

Progress on an automated co-axial bridge for capacitance comparison

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1. Abstract

The 10:1 four terminal-pair (4TP) co-axial capacitance bridge at NPL is to be converted to automatic operation using automated inductive voltage dividers (autoIVD's). A 6-decade autoIVD was developed recently at NPL as part of EU Framework IV project AcQHR. A computer algorithm for balancing a single autoIVD has been developed, and a simple 2 terminal pair (2TP) bridge has been constructed to test the algorithm. The algorithm balances the bridge in ≈ 12 s, the bulk of the time being due to transient voltages caused by the IVD switching.

2. Introduction

Bridge techniques for the accurate comparison of impedances at frequencies around 1 kHz are well developed [1]. Co-axial bridges are used, and chokes placed in the cables to equalize the currents in the inner and outer conductors. This ensures that the bridge does not respond to external electric and magnetic fields. Standards are defined using either the two or four terminal-pair definitions, which are extensions of the two and four terminal definitions for dc standards. Extra detectors in the bridge, combined with auxiliary balances, ensure that the defining conditions of the standards are met. Accurate ratio transformers provide stable voltage ratios, and finally, inductive voltage dividers (IVD's) provide the fine steps of voltage division necessary to balance the bridge. 4TP bridges can determine the ratio of two standards to accuracies of 1 in 10^8 , while a well constructed 2TP bridge can attain a few parts in 10^7 if the impedance of the standards is not too low.

At NPL, the major use of co-axial bridges is in the realization of the Farad, and calibration of capacitance standards. The primary standard of dc resistance is the quantum Hall resistance (QHR), and the Farad is derived from the QHR using a chain of dc and ac bridges. Fig. 1 shows the capacitance traceability chain, with emphasis on the co-axial ac bridges.

To balance an ac bridge, the operator adjusts one or more manual IVD's to bring a detector (usually a two-channel lock-in amplifier) to a null. The more complex bridges have several auxiliary balances to set up the defining conditions of the standards, and several points in the bridge circuit where the detector must be plugged in at different stages in the balancing procedure. The whole procedure (auxiliary balances followed by main balances) may have to be iterated several times. Furthermore, to achieve the highest possible sensitivity, the detector is operated with very high gain, and the operator has to judge the null condition in the presence of a large amount of noise.

Automation of this procedure is desirable for several reasons. Firstly, the time taken to balance a complex bridge could be reduced. The time saving may not be large, however, as a skilled operator using a manual bridge is limited only by the time constant of the detector, and the inevitable transient voltages which result from switching the IVD. More importantly, automation will enable the more complex bridges, such as the 4TP capacitance bridge, to be used on a routine basis. Primary capacitance standards will be measured more frequently and calibration uncertainties could be improved. Computerization of the measurement process

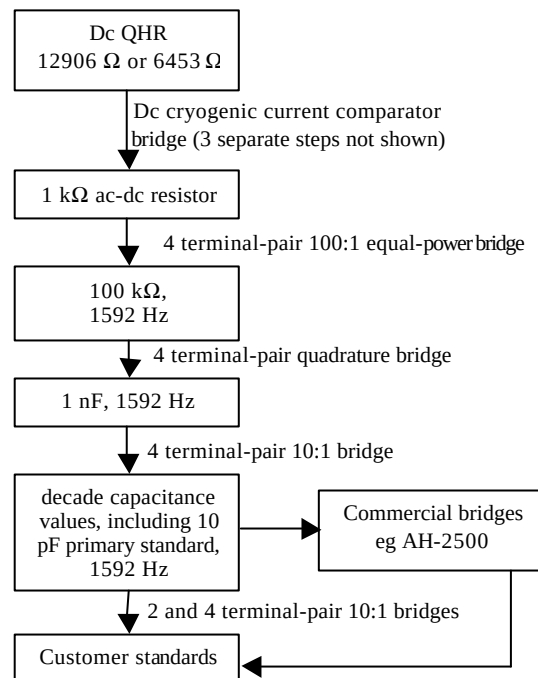


Fig. 1 Chain of bridges used to maintain the Farad at NPL

will have added benefits; the IVD settings can be stored after measuring a standard, and recalled the next time that standard is measured, for faster convergence of the balance.

3. Automated bridge components

The automated IVD is the key component in the automated bridge. A previous NPL design of autoIVD followed a binary approach [2]. Recently, a decade-based autoIVD was developed. It has 6 decades, and three magnetic cores, with successive pairs of decades wound onto a single core. The first decade core is two-stage, with a separate magnetizing winding. Each decade has -1 to $+10$ voltage taps switched by latching screened relays. Thus, there are 12 relays per decade, 72 per divider. The dividers are enclosed in μ -metal boxes, with 2 separate dividers in each box to enable one unit to act as a combining network, with a resistor and capacitor in series with the outputs. Power for the relays and controlling circuitry is from an on-board 8V battery pack.

Communication between the autoIVD and the controlling computer is via a fibre optic ring interface bus developed at NPL [3]. This, combined with the battery power, ensures complete electrical isolation of the IVD from any other mains powered equipment. The setting of the IVD is encoded as 3 bytes of data, with 4 bits encoding each decade. The design of the ring address space allows up to 6 autoIVD's to be controlled by one computer over the same fibre ring.

