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TRACEABILITY CHAIN OF THE CAPACITANCE UNIT TO QUANTUM HALL EFFECT AT INMETRO - FOUR-TERMINAL COAXIAL BRIDGE

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Abstract – This paper describes the development of a four-terminal coaxial bridge, part of the traceability chain of the capacitance unit to the quantum Hall effect, in construction at Inmetro. This bridge will also be used to calibrate AC resistance and high-value capacitance standards. Here we describe the final construction stages and preliminary measurements of the four-terminal coaxial bridge. We also describe the bridge main transformers, grounding scheme, and AC resistance standards.

Keywords: electrical metrology, coaxial current bridges, impedance measurements.

1. INTRODUCTION

There are two main motivations for the construction of a four-terminal coaxial bridge at Inmetro. The first one is the implementation of the traceability chain of the capacitance unit to the quantum Hall effect. Inmetro has recently acquired a quantum Hall effect (QHE), the DC resistance standard. The realization of the capacitance unit (farad) is related to the QHE by a calculable resistor, responsible for the DC/AC relation, and three low-uncertainty coaxial bridges: the two-terminal bridge, the four-terminal bridge, and quadrature bridge.

The two-terminal coaxial bridge [2], [3] is already in operation at Inmetro, with relative uncertainty of 10^{-8}. The calculable resistor will soon be acquired, and the quadrature bridge is in the first stage of construction. This paper describes the final stage of the four-terminal coaxial bridge construction, and also some preliminary tests and measurements.

The second motivation for the construction of a four-terminal coaxial bridge is the necessity to calibrate AC resistance and high-value capacitance standards. In the last years Inmetro has received several requests to calibrate AC standard resistors, from primary and secondary laboratories, industries, energy companies, research centers, and universities.

Although the calibration of AC resistors is often required, commercial bridges with the uncertainty level required by a primary laboratory are not available. Most NMIs developed or, as Inmetro, are developing their own four terminal coaxial bridges.

A few years ago, the Capacitance and Inductance Laboratory (Lacin - Inmetro) developed both a non-coaxial four-terminal bridge [4] to calibrate AC resistors and a two-terminal bridge to calibrate high-value capacitors, of 10 μF and 100 μF [5].

The non-coaxial four-terminal bridge has a relatively simple circuit. Unfortunately it presents high-uncertainty and instabilities at low-frequencies, preventing this bridge to be part of the traceability chain to QHE. The two-terminal bridge has also high-uncertainty, unsuitable to a NMI.

Our laboratory established a partnership with others NMIs, as the *Laboratoire National of Metrologie et Essais* (LNE), to construct a new four-terminal coaxial bridge, with high-stability and very low-uncertainty, suitable for both the QHE traceability chain and the calibration of Inmetro AC resistance and high-value capacitance standards. Inmetro four-terminal coaxial bridge is mostly based in the LNE design [6], we also considered the BIPM four-terminal bridge [7] design.

In the following section there is a description of the four-terminal coaxial bridge. In the third and fourth sections the bridge main transformers and grounding scheme are detailed. The fifth section describes the standards and preliminary measurements. The last section is a conclusion of the bridge construction and its future developments.

2. FOUR-TERMINAL COAXIAL BRIDGE

A non-coaxial four-terminal bridge [4] to calibrate AC resistors was developed at Lacin between 2000 and 2003. In 2006 this bridge was rebuilt by the authors, with some modifications to improve grounding and to reduce external influences. Several measurements were made to verify the uncertainty and stability of this bridge, obtaining an expanded uncertainty of 0.01%.

Since these results are insufficient to a primary laboratory, we opted to construct a new four-terminal bridge. To implement the traceability chain of the capacitance unit to the QHE it is necessary a four-terminal bridge with uncertainty of a few parts in 10^{-8}, which means, a thousandth of the non-coaxial bridge uncertainty.

In order to archive the desired low-uncertainty we decided to construct a new, coaxial four-terminal bridge. To construct this new bridge we had the technical support of Dr Alexandre Bounouh, from LNE-FRANCE and the financial support of Inmetro and Brazilian Government - FINEP.

The coaxial bridge is much more complex than the non-coaxial bridge previously constructed, but it has several

