Coaxial and Digital Impedance Bridges for Capacitance Measurements at the nF Range

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***Abstract*— This paper describes three impedance bridges in operation at INMETRO: the two- and four-terminal-pair coaxial bridges and a digital quadrature bridge, including several comparisons among them in the nanofarad capacitance range. These comparisons have the objective to verify the performance and reliability of the coaxial bridges between themselves and to infer on the capabilities of a digital one, recently put in operation. The results obtained indicate that the more accurate coaxial systems are compatible with one another in the 10^{-7} level. The digital bridge is in agreement with the coaxial ones within a few parts in 10^6 or even less in some cases.**

***Index Terms*— Capacitance standards, coaxial bridges, digital signal processing, impedance measurements, measurement uncertainty.**

I. Introduction

The Electrical Standardization Metrology Laboratory of INMETRO (*Lampe*) has two coaxial impedance bridges in operation, both part of the traceability chain of the capacitance unit to the quantum Hall effect (QHE) [1], [2]. The two terminal-pair coaxial bridge (2TCB) [3], [4] is used to measure capacitors at the picofarad range, and the four terminal-pair coaxial bridge (4TCB) [5], [6] was originally constructed to measure ac resistance, and later adapted to capacitance measurements [7].

Although the coaxial bridges present very low uncertainties and high stability, they have drawbacks as limited range and time-consuming measurements. In order to speed up measurements, a digital quadrature bridge (DigBrid) for impedance measurements, both in-phase and quadrature, with uncertainties at the μF/F level was developed at INMETRO [8]–[10].

After recent improvements at both the 4TCB [11] and the DigBrid [12], [13], a comparison between these two bridges and the 2TCB was done in the nanofarad (nF) capacitance range, using thermally controlled capacitance standards from 1 to 100 nF, and ac resistance standards of 1 and 10 kΩ for quadrature measurements with the digital impedance bridge.

Sections II and III present a description of the three bridges. The capacitance measurements with each bridge are detailed in Sections IV and V. Comparison results and uncertainties are presented in Section VI, verifying the agreement between the coaxial and digital bridges.

This paper is an extended version of [14], presenting details and improvements of the 4TCB and the DigBrid, additional measurements in a larger capacitance range, and a thorough analysis of the comparison results.

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II. Coaxial Bridges

The 2TCB, and specially the 4TCB are complex systems, with several technical advantages as high-stability, very low measurement uncertainties, and isolation from external noise sources, due to their coaxial design [1].

A. Two Terminal-Pair Coaxial Bridge

The INMETRO 2TCB is a well-known system with stability of parts in 10^8, being in operation for a decade, and validated trough an international comparison [15]. The 2TCB operates at the frequency range of 398 to 1.592 Hz and compares decade capacitors in the range from 10 pF to 1 nF at the ratios 1:1 or 1:10 [3].

The 2TCB main balance uses a two-stage inductive voltage divider (IVD) to provide the voltage ratio between the two impedances under comparison (that may have different nominal values) and a passive injection circuit. The auxiliary Wagner balance is also necessary to ensure that the IVD "central" tap is actually at zero potential with no parasitic current flow [1].

Although the 2TCB was not devised to operate at the 10-nF capacitance range, the passive injection circuit at the main balance was adapted to calibrate 10-nF standards in order to allow comparisons with the other systems (4TCB and DigBrid). However, one needs to consider the stray impedance of the cables, that for a 2TCB can be significant at the 10-nF range. These impendences have been calculated considering the cables characteristics. Nonetheless, they are responsible for a significant uncertainty component, as detailed in Section IV-A.

