Traceability of Capacitance Measurements at the µF Range at Inmetro

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Abstract: This paper describes the improvements made at the four terminal pair coaxial bridge developed at Inmetro, in order to compare a 100 nF with a 1 µF standard capacitor. This measurement allowed the validation of the digital quadrature bridge, also developed at Inmetro, at the micro-farad range, which is an essential step in providing traceability to high-value capacitance measurements.

Keywords: Coaxial bridges, digital signal processing, capacitance measurements, measurement uncertainty.

1. INTRODUCTION

In the last few years a digital quadrature bridge (DigBrid) for impedance measurements, both in-phase and quadrature, with uncertainties at the µF/F level was developed at Inmetro [1]-[2]. Initially the DigBrid was projected to calibrate capacitance standards in the nano-farad range, and AC resistance standards. This system is now employed to routine calibrations. There are also two coaxial impedance bridges [3] in operation at Inmetro, the two terminal-pair coaxial bridge (2TCB) [4] and the four terminal-pair coaxial bridge (4TCB) [5]-[6], both part of the traceability chain of the capacitance unit to the quantum Hall effect (QHE) [3]-[6]. The 2TCB is used to measure capacitors at the pico-farad range, wherever the 4TCB is used to measure capacitors at the nano-farad range.

However we also have to provide traceability to calibrate standard capacitors in the micro-farad range, as requested from primary and secondary laboratories, industries, electric power companies, research centers, and universities. At the present moment, the calibration of capacitors in the micro-farad range is being performed by a non-coaxial, two-terminal-pair bridge. However, this method presents several drawbacks such as poor repeatability, high uncertainty, and range limitations [3].

In order to improve measurement conditions for capacitors at the micro-farad range, we extended the Digbrid quadrature measurements range now able to compare a reference AC resistor of 100 Ω or 1 kΩ with a 1 µF capacitor, at frequencies between 200 Hz and 1592 Hz. To validate these measurements we also modified the 4TCB, in order to compare a 100 nF standard with the 1 µF capacitor.

In Sections 2 and 3, we will present a briefly description of the DigBrid and the 4TCB. In Section 4 we will analyze 1 µF capacitance measurements performed by both bridges, with a preliminary uncertainty analysis.

2. DIGITAL QUADRATURE BRIDGE

The digital quadrature bridge (DigBrid) is able to perform in-phase (like impedances) or quadrature (ac resistors with capacitors) comparisons of four-terminal pair impedances in a wide frequency range, from 200 Hz to 1.592 kHz, and impedance values from 10 Ω to 100 kΩ (or capacitance values from 1 nF to 1 μF), with measurement uncertainties around few μF/F [1],[5].

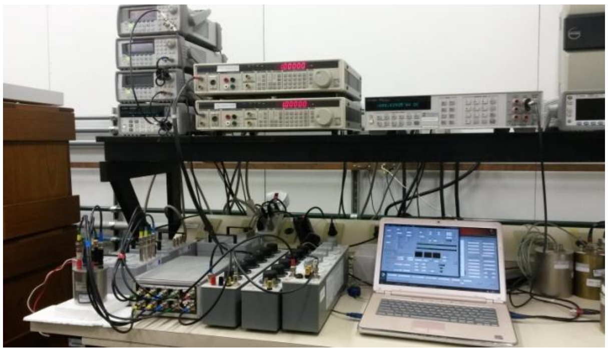

Figure 1: Digital quadrature bridge.

The DigBrid, shown in Figure 1, 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. The signals are sampled differentially by multiplexing the ADC´s high input between the high voltage potential terminals of the reference standard Z_S and the device under test Z_X. The complex voltage ratio is calculated through the fast Fourier-transform (FFT) of the sampled signals, at a specific frequency. Therefore, Z_X can be calculated by knowing the complex value of the reference standard Z_S and its time-constant. More details on the DigBrid construction and operation can be found in [1],[5],[7].