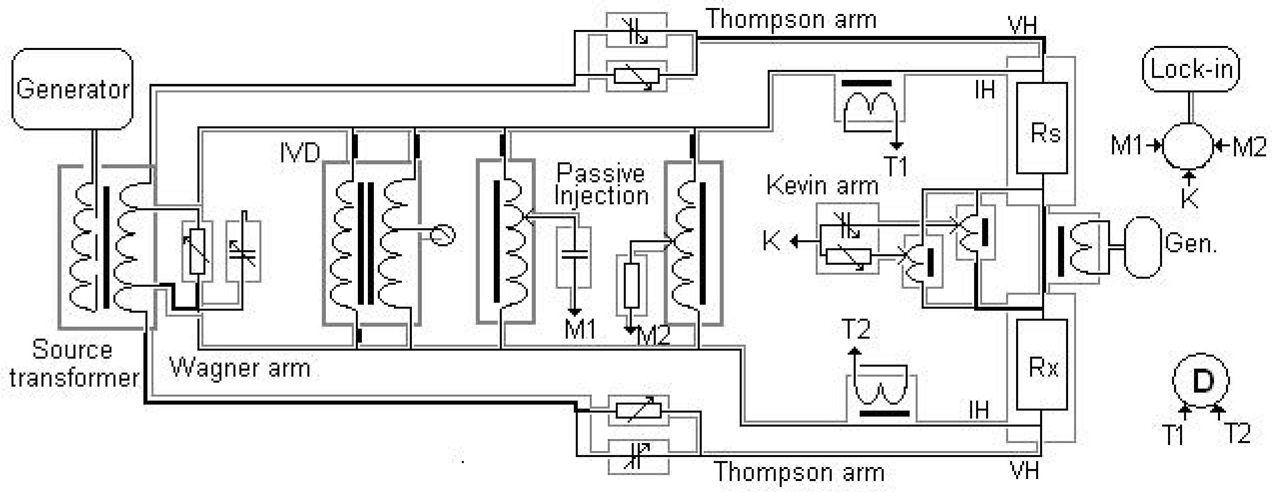

Fig. 1. Four-terminal coaxial bridge.

advantages, as high-stability, very low uncertainty and isolation for external noise sources. In the coaxial bridge several factors that were approximated or ignored in the non-coaxial bridge are compensated [6], allowing to reduce the expected uncertainty to some parts in 10^{-8}.

A simplified schematic circuit of the coaxial four-terminal bridge is shown in Fig. 1. In the coaxial bridge the voltage source, a pure sinewave oscillator, is connected through a source transformer. This transformer supplies the main and auxiliary balances with different amplitude, in-phase voltages. This transformer also isolates the bridge from the laboratory power supply, avoiding interference, especially at low-frequencies measurements.

The main balance of this bridge has a two stage inductive voltage divider (IVD), with very high-impedance, that isolates the resistors Rs and Rx from the two standard seven-decade inductive dividers (phase and quadrature balances). The IVD also allows the comparison between two resistors with different nominal values.

The injection in the main balance is a passive circuit, with high-stability resistor and capacitor. We decided to use a passive circuit for practical reasons, since at Inmetro's two-terminal coaxial bridge [2],[3], the injection circuit is also passive, with good results. The injection resistor R_{inj} is a high-stability metal foil resistor with low temperature and frequency dependences. The injection capacitor C_{inj} is air standard capacitor, that also presents high-stability and low-frequency dependence.

The output signal of the main balance is pre-amplified with a low-noise pre-amplifier and than directed to a DSP lock-in amplifier, operating as a null detector.

Besides the main balance, the four-terminal bridge has three auxiliary balances. The Kelvin arm is necessary to compensate the impedance of the cable connecting the resistors Rs and Rx. This arm also has two standard seven-decade inductive dividers associated with high-stability fixed resistor and capacitor.

The Thompson arm assure that there is no current in the voltage terminals VH, eliminating errors due to cables impedance, significant for low-resistance and high-capacitance standards. There are two separate arms, at Rs and Rx high-voltage terminals; each arm has a decade resistor, a decade capacitor and a 1:100 transformer to amplifier the Thompson balance signal before directing it to a null detector.

The third auxiliary balance, Wagner arm, is necessary to compensate parasite capacitances, assuring that the whole bridge is at the same potential, the virtual zero. The balance in the Wagner arm is archived by a decade resistor and a decade capacitor. The assembled bridge is shown in Fig.2.

Several factors can influence in four-terminal bridge stability and uncertainty. Some of them are the IVD calibration, the injection circuit, the standards stability, and grounding. Due to the construction of Inmetro four-terminal coaxial bridge, we expect a uncertainty inferior to a few parts in 10^{-7}.

Fig. 2. Four-terminal coaxial bridge.

3. TRANSFORMERS

The four-terminal coaxial bridge has two main transformers, the source transformer and the IVD auto-transformer. There are also two detection transformers and an injection transformer in the auxiliary arms. All transformers and chokes were built with toroidal cores of supermalloy, a high-magnetic permeability material, to reduce losses. In first two subsections the construction of the source transformer and the IVD will be described in more detail. The third section describes the calibration of the IVD.

3.1. Source Transformer

The source transformer has 1:2 gain between primary and secondary. This transformer has several outputs and supplies the input voltage for both the main balance and the auxiliary balances of the bridge. This transformer also isolates the bridge from the power line.

The source transformer was built with a toroidal core of supermalloy and copper wire windings. The primary winding has 140 turns with bootlace technique. The secondary was constructed using a 14-wire rope with 20 windings, creating 14 identical sections. The main balance of the bridge use 10 of these sections, the remaining sections provide the input voltage to the Thompson and Kelvin balances. The Wagner arm is supplied with same voltage as the main arm of the bridge, as shown in Figure 1.