B. Four Terminal-Pair Coaxial Bridge

The 4TCB was devised to measure low-value impedances in a four terminal-pair configuration, in order to minimize stray

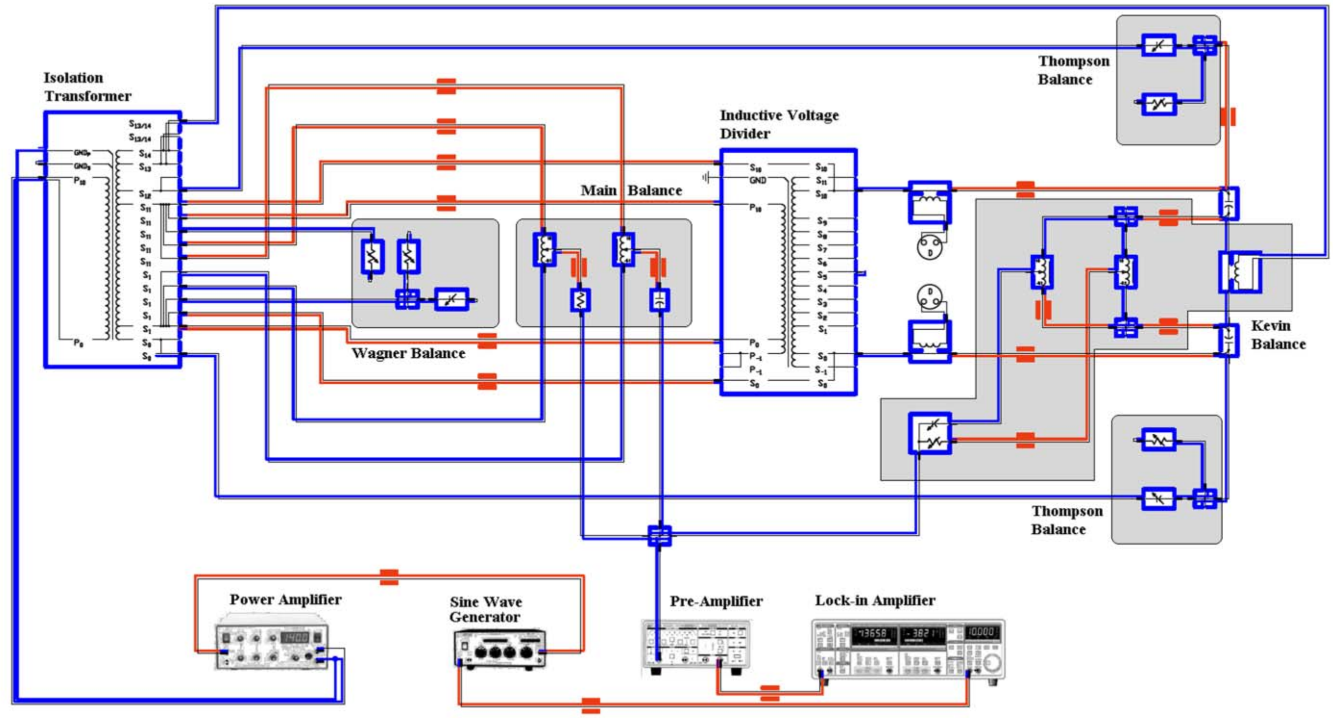

Fig. 1. Schematic circuit of the 4TCB dge, where the chokes are represented by the red rectangles.

impedances of cables [1]. It operates at the frequency range of 398–1.592 Hz and compares decade capacitors in the range from 1 to 100 nF at the ratios 1:1 or 1:10 [7]. The schematic circuit of this bridge is shown in Fig. 1.

The main balance of the 4TCB is similar to that of the 2TCB. It uses an IVD to provide a highly accurate voltage ratio between the two impedances under comparison (which may have different nominal values) and a passive injection circuit with a high-stability capacitor and resistor, and two standard decade inductive dividers.

Besides the main balance, the four-terminal coaxial bridge has three auxiliary balances [1]. The Thompson and Kelvin balances guarantee four terminal-pair conditions to be met at the high- and low-voltage terminals of the impedances under measurement. These auxiliary balances compensate for cable impedances, allowing the 4TCB to operate with very low uncertainty in the nF capacitance range. The Wagner balance, also part of both 2TCB and 4TCB, is necessary to ensure that the IVD "central" tap is actually at zero potential with no parasitic current flow.

C. Improvements and Coaxiality Tests at the 4TCB

Although the 4TCB has been in operation for the last three years, the attained repeatability was at the 10^{-6} level, i.e., much higher than our requirements, besides that the bridge balance was also difficult to be attained [7]. In order to improve the repeatability, the balance, and to reduce possible systematic errors, several structural changes in the 4TCB were made.

