FINAL PUBLISHABLE REPORT

17RPT04

VersICaL

A versatile electrical impedance calibration laboratory based on digital impedance bridges

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RMG: -		

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1 Overview

The overall objective of this project was the improvement of the European measurement infrastructure for electrical impedance measurement in the audio frequency range. This was achieved by developing versatile, affordable measurement set-ups (digital impedance bridges) for the realisation of the inductance scale in the range 1 mH to 10 H and the capacitance scale in the range 1 nF to 10 µF. This project has exploited the outcomes of previous EMRP-funded projects in this field to develop the research capacity of participating national metrology institutes (NMIs) and designated institutes (DIs). Access to local representations of scales for electrical impedance quantities based on digital impedance bridges will shorten and improve the traceability chain for this important measuring quantity and benefit accredited calibration centres and their customers.

2 Need

Electrical impedance is one of the most widely measured electrical quantities. Its measurement is important not just in electrical science but in fields ranging from life sciences to nanostructure characterisation. Impedance analysers of ever-increasing sophistication and accuracy are becoming commercially available and these instruments need to be calibrated. The calibration services needed for this rely upon the reference impedance scales maintained by NMIs and upon the NMIs maintaining metrological traceability of their measurement results.

At the highest level of accuracy, capacitance and inductance scales are realised using transformer ratio bridges which are complex, purpose-built, labour-intensive measuring systems beyond the means of all but the most advanced NMIs. Recently, with the advent of high-resolution analogue-to-digital (ADC) and digital-to-analogue converters (DAC) it has been shown that it is possible to maintain impedance scales with the requisite accuracy using digital impedance bridges. Such measurement set-ups were evaluated as part of EMRP project SIB53 AIM QuTE and appear to offer an ideal solution for smaller NMIs/DIs and calibration services providers because they use components that are inexpensive and readily available, and do not require highly skilled operators. Moreover, digital bridges are versatile and can be easily adapted to measure different impedance parameters.

Improved access to high quality realisations of impedance scales are needed to improve the calibration services which depend upon them, in particular, those for the most commonly measured capacitance and inductance ranges at audio frequencies (~120 Hz – 1600 Hz). NMIs/DIs that depend on the external calibration of sets of artefact impedance standards can develop digital impedance bridges to independently realise their reference scales of impedance and, ultimately, submit new or improved Calibration and Measurement Capabilities (CMCs), based on these developments.

By developing six digital impedance bridges which were made operational and were validated within the timeframe of the project, it was clearly demonstrated that digital impedance bridges offer a viable and cost - effective alternative to traditional, specialised, manually operated, transformer ratio bridges, even for laboratories with limited experience in this field. Useful resources such as a high performance digital multichannel sinewave source, the design details and operating software for a reference model bridge, an associated virtual training laboratory, a software tool for evaluating measurement uncertainty and a good practice guide were developed to assist those new to the field of digital impedance bridges.

It was shown that research-level digital impedance bridges can be adapted for practical use. The evaluation of measurement uncertainties for these bridges is not straightforward and the research on error modelling which culminated in a detailed publication and an uncertainty evaluation tool will be a valuable addition to metrologists and technical assessors. The virtual training laboratory and good practice guide provide an effective means of disseminating knowledge about the latest developments in digital impedance measurement techniques.

3 Objectives

The overall aim of the project is to develop user-friendly and accurate digital impedance bridges of moderate cost, suitable for the realisation and maintenance of the impedance scales 1 mH to 10 H for inductance and 1 nF to 10 µF for capacitance at uncertainty levels appropriate to industrial and stakeholder needs. The project also aims to increase the research capability of EURAMET members in the field of electrical impedance measurement. The specific objectives of the project are:

