Bootstrap Calibration of Inductive Voltage Dividers at Inmetro

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The Laboratory of Metrology in Electrical Standards of Inmetro (Lampe) has built, in 2010, a transformer which is able to perform inductive voltage divider ratio calibrations using the bootstrap method. This transformer was idealized according to the design adopted at Physikalisch-Technische Bundesanstalt (PTB), and has very similar characteristics to that system. Lampe’s bootstrap system is not yet in operation, and DIT calibrations are presently being carried according to a triangular set of measurements involving standard capacitors. This method, though, has uncertainties limited to a few parts in 10^6; the primary objective of Lampe’s bootstrap system project is to achieve uncertainties at least 10 times smaller than this.

Keywords: Measurement, electrical standards, inductive voltage dividers, bootstrap

I. INTRODUCTION

The project of a DIT calibration system at Lampe is centered on a two-stage transformer capable of making bootstrap measurements of the ratio between inductive voltage dividers (IVD) steps, as thoroughly described in [1, 2]. Inmetro’s bootstrap transformer has been constructed in a 2010 cooperation with PTB [3] (and is itself based on the PTB system), in order to develop a system capable of calibrating the 10:-1 ratio of the main IVD used in coaxial 2- and 4-terminal-type impedance bridges.

Lampe has two capacitance bridges which have been in operation for 5 to 6 years now. These bridges are an important link in the traceability chain to derive the capacitance unit from the quantum Hall resistance [4]. And with the intent of showing how we plan to improve our calibration uncertainty of measurements carried in these bridges, this work presents a brief description of our bootstrap system project, and points a few important characteristics of the bootstrap transformer constructed here.

II. SYSTEM DIAGRAM

Following the original PTB project, the bootstrap transformer constructed at Inmetro is capable of providing voltage (both in-phase and quadrature) to two current injection systems simultaneously. Fig. 1 shows an updated schematics for the complete IVD calibration setup; in this figure, we highlight the bootstrap transformer constructed at Inmetro [3], at the extreme left of this drawing. This transformer is two-stage-type, and is apt to calibrate two-stage IVDs at 10:-1 ratio. For a revision of the two-stage principle of transformers, as well as the bootstrap method, the reader is referred to [1, 2].

The potential difference to be used as reference to the taps of the object IVD is provided through the triaxial connectors FH,FL. These two output terminals, and both IVD and bootstrap windings wired by them, make the main loop of the calibration circuit. The potential difference between any given IVD taps n, n+1 for each n = −1, · · · , 9 is to be compared to the reference voltage $U_{Ref}$ at the bootstrap terminals FH and FL, and is denoted [1]

$$U_n - U_{n-1} = U_{Ref} (1 + \alpha_n), \quad (1)$$

where $\alpha_n$ is the reading of the ratio on the knobs of the panel of the injection inductive decade $CN_1$. $CN_1$ is a 6-decade, single-core coaxial divider with two output taps; $T_1$ is a 100:1 ratio toroidal transformer. The subsystem formed by $CN_1$, $T_1$ and the RC phase shifter make the voltage injection system over the main loop, to be described in Sec. [11].

In the triaxial branches, the outermost shields of the cables are taken to guard potential levels, which equal the potentials of the two IVD taps to be measured. These guard potentials are selected through two cursors (labelled SW1 in Fig. 1) that run jointly between the potentials of $A_{10}$, $A_{-1}$. Guarding is meant to suppress the parasitic currents from the center conductors of FH, FL terminals by taking them to the same potential as the innermost shield of the cables. For a revision of the guarding/shielding principles, see, e.g., [5].

The bridge is balanced by connecting two taps of the IVD to the FH, FL terminals of the bootstrap transformer. Then a guard potential should be adjusted on SW2 that suits to the selected taps of the IVD. Finally, $CN_1$ and $CN_2$ are serially adjusted. All these steps are sequentially and interactively repeated until the voltage read through the lock-in amplifier fluctuates below 30 or 20 $\mu$V, when the net gain in the pre- and lock-in amplifier stages are set to about 10^3.

A. Supply and compensation

The system shown in Fig. 1 is supplied through a sinewave generator, a power amplifier and an isolation two-stage transformer, which provide the needed voltage sub-multiples. The isolation transformer output provide the proper supply to the IVD to be calibrated (shown at the center of Fig. 1) and the bootstrap transformer (shown at the extreme left of the schematics.)