With the objective to reduce noise contributions from the electric grid, the bridge power is now supplied through a power transformer. All the 4TCB cables and connectors were replaced whenever necessary. The original banana connectors were substituted by BNC/TNC connectors in the decade IVDs at the main balance and in the capacitive and resistive decades, which are part of the auxiliaries balances.

The two capacitive decades of the Thompson auxiliary circuit were modified to include an outer metallic shield. In order to get more robustness to the continuity of the shielding layer of the input isolation transformer, the metal strips that made the connection between the carcasses of BNC connectors were reinforced by metal ropes solidly connected to the housing of the transformer. The Thompson auxiliary balance design was also modified, and the resistive decades are now placed between the output of the respective capacitive decades and the reference point (ground) of the bridge. This modification allowed the balance of the bridge in calibration of 100-nF capacitors to be attained.

As part of the 4TCB improvement process, its design was reviewed with especial care to the shielding layer and the placement of chokes. In order to verify the coaxiality of the 4TCB, various measurements were done by making use of a 1:100 detector transformer, a lock-in amplifier, and a digital oscilloscope. The detector was constructed using the bootlace technique by winding 100 (50 + 50) turns of a thin wire (25 AWG) on a toroidal supermalloy core.

By passing the cable of each mesh through the detector and measuring the induced voltage at its secondary, it was possible to verify the usefulness of each choke, and also the necessity of additional ones [4], [16]. During the coaxiality testing, the lock-in amplifier and oscilloscope were used to

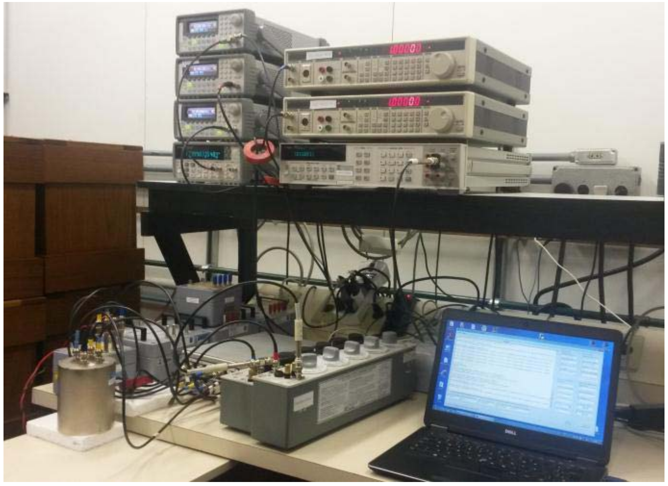

Fig. 2. DigBrid with two audio sources.

verify the amplitude of the induced voltage and to verify its shape.

After careful analysis of all measurements, two chokes of the Thompson auxiliary balance circuit were removed and a choke was included in the main balance circuit. All measurements were performed with the bridge in balance in the ratio 1–10 (1–10 nF) and at the frequency of 1 kHz.

After the modifications at the 4TCB, several calibrations have been made in the capacitance range of 1 to 100 nF, at frequencies ranging from 398 Hz to 1.592 kHz. One could observe significant improvements, both of the calibration results as in the ease to achieve the bridge balance, which can now be done in a few minutes with highly repetitive results with typical standard deviations of 0.01 μF/F for 10-nF calibrations and 0.03 μF/F for 100-nF calibrations. Those results are detailed in Section IV-B.

III. Digital Quadrature Bridge

The inherent difficulty in operating coaxial bridges, such as the bridge balance, is only achieved after several adjustments in the main and auxiliary circuits, and their restrictions, as limited capacitance and frequency range, and inability to compare impedances of different natures led to the development of a DigBrid that can be used in routine laboratory calibrations. The DigBrid, shown in Fig. 2, is able to perform in-phase (like impedances) or quadrature comparisons, i.e., ac resistors with capacitors, of four-terminal pair impedances in a wide frequency range, from 200 to 1.592 Hz, and impedance values, 1 nF to 1 μF or 10 Ω to 100 kΩ, with measurement uncertainties around a few μF/F [8]–[10].