1. To review the developments in digital impedance bridges in previous research projects, including e.g. EMRP JRP SIB53 AIM QuTE, and to determine the most suitable approach(es) to be adopted in this project based on industrial and stakeholder needs.
2. To realise and validate inductance scales in the range 1 mH   10 H, with uncertainties in the 10-5 range, and a capacitance scale in the range 1 nF   10 µF, at frequencies in the range 120 Hz   1592 Hz, with uncertainties in the 10-6 range, suitable for primary dissemination towards industry and calibration centres.
3. To develop a good practice guide for the application of digital impedance bridges and the realisation of inductance and capacitance scales and a software tool for modelling uncertainties.
4. To develop new and/or improved draft Calibration and Measurement Capabilities (CMCs) in the context of the CIPM Mutual Recognition Arrangement (MRA) for the new inductance and capacitance capabilities.
5. For each partner, to develop an individual strategy for the long-term operation of the capacity developed, including regulatory support, research collaborations, quality schemes, and accreditation. Each participant will also develop a strategy for offering calibration services from the established facilities to their own country and neighbouring countries. The individual strategies will be discussed within the consortium and with other EURAMET NMIs/DIs, to ensure that a coordinated and optimised approach to the development of traceability in this field is developed for Europe as a whole.

4 Results

4.1 State-of-the-art review and design plans for digital impedance bridges

Objective 1

To review the developments in digital impedance bridges in previous research projects, including e.g. EMRP JRP SIB53 AIM QuTE, and to determine the most suitable approach(es) to be adopted in this project based on industrial and stakeholder needs.

Relevance to the project needs and objective

VersiCal was a follow-on project that sought to build on the work done in previous research projects, particularly AIM QuTE, on digital impedance bridges. An important aim was therefore to determine if emerging NMIs with limited experience and resources could exploit the outcomes of the previous research in order to realise local scales of electrical impedance by means of digital impedance bridges. The first step was to determine stakeholder needs so that the newly developed capabilities were fit for purpose. Although impedance measurement using digital techniques is a relatively new field there is already a multiplicity of bridge designs. A review of research in this field provided partners with the information needed to choose the optimum design based on available resources and customer requirements.

Work Undertaken

Review of stakeholder needs and selection of traceability schemes

All the funded partners carried out a review of the users of their calibration services for impedance quantities to determine those areas where their CMCs were dependent on the external calibration of sets of impedance standards or where no CMCs existed. While INRIM and CMI maintained independent and partly independent realisations of the impedance scales the other partners all depended, in one way or another, on calibrations of artefact impedance standards (capacitance, inductance, resistance) performed at higher echelon laboratories (Figure 4.1).

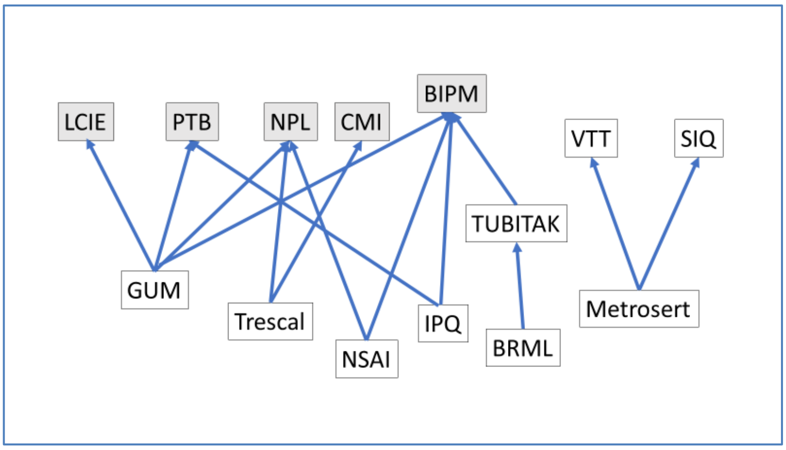

Figure 4.1 External traceability links of the VersICaL partners for impedance quantities

It should be noted that, in most cases, the partners needed to import the entire measurement scale via the calibration of sets of standards.

In the main, the claimed uncertainties in the current CMC tables were found to be adequate for stakeholder needs although some improvement was envisioned should digital impedance bridges be used. There were, however, gaps in the CMC tables for some partners which could be filled by the planned deployment of a digital impedance bridge.