Because most bridges require the voltage to be nulled at more than one position in the circuit to achieve balance, automation requires either multiple detectors or a multiplexer to switch a single detector to multiple bridge nodes. We have chosen to use a multiplexer. The multiplexer consists of a central switch box, to which the detector is connected, and remote switches, which are connected directly to the bridge at the desired detector positions. The cables connecting a remote switch to the central switch box are held at screen potential when that switch is open, to prevent capacitive currents flowing through the multiplexer between two detector positions.

4. Four Terminal-Pair Capacitance Bridge

The 10:1 4TP capacitance bridge currently used at NPL is shown in fig. 2, and its role in the capacitance traceability chain is shown in fig. 1. T_1 is a two-stage transformer with current and potential outputs. C_1 and C_{10} are the four terminal-pair standards to be compared. This bridge could be automated using the components already described. 5 double IVD's are required, and two source/detector multiplexers. Table 1 illustrates the steps taken to balance the bridge. If the bridge is initially far from balance, this set of balancing steps must be iterated two or three times.

To convert this bridge to automated operation, the manual dividers E,F,L,M,J will be replaced by autoIVD's. L,M and N are configured as combining networks, while E and F are configured as double tracking IVD's. and a detector multiplexer will switch the detector between positions D1, D2 and D3. A second multiplexer will switch the bridge source between the main transformer T_1 and the injection transformer J' . A computer algorithm will switch the IVD's and the multiplexer, and read the voltage on the PSD. Since the balancing procedure consists of a series of stages, each of which involves balancing one IVD based on one detector reading, the algorithm will use a single subroutine which balances one IVD while reading one detector. A master algorithm will call the subroutine repeatedly to execute the steps 1 to 4.

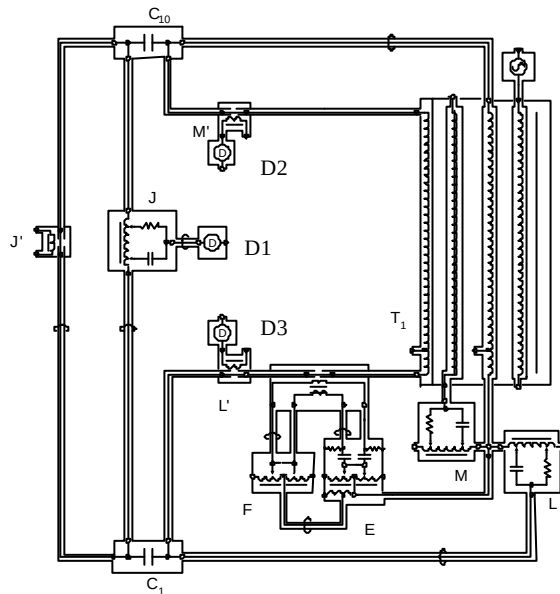


Fig. 2 Four terminal pair 10:1 capacitance bridge

Table 1. Procedure for balancing 10:1 4TP bridge.

Step	Adjust IVD	...To null detector	source plugged into	Function
1	M	D2	T ₁	Zero current in high potential cable of C ₁₀ .
2	L	D3	T ₁	Zero current in high potential cable of C ₁ .
3	J	D1	J'	Kelvin balance: current flowing in low potential cables has no effect on balance.
4	E,F	D1	T ₁	Main balance, in-phase and quadrature.

5. Algorithm testing using a simple IVD bridge

A program to balance a single IVD has been written, and tested in the simple 2TP capacitance bridge shown in fig. 3. The IVD is energized by an isolating transformer Ts. The two capacitors C_A and C_B are connected across the IVD, and the output of the IVD is connected to the screen. The balance condition yields $C_A/C_B = n/(1-n)$. The resolution of the bridge is limited by the number of decades in the IVD, but a more serious limitation to the *accuracy* of the bridge comes from the loading of the IVD by the capacitors, and the potential drops in the cables connecting the capacitors to the bridge. A bridge of this type has a typical uncertainty of 5 ppm [1]. Comparison of fig. 3 with fig. 2 shows the added complexity required to eliminate unwanted potential drops and loading effects, through a 4TP definition of the standards. Also, the voltage ratio of the bridge in fig. 2 is determined by a fixed ratio transformer, and the IVD's E and F introduce just a small perturbation to the balance condition, usually a maximum of 100 ppm. A 6-decade IVD is then sufficient to yield a resolution in excess of 1 part in 10⁹.

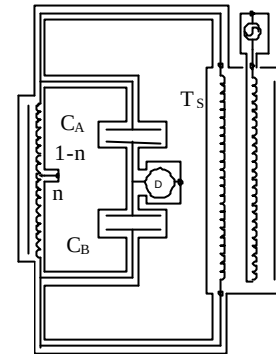


Fig. 3 Simple capacitance bridge used to test balancing algorithm

The algorithm for balancing the bridge operates as follows:

1. Measure detector voltage V_1 with IVD set to $n_1 = C_A/(C_A + C_B)$.
2. Measure V_2 with IVD set to $n_2 = n_1 + \delta n$ [$\delta n = 10^{-4}$ or 10^{-5}].
3. Measure V_3 with IVD set to $n_3 = n_1 - V_1 \delta n / (V_2 - V_1)$.
4. Calculate final balance $n_b = n_3 - V_3 \delta n / (V_2 - V_1)$.