The DigBrid employs digital synthesizers that operate synchronously with an external frequency reference that can be the internal clock of a digitizer (ADC) or a Cesium atomic clock. Initially, the DigBrid employed workbench synthesizers, of poor amplitude stability, whose derating effects were partially compensated by an internal tracking amplifier, which aided the balancing of voltages. The DigBrid now employs much more stable audio sources, which were modified to operate synchronously, significantly reducing the measurement standard deviations. More details on the DigBrid construction and operation can be found in [12] and [13].

The signals are sampled differentially by multiplexing the ADC's high input between the high voltage potential terminals of the reference standard R_S and the capacitor under test C_X. The complex voltage ratio $(A + jB)$ is calculated through the fast Fourier transform of the sampled signals, at a specific frequency $2\pi f \approx 1/(C_X R_S)$. Therefore, C_X can be calculated by knowing the value of the standard resistor R_S and its time-constant τ as

$$C_X = \frac{1}{\omega R_S(B + \omega\tau A)}. \tag{1}$$

In Section V, we will detail several quadrature measurements done with the DigBrid with uncertainties of a few parts in 10^6.

TABLE I

Capacitance Measurements at 1 kHz With the 2TCB

Quantity	Deviation of Nominal Value (μF/F)	U (μF/F)
C_{1nF_A}	-12,29	0.40
C_{1nF_B}	-3,51	0.40
C_{10nF_A}	-2.70	0.80
C_{10nF_B}	29.33	0.80
$(C_{10nF_B} - C_{10nF_A})/C_{10nF_A}$	32.03	----

IV. Coaxial Bridges Measurement Results

In order to verify and validate the 4TCB, several measurements were made, with both the 2TCB and 4TCB, using thermally controlled capacitance standards of 1, 10, and 100 nF at 1 and 1.592 kHz. The 1-nF capacitors, $C_{1\,\mathrm{nF}_A}$ and $C_{1\,\mathrm{nF}_B}$, are GenRad 1404A standards placed in a thermally controlled enclosure [17]. The 10- and 100-nF capacitors ($C_{10\,\mathrm{nF}_A}$, $C_{10\,\mathrm{nF}_B}$, and $C_{100\,\mathrm{nF}}$) are NPL C03 type thermally controlled standards. The 2TCB and 4TCB measurements will be detailed in Sections IV-A and IV-B, respectively. Most measurements described in sections IV and V were done in a short time period to reduce the standards' temporal drift influences.

A. 2TCB Measurements

Initially, the 2TCB was used to calibrate the two 1-nF capacitance standards $C_{1\,\mathrm{nF}_A}$ and $C_{1\,\mathrm{nF}_B}$ against a 100-pF AH11A reference capacitor, traceable to the BIPM QHE. Then, the 2TCB injection circuit was modified to calibrate $C_{10\,\mathrm{nF}_A}$ and $C_{10\,\mathrm{nF}_B}$, using $C_{1\,\mathrm{nF}_A}$ as the reference standard (1:10 ratio measurements). These results are shown in Table I for 1-kHz measurements, for all capacitors, and in Table II for 1.592 kHz, for all capacitors except for $C_{1\,\mathrm{nF}_B}$.

Tables I and II show the 2TCB measurement results as deviations from the standard nominal value in μF/F. The tables also show the extended uncertainty for $k(t_{95}) = 2$, $\nu_{\mathrm{eff}} \to \infty$. As all the main uncertainty components are of the same order for capacitors of equal nominal values, the difference $(C_{10\,\mathrm{nF}_B} - C_{10\,\mathrm{nF}_A})/C_{10\,\mathrm{nF}_A}$ was also considered as a

TABLE II
CAPACITANCE MEASUREMENTS AT 1.592 kHz WITH THE 2TCB

Quantity	Deviation of Nominal Value (μF/F)	U (μF/F)
C_{1nF_A}	-12.93	0.40
C_{10nF_A}	-24.1	1.0
C_{10nF_B}	-22.8	1.0
$(C_{10nF_B} - C_{10nF_A})/C_{10nF_A}$	1.3	----