Since all of the partners who intended to develop a digital impedance bridge maintained a national standard for DC resistance at a high level of accuracy it was determined that the best traceability route to the SI unit for their impedance measurements was via this national standard. It was not considered feasible for laboratories to maintain a resistance standard with calculable AC characteristics (AC-DC difference and time constant) so, as shown in figure 4.2, this traceability scheme employs one or more standard resistors whose AC characteristics must be determined by a higher echelon laboratory.

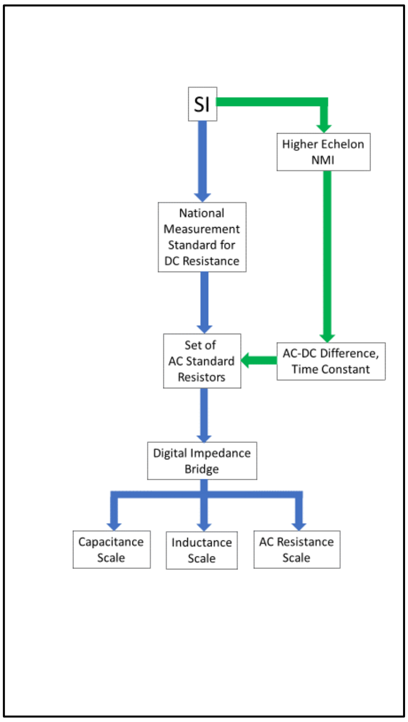

Figure 4.2 Typical traceability scale using national measurement standard for DC resistance

Such a scheme is still dependent, to some extent, on external calibrations but it represents a significant improvement on that which depends on external calibration of sets of capacitance and inductance standards. This is because standard resistors, unlike inductance and capacitance standards, are robust and suitable for transport and their AC characteristics are usually very stable. Any drift in their DC value can be corrected for using in-house measurements.

Review of research pertaining to digital impedance bridges

POLITO, with assistance from the other partners, produced an annotated bibliography of books, papers, conference proceedings and reports about digital impedance bridge set-ups published over the last 10 years. This bibliography contains more than 100 titles and is available to download from the project's website. It was also included in the good practice guide.

The partners who had participated in EMPIR project AIM QuTE "Automated Impedance Metrology extending the quantum toolbox for electricity", (INRIM, POLITO, CMI, Trescal, GUM, TUBITAK, and UZG) reviewed that project, in particular the work which was concerned with digital bridges. They produced an annotated meta-document containing relevant excerpts from AIM QuTE reports. Topics covered in the document included the classification of digital bridges, the evaluation of digital signal sources, and bridge architectures.

Selection of suitable techniques, bridges, and standards

Following extensive consultation between the experienced and less experienced partners and a programme of secondments hosted by INRIM, Trescal and CMI several partners drew up designs for digital impedance bridges to meet their identified needs. One of the designs, due to INRIM, for a 4-terminal pair (4-TP), source-based, fully-digital impedance bridge is intended as a model that can be employed by those new to the field to fast track the bridge development (figure 4.3).