This transformer has cooper shields after both primary and secondary windings. It also has a cylindrical aluminum shield that works both as electrostatic shield and mechanical protection.

The source transformer is placed inside a mumetal box that works as an electromagnetic shield. The transformer has also a spring system to reduce mechanical vibrations, assuring its stability and independence of external factors.

3.2. Inductive Voltage Divider Auto-transformer

The IVD is an auto-transformer in two stages. Due to the employed construction method, the IVD allows Rs and Rx to have different nominal values. The gain of this transformer can be calibrated with low-uncertainty, in the order of 10^{-8}.

The IVD has two supermalloy cores and copper wire winding. In the first stage, the winding, through only one core, uses bootlace technique. This winding is covered by a copper shield. Another core is then added to transformer. The second winding uses a rope with 12 wires. This kind of winding allows several gain relations, from 1 to 11. Due to it, impedances with different nominal value can be compared. The construction of the IVD auto-transformer is showed in Fig. 3. The use of a two-stage auto-transformer allows high impedance in the main arm that isolates both Rs and Rx from other parts of the bridge. This type of auto-transformer is very stable with near constant gain.

The IVD auto-transformer also has an aluminum cylindrical shield that works both as electrostatic shield and mechanical protection, a mumetal electromagnetic shield, and a spring system to reduce mechanical vibrations that can cause variations in the auto-transformer gain.

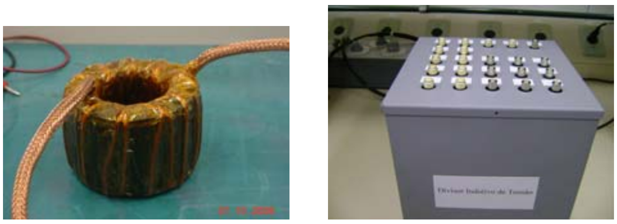

Fig. 3: Inductive Voltage Divider Auto-transformer.

3.3. IVD Calibration

It is necessary to calculate the gain of the IVD when Rs and Rx have different nominal values. Due the construction method employed with the IVD, its gain can estimated, considering only the number of turns, with an uncertainty of parts in 10^{-6}. Since this value is still too high for our applications, it will be necessary to calibrate the IVD.

Initially we intend to calibrate the IVD by comparison with standards capacitors [1]. This calibration will be performed using silica standard capacitors and a two-terminal coaxial bridge [2], with uncertainty of a few parts in 10^{-7}. Later a system to calibrate the gain of auto-transformers using a calibration transformer will be developed in our laboratory. For this system the uncertainty should be of parts in 10^{-8}.

4. GROUNDING SCHEME

The four-terminal bridge is shielded against external electromagnetic fields due to its coaxial design. This is reached with the use of chokes in some chosen cables of the bridge [1],[3]. Each choke is passive current equalizer constructed by threading the coaxial cable through a high-permeability core, with inductance in the order of 40 mH.

In order to maximize the effectiveness of the current equalizers, it is necessary to analyze the ground network of the bridge and define the correct number of chokes and their best location. Every node should be connected to a central ground point with just one path without a current equalizer, to avoid grounding loops. This central point is then connected to earth ground. About 14 chokes, constructed with a mumetal core, are used to in the four-terminal coaxial bridge.

5. RESISTANCE STANDARDS AND PRELIMINARY MEASUREMENTS

Resistors have different behavior for continuous and alternating currents. The reason for this is that resistors almost always have parasite reactances that cause frequency dependence. Besides that, low-value resistance and high-value capacitance standards are built with four terminals to eliminate the cable influence in measurements.

Our resistance standards are four-terminal, constructed with high-stability foil resistors. To reduce temperature dependence our original standards are in an oil bath [8], which can cause an increase of frequency dependence [7].

Considering the high frequency dependence of oil standards and low temperature dependence of foil resistors, we have constructed new resistance standards in air.

6. CONCLUSION

The Capacitance and Inductance Laboratory at Inmetro is developing a four-terminal coaxial bridge. This bridge is expected to present uncertainty in order of 10^{-8}. This low-uncertainty can be expected due to this bridge construction method, where the main error sources are verified and corrected. This bridge is a fundamental part of the traceability chain of the capacitance unit to the quantum Hall effect. It will also be the main calibration system for AC resistance and high-value capacitance standards at Inmetro.

In the last two years, all the transformers used in the bridge have been constructed and the necessary equipment acquired. The bridge is already assembled, and some preliminary measurements are been made. In a later occasion our results will be compared with others laboratories to validate our system.

The traceability chain of the capacitance unit to the quantum Hall effect is expected to be completed in the next three years. This chain and Inmetro recently acquired quantum Hall effect will allow our Institute to reproduce both the resistance and the capacitance units.

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