TABLE III
CAPACITANCE MEASUREMENTS AT 1 kHz WITH THE 4TCB

Quantity	Deviation of Nominal Value (μF/F)	U (μF/F)
C_{1nF_B}	-3,34	0.50
C_{10nF_A}	-3.45	0.50
C_{10nF_B}	28.51	0.50
$(C_{10nF_B} - C_{10nF_A})/C_{10nF_A}$	31.96	----
C_{100nF}	-6.42	0.60

TABLE IV
CAPACITANCE MEASUREMENTS AT 1.592 kHz WITH THE 4TCB

Quantity	Deviation of Nominal Value (μF/F)	U (μF/F)
C_{10nF_A}	-24.41	0.50
C_{10nF_B}	-26.21	0.50
$(C_{10nF_B} - C_{10nF_A})/C_{10nF_A}$	-1.80	----
C_{100nF}	-29.01	0.60

figure of merit for reducing systematic errors when comparing measured values.

The main uncertainty components are due to the reference capacitor's calibration uncertainty, the correction of IVD's gain, and stray impedance of cables [20], [21]. Although the 2TCB is a very stable system and of low uncertainty, it was devised to calibrate low value capacitances up to 1 nF [3]. For a 10-nF capacitor, especially at 1.592 Hz, the effect of cables in the measurement is very significant.

B. 4TCB Measurements

The $C_{10\,\mathrm{nF}_A}$ and $C_{10\,\mathrm{nF}_B}$ capacitors were measured with the 4TCB using $C_{1\,\mathrm{nF}_A}$ as the reference standard. Then, $C_{100\,\mathrm{nF}}$ was measured using $C_{10\,\mathrm{nF}_A}$ as the reference standard (1:10 ratio measurements). These results are shown in Table III, for measurements at 1 kHz, and in Table IV for 1.592 kHz. Table III also shows the results for the 1-nF standard $C_{1\,\mathrm{nF}_B}$ measured with the 4TCB, using $C_{1\,\mathrm{nF}_A}$ as the reference standard (1:1 ratio measurements).

Tables III and IV show the 4TCB measurement results as deviations from the standard nominal value in μF/F. The tables also show the extended uncertainty for $k(t_{95}) = 2$, $\nu_{\text{eff}} \to \infty$. Again, the difference $(C_{10\,\mathrm{nF}_B} - C_{10\,\mathrm{nF}_A})/C_{10\,\mathrm{nF}_A}$ was considered in order to reduce systematic errors.

Table V shows the main uncertainty components for a 10-nF capacitance calibration at the 4TCB with a 1 nF as the reference standard (ratio 1:10), at 1.592 kHz. This budget is similar for other frequencies.

TABLE V
UNCERTAINTY BUDGET—10-nF CAPACITANCE MEASUREMENT AT 1.592 kHz WITH THE 4TCB

Quantity	$u\ (\mu F/F)$	Type
Reference Standard	0.20	B
IVD Gain Correction	0.14	B
Repeatability	0.04	A
u_C	0.25	Combined ($k(t_{95}) = 1$)
U_C	0.50	Expanded ($k(t_{95}) = 2$)

TABLE VI
CAPACITANCE MEASUREMENTS AT 1 kHz WITH THE DigBrid

Quantity	Deviation of Nominal Value (μF/F)	U (μF/F)
C_{10nF_A}	-1.0	4.0
C_{10nF_B}	30.3	4.0
$(C_{10nF_B} - C_{10nF_A})/C_{10nF_A}$	31.3	----
C_{100nF}	-6.6	4.0

TABLE VII
CAPACITANCE MEASUREMENTS AT 1.592 kHz WITH THE DigBrid

Quantity	Deviation of Nominal Value (μF/F)	U (μF/F)
C_{1nF_A}	-7.4	6.0
C_{10nF_A}	-23.1	3.0
C_{10nF_B}	-23.3	3.0
$(C_{10nF_B} - C_{10nF_A})/C_{10nF_A}$	-0.2	3.0
C_{100nF}	-27.1	3.0

The main uncertainty components are due to the reference capacitor calibration uncertainty, and uncertainties in the IVD gain correction [21]. The Thompson and Kelvin auxiliary balances of the 4TCB allow a significant reduction of the influence of cables to be attained, what led to a reduction of the bridge's measurement uncertainty by as much as 50%, in comparison with the 2TCB. With improvements in the IVD calibration method, in development, the uncertainties of the 4TCB should significantly be reduced as well [7], [11].