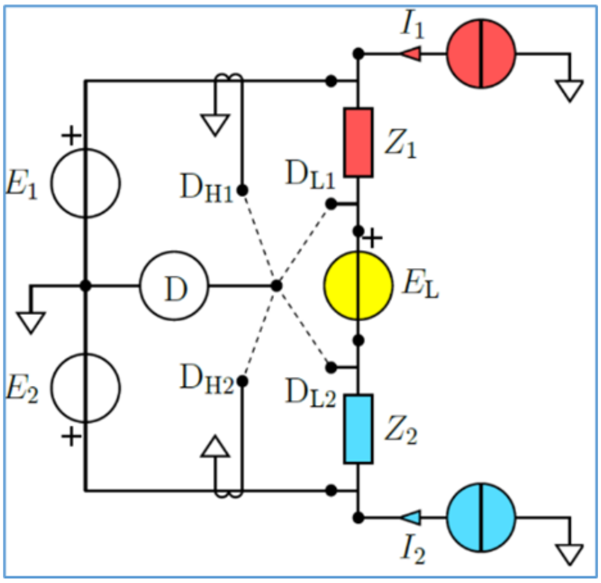

Figure 4.3 Schematic of model 4-TP source-based fully-digital impedance bridge

The bridge is an electronic sourcing bridge and measures the ratio of impedances Z_1 and Z_2. The reference ratio is defined by the two voltage sources E_1 and E_2. The main bridge balance is monitored by the null detector D. All signals are generated by a multichannel source based on high accuracy DACs. For the 4-TP version of the bridge, the working conditions of Z_1 and Z_2 are monitored by the null detector D, which is sequentially connected to different measurement points. The 4-TP conditions of Z_1 and Z_2 are met by adjusting the auxiliary sources E_L, I_1 and I_2. Current sources can be implemented by connecting a voltage source to a series impedance.

In order to make optimum use of existing resources, three partners (Trescal, Metrosert, and GUM) chose to develop sampling-based bridges whose schematics are shown in figures 4.4, 4.5 and 4.6.

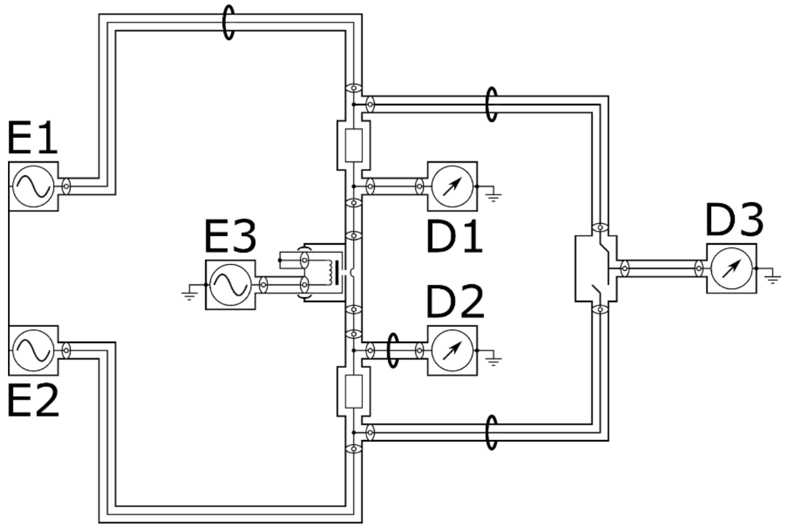

Figure 4.4 Schematic diagram of 4-TP, sampling-based fully-digital bridge due to Trescal

The Trescal bridge is a sampling-based bridge and measures the ratio of two impedances. An AC resistor acts as the reference impedance. Source E1 is kept fixed at all times. E2 is adjusted to obtain a zero reading on the detector D2. Source E3 is adjusted to get zero reading on detector D1. This process is repeated numerous times until both D1 and D2 have zero readings (below 10^{-6} of source voltage). The impedance ratio is measured by digitizer D3 by alternately measuring the high potential ports of the two impedances.