The transformer is supplied through coaxial terminals $A_{10}, A_{-1}$ (magnetising stage) and $B_{10}, B_{-1}$ (ratio stage.) Connectors labelled $TQ, MQ$ supply in-phase and quadrature components to (the magnetising stage of) the injection system. In practice, however, the inductive decades available in Lampe to build the injection system are single-core type. So, only the output $MQ$ of the transformer is connected to the current injection system.

IVD-based bridge comparison circuits establish the relation between the IVD ratio in one arm and unknown impedances on the other, under the constraint that equilibrium holds between two defined nodes. Parasitic admit-
The potentials of the pairs of terminals \( \text{MP}, \text{MQ} \) and \( \text{TP}, \text{TQ} \) are selected through individual switches to ratios \( \pm 0.0001 \) to \( \pm 1 \) of the potential difference between the terminals \( \text{FH} \) and \( \text{FL} \). These potentials are straight derivations from the magnetising (\( \text{MP}, \text{MQ} \)) and ratio (\( \text{TP}, \text{TQ} \)) windings, and can provide voltage source to the magnetising and ratio stages of a two-stage combining network. For the sake of concision, only \( \text{TQ} \) and \( \text{MQ} \) are shown in Fig. 1. The omitted \( \text{TP} \), \( \text{MP} \) derivations, coupled to the magnetising and ratio windings, are in everything symmetric to \( \text{TQ}, \text{MQ} \), though.

### III. INJECTION TRANSFORMER DETAIL

Aside \( \text{FH}, \text{FL} \) triax terminals, the connections to the bootstrap and the injection/detection transformers all are of the coaxial BPO type; the \( \text{FH}, \text{FL} \) terminals are of the 1051 DKE/Fischer type. Fig. 2 shows an exploded view of such an injection/detection transformer. It shows the coaxial chassis with BPO- and Fischer-type connectors, the toroidal windings and the central triaxial cable that works as the one-winding coil of this device.

The guarding at the point where \( \text{T}_1 \) (alternatively, \( \text{T}_2 \)) couples to \( \text{FH} \) (\( \text{FL} \)) brings about some delicate management of the internal shielding of this transformer. A special geometry of the two shield layers of the cable is required to avoid stray currents and the resulting leakage inductance.

Fig. 3 shows a plane section of the windings coupling. At the middle of the triax cable shown in this figure, there is a small section of the shields (not explicit shown in the picture) that leaves the center conductor electrically exposed.
to the magnetic flux in the toroidal core. This sectioning follows the techniques described in [1] for minimizing stray capacitances between the shields sections. These parasitic effects are well discussed in [1] and references therein, and they can be avoided (or at least greatly attenuated) with a particular, distinct superposition of the shields at the point of magnetic coupling also applied in [3]. Its application to $T_1, T_2$, as well as its effectiveness will be detailed elsewhere, after further tests have been carried on.

IV. CONCLUSIONS

As said before, Lampe’s bootstrap measurement system is not yet in operation, and DIT calibrations are presently being carried based on the external calibration values of standard capacitors. This method has uncertainties limited to a few parts in 10$^6$, which may be considered to be large for this type of measurement. In addition, having our standards calibrated externally involves large costs, both on financial and logistic sides.

The main objective of Lampe’s bootstrap system project is to achieve uncertainties in the 10$^{-7}$ or 10$^{-8}$ range. The circuit element on which the system is based, the bootstrap transformer, was built in 2010. This project went into a halt for some time now, and measurements still must be made on the transformer to test for some of its characteristics, like its behaviour under loading conditions and stability.

We’re still short of but a few circuit elements in order to assemble the bootstrap bridge system shown in Fig. 1 but the next stages are already in progress. We have already submitted to Inmetro’s precision workshop the projects of Figs. 2 and 3 which should be ready soon, and started the building of cabling and peripheral connections. For instance, we already dispose of a rich supply of choke cores, an important part of any AC precision coaxial circuit used to equalize currents between inner and outer shields of the cables, and thus minimize the effects of electromagnetic noise on closed loops [1, 5, 6].

Also, most of the connectors and cabling are of the coaxial BNC/RG-56, 50Ω commercial type, and are not currently a problem. All in all, we expect to start making measurements over the next year.

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