V. DIGITAL BRIDGE MEASUREMENT RESULTS

We also used the DigBrid to measure all the standard capacitors, although here the reference standards were ac resistors of 1 and 10 kΩ and $R_{1k\Omega}$ and $R_{10\,\mathrm{k}\Omega}$, respectively, both traceable to QHE (quadrature measurements).

At 1.592 kHz, the DigBrid voltage ratio is approximately 1 ($2\pi f \approx 1/CR$) for the impedance pairs $C_{10\,\mathrm{nF}}$ and $R_{10\,\mathrm{k}\Omega}$ or $C_{100\,\mathrm{nF}}$ and $R_{1k\Omega}$; and 10 for the impedance pair $C_{1\,\mathrm{nF}}$ and $R_{10\,\mathrm{k}\Omega}$. At 1 kHz, the DigBrid voltage ratio is approximately 1.6 for the impedance pairs $C_{10\,\mathrm{nF}}$ and $R_{10\,\mathrm{k}\Omega}$ or $C_{100\,\mathrm{nF}}$ and $R_{1k\Omega}$. It was not possible to measure the 1-nF capacitor due to voltage ratio limitations of the DigBrid.

Tables VI and VII show the DigBrid measurement results for 1 and 1.592 kHz, respectively, as deviations from the standard nominal value in μF/F. The tables also show the extended uncertainty for $k(t_{95}) = 2$, $\nu_{\text{eff}} \to \infty$. Each capacitance value corresponds to a set of at least 25 measurement

TABLE VIII
UNCERTAINTY BUDGET—10-nF CAPACITANCE MEASUREMENT AT 1.592 kHz WITH THE DigBrid

Quantity	$u\ (\mu F/F)$	Type
Reference Standard	0.2	B
Digitizer Intrinsic Noise	0.04	B
Digitizer Quantization Noise	0.08	B
Digitizer Sampling Noise	0.08	B
Noise of the AC Sources	1.4	B
Jitter of Sampling Process	0.3	B
Repeatability (on 25 runs)	0.1	A
u_C	1.5	Combined
U_C	3.0	Expanded ($k(t_{95}) = 2$)

runs, where each run consists of five single determinations by digital sampling [12], [13]. Again, we consider the difference $(C_{10\,\mathrm{nF}_B} - C_{10\,\mathrm{nF}_A})/C_{10\,\mathrm{nF}_A}$ when comparing measured values.

Table VIII shows the main uncertainty components for 10-nF capacitance calibration at the DigBrid, with a 10-kΩ ac resistor as the reference standard (quadrature measurement, ratio 1:1), at 1.592 kHz.

The main uncertainty contributions using the digital bridge arise from noise contributions of the sources. For frequencies different from 1.592 kHz, there is an increase in the digitizer uncertainty, due to its nonlinearity for voltage ratios different from one. Amplitude instabilities of the voltage sources were significantly reduced due to the use of modified audio sources [9], [13]. The results of the DigBrid are better than the equivalent system [18]. However, when comparing the DigBrid uncertainty with another equivalent system [19] results, we see that depending on capacitance and frequency measurement range, it can be somewhat higher, similar or even smaller.

VI. MEASUREMENT ANALYSIS

Here, the analysis of the three bridges measurement results for standard capacitors set is presented. The difference in μF/F, where C_A and C_B represent the values of a given capacitor measured by two different bridges, at a determined frequency, is considered.

The normalized error ratio (NER $= |C_A - C_B|/(U_A^2 + U_B^2)^{1/2}$) is also considered, where U_A and U_B represent the expanded uncertainties $[k(t_{95}) = 2]$ of a given capacitor measured by two different bridges. In order to confirm the agreement between any two bridges, NER should be less than 1.

The results for 1- and 1.592-kHz measurements are presented in Sections VI-A and VI-B, respectively.