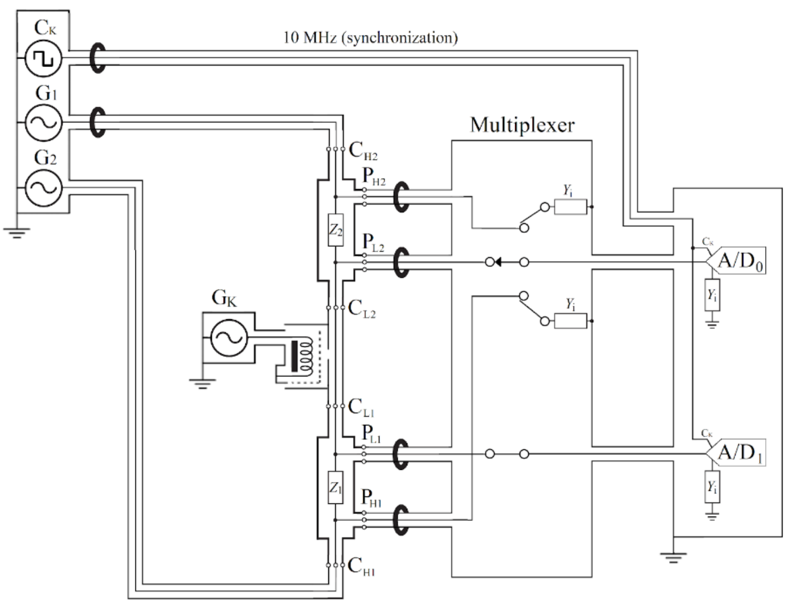

Figure 4.5 Schematic diagram of 4-TP, sampling-based fully-digital bridge due to Metrosert

In the Metrosert bridge the impedance ratio is obtained from the measurement of the voltage ratio at the P_H terminals of the impedances to be measured. The balance of the bridge is achieved when the voltages at P_{L1} and P_{L2} are both zero. The voltage ratio is measured by a high-accuracy digitizer ADC_0. During the measurement sequence, an admittance Y_i equal to the input impedance of the digitizer is connected to the channel which is not being sampled so as to minimise current redistribution within the bridge.

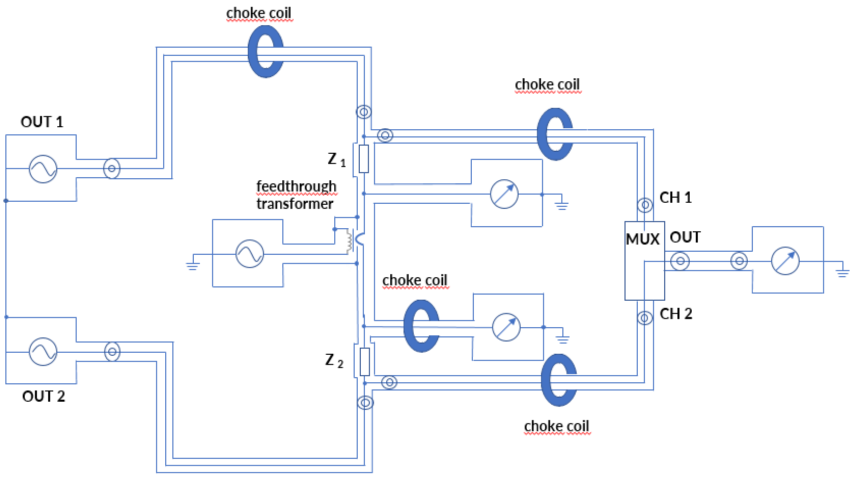

Figure 4.6 Schematic diagram of 4-TP, sampling-based fully digital bridge due to GUM

This GUM bridge has a similar operating principle to the other two sampling-based bridges.

TUBITAK chose to develop a digitally assisted bridge based on a CMI design whose schematic is shown in figure 4.7.