Note that just 3 separate settings of the IVD are used. Since the IVD's are battery powered, and the relays have a finite mean time between failures, it is desirable to minimize the number of relay switchings. The program does not attempt to attain a perfect balance, the way a human operator would balance the bridge. Rather, it attains a close balance (a few μV detector voltage), and then calculates the perfect balance condition from this voltage n_3 and the linear $V(n)$ characteristic found in steps 1 and 2. This procedure assumes that the circuit is linear over several decades of $V(n)$.

To check the linearity of $V(n)$, the bridge was set up with two 5 nF NPO-dielectric capacitors, and the in-phase component of $V(n)$ measured with n ranging from 0.49 to 0.51, using a lock-in amplifier. A logarithmic plot of $V(n)$ is shown in fig. 4. Fig. 5 shows the balance point of the bridge calculated in the same way as n_3 above, taking (n_1, V_1) and (n_2, V_2) from the measured (n, V) dataset such that $(n_2 - 0.5) = (0.5 - n_1)$. The calculated balance point exhibits a strong dependence on n_1, n_2 , especially when n_1 and n_2 are close to 0.5. This behavior suggests that an un-balanced quadrature component of the detector voltage is affecting the in-phase signal, due to imperfect phase adjustment of the detector. This result has highlighted the importance of investigating the $V(n)$ characteristic of each IVD in the bridge both close to, and far from, balance.

The time taken to balance the bridge was ≈ 12 s. The bulk of this time was the result of delays deliberately inserted into the program to wait for transients to decay. Each IVD switching caused a brief overload condition in the detector. The detector reading was not stable for 2-3s after this transient.

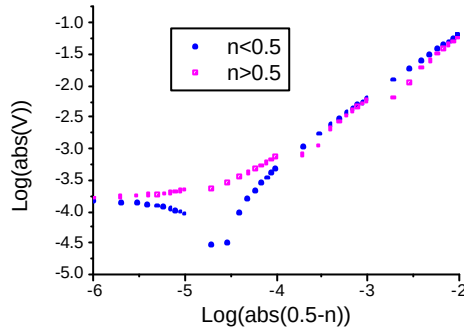


Fig. 4. Plot of detector voltage against IVD setting for the bridge in fig. 3

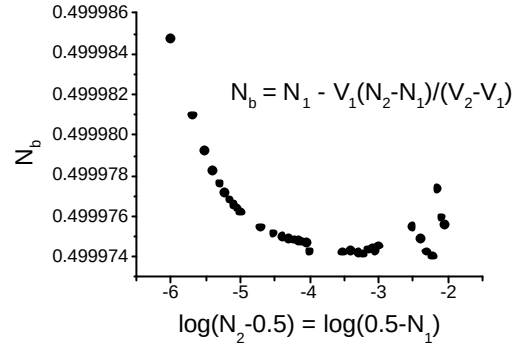


Fig. 5. Calculated balance points using pairs of data points from fig. 4 for linear extrapolation.

Furthermore, changing the sensitivity of the detector often resulted in a ‘dead time’ of ≈ 0.5 s during which no voltage measurement was available from the instrument. A simple extrapolation to the bridge in fig. 2, with 4 *double* IVD’s, requiring 2 iterations of the balancing procedure, yields a balance time for this bridge of 192 s. This estimate is likely to be overly pessimistic, since the auxiliary balances (L,M and J in fig.2) only need to be adjusted to the 3’rd or 4’th decade. It is likely that the balance time could be reduced below 100s, which is significantly faster than a human operator could achieve.

The type A uncertainty in the ratio C_A/C_B due to the detector noise was $<10^{-7}$. There is a larger type B uncertainty due to the errors in extrapolating the balance point along the non-linear part of the $V(n)$ characteristic, which can be minimized, as discussed above, through careful choice of n_1 and n_2 . For the automated bridge to equal the performance of an equivalent manual bridge, the extrapolation error must be minimized so that it is not a significant contributor to the overall uncertainty budget of the bridge.

6. Concluions and Further Work

Important first steps have been taken towards the automation of co-axial ac bridges used in the highest accuracy impedance metrology. An automated IVD has been implemented in a simple capacitance bridge, and an algorithm written to balance the bridge.

This work has highlighted several areas, which need more detailed investigation. Before the full 4TP bridge is constructed using autoIVD’s, the following problems must be solved;

- Extension of algorithm to balance in-phase and quadrature components of voltage, using a double autoIVD configured as a combining network (e.g. L,M,J in fig. 2).
- Careful investigation of the transient condition produced by switching the IVD, to optimize the delay required in the program.
- Optimization of the detector range changing, to minimize the ‘dead time’.

7. Acknowledgements

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8. References

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