A. 1-kHz Measurements

Table IX shows the comparison results for the 10-nF capacitance standards $C_{10\,\mathrm{nF}_A}$ and $C_{10\,\mathrm{nF}_B}$, and Table X shows the comparison results for the 1- and 100-nF capacitance standards.

From Table IX, it can be seen that, at 1 kHz, at the 10 nF range, there is an agreement between the 2TCB and 4TCB of parts in 10^7. This difference is attributed to the

TABLE IX
10-nF CAPACITANCE MEASUREMENTS AT 1 kHz

Systems	$\Delta\, C_{10nF_A}$ $(\mu F/F)$	$NER\ C_{10nF_A}$	$\Delta\, C_{10nF_B}$ $(\mu F/F)$	$NER\ C_{10nF_B}$
4TCB x 2TCB	0.75	0.80	0.82	0.86
4TCB x DigBrid	2.5	0.61	1.8	0.44
2TCB x DigBrid	1.7	0.42	1.0	0.24
AH2700 x DigBrid	4.4	0.29	2.3	0.15

TABLE X
1- AND 100-nF CAPACITANCE MEASUREMENTS AT 1 kHz

System	$\Delta\ C_{1nF_B}\ (\mu F/F)$	$NER\ C_{1nF}$
2TCB x 4TCB	0.17	0.27
System	$\Delta\, C_{100nF}(\mu F/F)$	$NER\ C_{10nF_A}$
4TCB x DigBrid	0.2	0.04

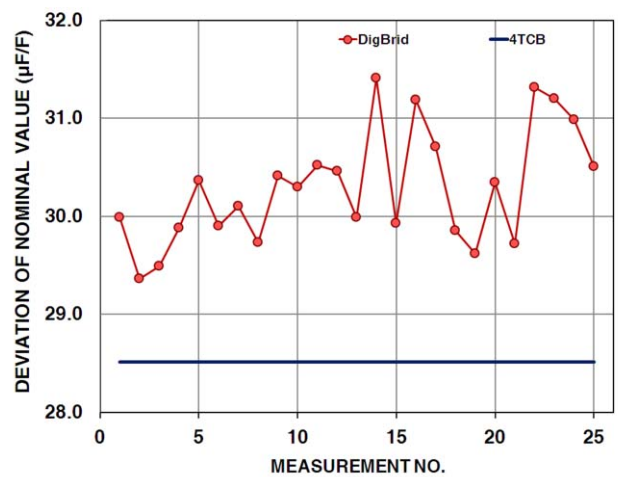

Fig. 3. Comparison between 4TCB and DigBrid, measurements for $C_{10\,\mathrm{nF}_B}$ at 1 kHz, with the DigBrid relative standard deviation $\sigma = 0.57\ \mu$F/F.

2TCB estimated cable corrections and short-time drifts of the standards. The agreement between the DigBrid and both the coaxial bridges, for the 10-nF standards, is within three parts in 10^6 or even better. The same is true for the 1- and 100-nF standards, see Table X. In all the cases, NER < 1.

Table IX also shows the compatibility between the DigBrid results and these of a commercial system (Andeen Hageling bridge model AH 2700A), considering AH 2700A uncertainties of 15 and 17 μF/F, for 1 and 1.592 kHz, respectively.

Figs. 3 and 4 show the DigBrid measurement results for $C_{10\,\mathrm{nF}_B}$ and $C_{100\,\mathrm{nF}}$, respectively. The results of the 4TCB for these standards are also shown by the blue line.

When comparing the differences $(C_{10\,\mathrm{nF}_B} - C_{10\,\mathrm{nF}_A})/C_{10\,\mathrm{nF}_A}$ obtained to each bridge at 1 kHz, for the 10-nF capacitance standards, we can observe an agreement of parts in 10^8 between the two coaxial bridges and of parts in 10^7 between the DigBrid and both coaxial bridges (see Tables I, III, and VI), which is almost one order of magnitude better than $\Delta C_{10\,\mathrm{nF}_A}$ and $\Delta C_{10\,\mathrm{nF}_B}$, shown in Table IX, in which we have the presence of systematic effects. From this analysis, we can conclude that the bridges present high