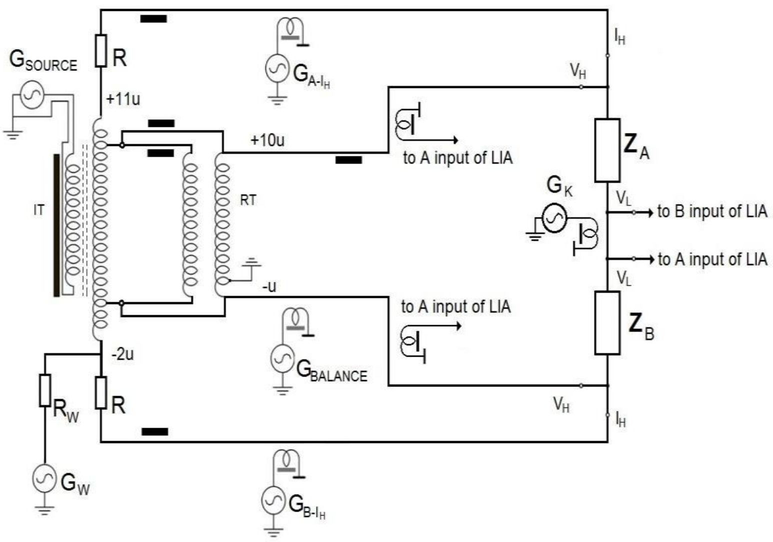

Figure 4.7 Schematic diagram of 4-TP, digitally assisted bridge due to GUM

The reference ratio of this bridge (1/1, 1/10) is provided by a guarded 2-stage transformer. PXI 4461 DAQ cards are used as sources. There are current source arms that provide zero current conditions in the voltage arms. All balances are detected using Lock-in amplifiers.

Three partners (BRML, NSAI and IPQ) chose to follow the design of the INRIM reference model bridge.

TUBITAK with the assistance of the other partners compiled a listing of artefact resistance, capacitance and inductance standards suitable for use with the proposed digital impedance bridges. The list ranges from commercially available standards, through self-built standards containing high quality component impedances, to specially constructed calculable standards. The range of values, connection types, operating frequency range, environmental sensitivity coefficients, AC characteristics as well as their suitability for use a travelling standard were recorded. The listing comprised 11 types of AC standard resistors, 5 types of standard inductors and 9 types of standard capacitors. The compilation is included as a section of the good practice guide.

Key outputs and conclusions

A review of recent research in the field of digital impedance bridges was carried out with particular attention to the outcomes of the AIM QuTE project. An extensive bibliography, which will be a useful resource for those starting to work in the field, has been produced. Based on this review, on the resources available to the partners and on the calibration demand the most suitable approaches to the local maintenance of a local scale of impedance by means of digital bridges were identified for each project partner. This project was successfully completed.

4.2 Construction and validation of the digital impedance bridges

Objective 2

To realise and validate inductance scales in the range 1 mH - 10 H, with uncertainties in the 10^{-5} range, and a capacitance scale in the range 1 nF - 10 µF, at frequencies in the range 120 Hz - 1592 Hz, with uncertainties in the 10^{-6} range, suitable for primary dissemination towards industry and calibration centres.

Relevance to the project needs and objectives

In all, six digital impedance bridges were constructed and validated in the VersICaL project. The performances of the bridges were tailored to meet the stakeholder needs identified during the initial stages of the project but, at a minimum, they were required to be capable of realising the inductance scale in the range 1 mH to 10 H and the capacitance scale in the range 1 nF to 10 µF at frequencies in the range 120 Hz to 1592 Hz. In fact, most of the bridges exceeded this minimum specification.

Due to time constraints, it was not envisioned that it would be possible to organise any intercomparison exercises for the purposes of bridge validation. This proved to be the case, so that the validation tests relied on in-house resources such as the measurement of impedance standards with well know calibration histories and consistency checks using RLC triangle tests.

Work undertaken

Improved multichannel digital signal source

The core element of the reference model source-based bridge developed within the project was a digitally synthesized polyphase sinewave source which provides the signals for the main and auxiliary bridge balances. This source was developed by UZG and was an improved version of that developed in the AIM QuTE project. The main improvement was the increased current drive capacity of the source which was increased from 20 mA to 100 mA by the addition of a new high-performance buffer at the output stage. In addition, other improvements were made. The structure of the source system was modified by changing the position of the low-pass filter and the power system was also been redesigned by using ultralow noise linear regulators, with ultrahigh power supply rejection ratio.

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The structure of the DSS consists of the three units as shown in Figure 4.8: the analogue circuits and DAC converters, the polyphase numerically controlled oscillator (NCO) and the power supply. The analogue circuits and DAC converters unit contains the 7-channel DAC stage, high performance low-pass filter stage and precise output buffers. The polyphase NCO is based on commercially available modular components which can be controlled by the bridge operating software or by an embedded controller for stand-alone operation.