3. FOUR TERMINAL-PAIR COAXIAL BRIDGE

The four-terminal-pair coaxial bridge (4TCB), shown in Figure 2, is a complex system, with several technical advantages as high-stability, very low uncertainties, and isolation from external noise sources due to its coaxial design [3]. However, the 4TCB has drawbacks as limited range and time-consuming measurements.

The 4TCB was devised in order to minimize stray impedances of cables [3], thus allowing the measurement of low-value impedances in a four terminal-pair configuration. It operates at the frequency range of 398 Hz to 1.592 kHz and usually compares decade capacitors in the range from 1 nF to 100 nF at the ratios 1:1 or 1:10 [6].

The main balance of the 4TCB uses an inductive voltage divider 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 4TCB has three auxiliary balances [3]. 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. The Wagner balance is necessary to ensure that the IVD “central” tap is actually at zero potential with no parasitic current flow.

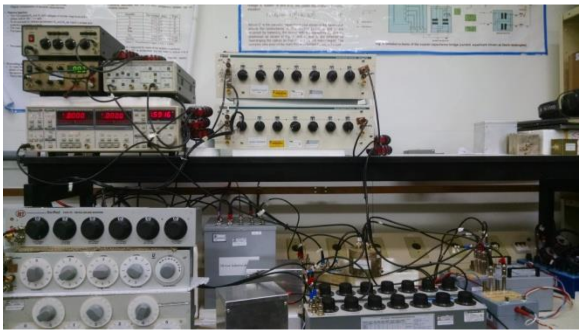

Figure 2: Four terminal-pair coaxial bridge.

In order to verify and validate the DigBrid measurements at the micro-farad range, the 4TCB was modified to calibrate a 1 μF capacitance standard ($C_{1\mu F}$) using a 100 nF capacitance standard as reference (C_{100nF}) traceable to QHE. Both capacitors are NPL C03 type thermally controlled standards. Initially only the 4TCB injection circuit was modified, replacing the original injection capacitor by a larger one. However there was additional issues with the 4TCB auxiliary balances, due to the small impedance value of $C_{1\mu F}$.

An incompatibility between the 4TCB main and Kelvin balances, made it impossible to obtain reliable measurements of $C_{1\mu F}$. In order to attain stable measurements, it was necessary to remove the Kelvin balance. With this procedure, the impedance of the low-voltage terminal cable between the standard capacitors now has to be considered. In order to minimize this cable influence, we connected both capacitors low-current terminals directly, using an adapter. Even so, there is an additional uncertainty component of approximately 2 µF/F in the 4TCB budget, due to this cable impedance.

4. MEASUREMENT ANALYSIS

The DigBrid was applied to measure the standard capacitor $C_{1\mu F}$, although here the reference standard was an AC resistor of 100 Ω ($R_{100\Omega}$) traceable to QHE (quadrature measurements).

At 1.592 kHz the DigBrid voltage ratio is approximately 1 for the impedance pair $C_{1\mu F}$ and $R_{100\Omega}$. At 1 kHz the DigBrid voltage ratio is 1.6 for the impedance pair above.

Tables 1 and 2 show the DigBrid and the 4TCB measurement results for 1 kHz 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, $\nu_{eff} \rightarrow \infty$. Each capacitance value corresponds to a set of 50 measurement runs, where each run consists of 5 single determinations by digital sampling [1],[5]. Table 1 also shows the compatibility between the DigBrid and a commercial system (Andeen Hageling bridge model AH 2500A) at 1 kHz.

Table 1: 1 µF measurements at 1 kHz.

Systems	Deviation of Nominal Value (μF/F)	U (μF/F)
DigBrid	93.9	7.6
4TCB	95.3	3.8
AH 2500	100	13

Table 2: 1 µF measurements at 1.592 kHz.

Systems	Deviation of Nominal Value (μF/F)	U (μF/F)
DigBrid	55.0	7.3
4TCB	56.5	4.2

Figures 3 and 4 show the DigBrid measurement results for $C_{1\mu F}$, at 1 kHz and 1.592 kHz, respectively. The results of the 4TCB for these frequencies are also shown by the blue line.