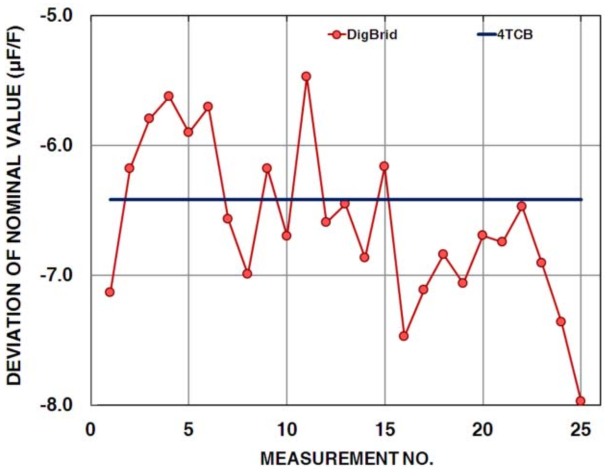

Fig. 4. Comparison between 4TCB and DigBrid, measurements for $C_{100\,\mathrm{nF}}$ at 1 kHz, with the DigBrid relative standard deviation $\sigma = 0.62\ \mu$F/F.

TABLE XI
10-nF CAPACITANCE MEASUREMENTS AT 1.592 kHz

Systems	$\Delta\, C_{10nF_A}$ $(\mu F/F)$	$NER\ C_{10nF_A}$	$\Delta\, C_{10nF_B}$ $(\mu F/F)$	$NER\ C_{10nF_B}$
4TCB x 2TCB	0.30	0.27	---	---
4TCB x DigBrid	1.3	0.43	2.9	0.94
2TCB x DigBrid	1.0	0.32	0.5	0.17
AH2700 x DigBrid	4.9	0.28	1.7	0.10

TABLE XII
1- AND 100-nF CAPACITANCE MEASUREMENTS AT 1.592 kHz

System	$\Delta\ C_{1nF_A}\,(\mu F/F)$	$NER\ C_{1nF}$
2TCB x DigBrid	5.5	0.92
System	$\Delta\, C_{100nF}(\mu F/F)$	$NER\ C_{100nF}$
4TCB x DigBrid	1.9	0.62

repeatability and linearity, and the quantities $\Delta C_{10\,\mathrm{nF}_A}$ and $\Delta C_{10\,\mathrm{nF}_B}$ are mostly due to systematic effects.

B. 1.592-kHz Measurements

Table XI shows the comparison results for the 10-nF capacitance standards $C_{10\,\mathrm{nF}_A}$ and $C_{10\,\mathrm{nF}_B}$, and Table XII shows the comparison results for the 1 and 100-nF capacitance standards.

We can see in Table XI that, at 1.592 kHz, there is an agreement between the 2TCB and 4TCB of a few parts in 10^7 for $C_{10\,\mathrm{nF}_A}$. The quantity $\Delta C_{10\,\mathrm{nF}_B}$ is not shown in Table XI for the comparison between 2TCB and 4TCB due to the significant time drift of $C_{10\,\mathrm{nF}_B}$, which made it difficult to obtain reliable results.

The agreement between the DigBrid and both the coaxial bridges for the 10-nF standards is within three parts in 10^6. The same is true for the 100-nF standards. Even when considering the 10-nF standard, where the DigBrid digitizer voltage ratio is 10 which implies in an additional uncertainty component of 2 μF/F, the agreement of the DigBrid with the 2TCB was within its expected uncertainty ($U_{\mathrm{DigBrid}} = 6\ \mu$F/F). This uncertainty value could be improved with the use of a dedicated digitizer and high stable ac voltage sources. In all the cases, NER was smaller than 1.

VII. CONCLUSION

After several measurements in the nF capacitance range, we were able to confirm the metrological agreement between the coaxial and digital impedance bridges within parts in 10^6, and between the two coaxial bridges within a few parts in 10^7.

There are now at INMETRO three full-operational systems, allowing high-accurate measurements at large capacitance range (1 to 100 nF) with the coaxial bridges, or alternatively, with the automated and flexible digital impedance bridge.

As future work, we intend to reduce the DigBrid uncertainty and eliminate possible systematic errors with the construction of dedicated digitizer and high stable ac voltage sources, among other improvements.

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