was considered according to [11]. As the different shunts used by CEM have almost the same temperature coefficient, when they are compared, one against the other, their temperature dependence cancels. According to these studies, the uncertainty component for uncompensated temperature dependence (u_{CT}) is estimated to be less than 0.2 μA/A.

The uncertainties due to the nonlinearity of the voltmeters (u_{CDMM1} and u_{CDMM2}) have been evaluated by means of the CEM Josephson voltage standard. The reproducibility (u_{CM}) has been estimated from the variation of several measurements, after connecting and disconnecting the measurement system.

The low frequency level dependence uncertainty (u_{CLF}) is assumed to be mainly due to the thermal voltage converter and it is estimated from the uncertainty of the method described in Section III.

The $u_{\delta s}$ is the contribution to the uncertainty due to the previous standard in the step-up. The u_{Ccon} corresponds to the uncertainty due to the connectors influence. The u_{CLEV} is the uncertainty due to the shunt level dependence correction, including the correlation with previous steps. The u_{Cguard} has been estimated by comparing the results from different configurations at high frequencies. Finally, u_{Casym} is the estimation of the uncertainty due to the noncompensated tee connector

TABLE IX

UNCERTAINTY BUDGET AT 5 A AT SEVERAL FREQUENCIES (VALUES IN μA/A)

Component	Frequency (kHz)					Type	Distribution
	0.01	1	10	50	100		
u_{δ_S} (2 A)	7.5	4.5	4.5	6.5	9.5	B	Normal
u_{Cdrift}	1.2	1.2	1.2	1.2	1.2	B	Rectangular
u_{CDMM1}	0.2	0.2	0.2	0.2	0.3	B	Rectangular
u_{CDMM2}	0.2	0.2	0.2	0.2	0.3	B	Rectangular
u_{Cn}	0.6	0.0	0.1	1.2	1.7	B	Rectangular
u_{Casym}	1.2	0.3	0.6	2.3	2.3	B	Rectangular
u_{Cguard}	1.2	0.3	0.6	2.3	2.3	B	Rectangular
u_T	0.1	0.1	0.1	0.1	0.1	B	Rectangular
u_{Ccon}	0.1	0.1	0.1	0.1	0.1	B	Rectangular
u_{CLEV}	1.2	0.3	1.2	2.3	2.3	B	Rectangular
u_{CLF}	1.7	1.7	1.7	4.6	5.2	B	Rectangular
u_{dif}	0.6	0.8	0.6	2	3	A	Normal
u_{CM}	1.2	0.6	0.6	1.7	1.7	B	Rectangular
$u_{\delta t}$ (5 A)	8.2	5.1	5.2	9.5	12.2		
U (k=2)	17	10	11	19	25		

TABLE X

EXPANDED UNCERTAINTIES ($k = 2$) FOR THE CEM CURRENT STANDARDS (VALUES IN μA/A)

Current	Frequency (kHz)				
	0.01	1	10	50	100
0.01 A	4.1	3.3	3.4	3.7	3.8
0.02 A	6.7	3.6	3.8	6.1	8.3
0.05 A	8.1	4.3	4.6	7.2	9.6
0.1 A	9.4	5.0	5.4	8.2	11
0.2 A	11	5.8	6.3	9.3	13
0.5 A	12	7	7	10	15
1 A	13	8	8	12	17
2 A	15	9	9	13	19
5 A	17	10	11	19	25
10 A	18	11	12	18	27
20 A	20	12	17	30	37
50 A	24	17	28	46	51
100 A	30	29	37	66	70

asymmetry when the position of the standards are interchanged and it is evaluated from the results in Section IV.

In Table IX, the uncertainty budget for the standard at 5 A at several frequencies is shown.

Finally, Table X summarizes the estimated expanded uncertainty ($k = 2$) for each of step of the whole process that corresponds with the uncertainty of the different CEM current standards at several frequencies.

VII. CONCLUSION

The new CEM current standard has been validated by the comparisons with external standard at two current levels in the build-up chain. The complete build-up has been verified by the comparison of the results obtained using two different methods. The comparison at the two current levels shows an excellent agreement with the SP certified values. The results also show a good agreement between the values obtained with both methods, when the mean of the measurement obtained with the position of the standards interchanged (high and low potential) is used. The differences, at high frequency, in the values obtained with the differential method when the positions of the standard are interchanged, have been investigated. They are due to the leakage current from the heater and thermocouples wires in the standard that is not guarded. The shield of the thermocouples wires and the guard of the voltmeter are not connected to the low or high current source. A correction has been evaluated for this leakage current, and the corrected values compared with those obtained by means of the two voltmeter method, showing an excellent agreement. These results support the new CEM ac–dc reference realization.

In the future, the measurements will be extended to 1 MHz by means of the two voltmeter method and also to very low frequencies by means of a sampling measurement system that will provide absolute values directly related with the CEM Josephson voltage standard.

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