Tables 3 and 4 show the difference $\Delta = |C_A - C_B|$, in µF/F, where C_A and C_B represent the values of $C_{1\mu F}$ measured by two different bridges, at a determined frequency. The Normalized Error Ratio $(NER = |C_A - C_B|/\sqrt{U_A^2 + U_B^2})$ is also considered, where U_A and U_B represent the expanded uncertainties (k(t_{95}) = 2) of $C_{1\mu F}$ measured by two different bridges. In order to confirm the agreement between any two bridges NER should be less than 1.

Table 3: 1 µF measurements at 1 kHz.

Systems	Δ (μF/F)	NER
4TCB x DigBrid	1.4	0.17
AH2500 x DigBrid	6.1	0.40
AH2500 x 4TCB	4.7	0.34

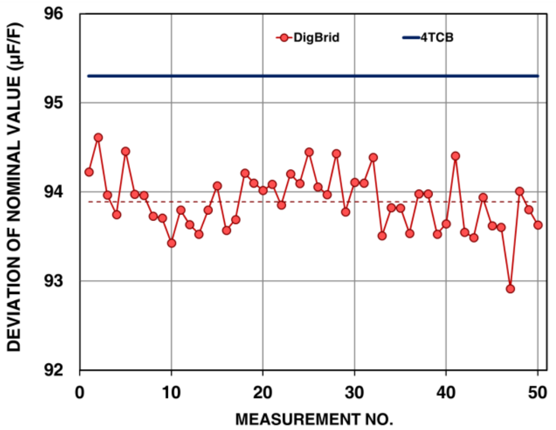

Figure 3: Comparison between 4TCB and DigBrid, measurements for $C_{1\mu F}$ at 1 kHz, with the DigBrid relative standard deviation $\sigma = 0.30\ \mu F/F$.

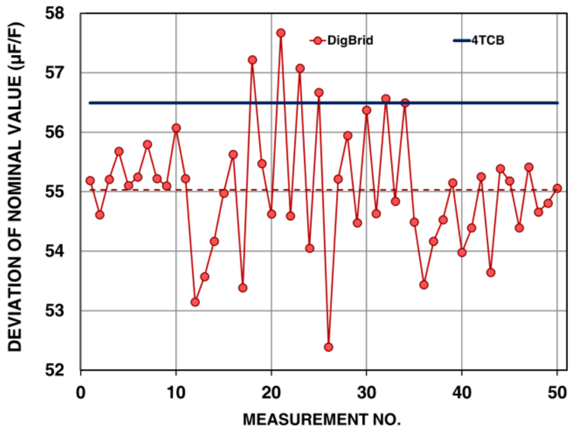

Figure 4: Comparison between 4TCB and DigBrid, measurements for $C_{1\mu F}$ at 1.592 kHz, with the DigBrid relative standard deviation $\sigma = 1.1\ \mu F/F$.

Table 4: 1 µF measurements at 1.592 kHz.

Systems	Δ (μF/F)	NER
4TCB x DigBrid	1.5	0.17

The agreement between the DigBrid and the 4TCB, for both frequencies, are within 2 parts in 10^6 or better. Table 3 also shows the compatibility between the DigBrid and the commercial system AH 2500, within 5 parts in 10^6. In all cases NER $\ll$ 1.

The main uncertainty contributions using the DigBrid arise from noise contributions of the sources, and of the AC resistor $R_{100\Omega}$ calibration. For frequencies different from 1.592 kHz, there is an increase in the digitizer uncertainty, due to its non-linearity for voltage ratios different from one [1]. The results of the DigBrid are equal or better than an equivalent system [8].

The main uncertainty components using the 4TCB are due to the reference capacitor calibration uncertainty, uncertainties in the IVD gain correction [5], and the impedance of the low-voltage terminal cable (see Section 3).

6. CONCLUSIONS

After several measurements in the 1 µF capacitance range, we were able to confirm the metrological agreement between the coaxial and digital impedance bridges within parts in 10^6, thus validating the DigBrid for this capacitance range.

As future work we intend to expand the DigBrid range to 10 µF measurements, and in a near future, develop an additional digital system to calibrate higher capacitors and AC shunts.

7. REFERENCES

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