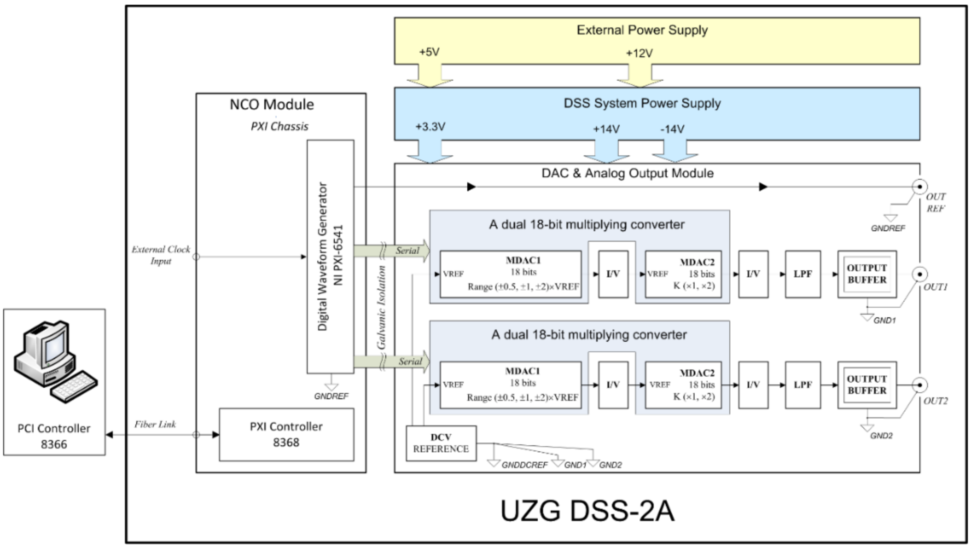


Figure 4.8 Schematic diagram of UZG DSS-2A

The accuracy of a digital bridge based on a source is directly dependent on the performance of the source. In particular, the ratio of the amplitudes of any pair of the source's outputs, as well as the phase relationship between them, must be extremely stable. Also, the amplitude of harmonics and inter harmonics must be very low. These parameters of the source were tested with satisfactory results.

Figure 4.9 Digitally synthesized source UZG-DSS-2A

UZG measured the spurious free dynamic range (SFDR) of the source for various loads and the results are shown in table 4.1.

	without load	load 100 Ω (I_{OUT} = 10 mA$_{rms}$)	load 50 Ω (I_{OUT} = 20 mA$_{rms}$)	load 20 Ω (I_{OUT} = 50 mA$_{rms}$)	load 10 Ω (I_{OUT} = 100 mA$_{rms}$)
Chan1 (Out 1)	97,6 dBc	97,8 dBc	96,3 dBc	92,6 dBc	90,1 dBc
Chan2 (Out 2)	100,1 dBc	100,3 dBc	98,2 dBc	93,0 dBc	90,0 dBc
Chan3 (Out 3)	100,3 dBc	99,9 dBc	96,1 dBc	93,9 dBc	88,7 dBc
Chan4 (Out 4)	98,8 dBc	97,4 dBc	96,3 dBc	93,2 dBc	90,3 dBc
Chan5 (Out 5)	98,9 dBc	97,5 dBc	96,6 dBc	92,8 dBc	90,2 dBc
Chan6 (Out 6)	101,8 dBc	99,9 dBc	98,3 dBc	95,6 dBc	92,1 dBc
Chan7 (Out 7)	100,0 dBc	99,8 dBc	98,8 dBc	95,7 dBc	92,6 dBc

Table 4.1 Measured SFDR of DSS-2A at 1 kHz

The channel crosstalk, as measured by UZG was less than -150 dB at 1 kHz.

Both UZG and NSAI measured the temporal stability of the source and found the stability of the amplitude ratio over a period of 1 hour to be less than 1 parts in 10^6 and the phase difference between channels to be stable to 1 µrad. The stability of a single output channel using both internal and external reference by comparison with that of a high-performance AC calibrator (Fluke 5720A) is shown in figure 4.10. These measurements were made by NSAI using the TWM sampling tool developed in project TracePQM.

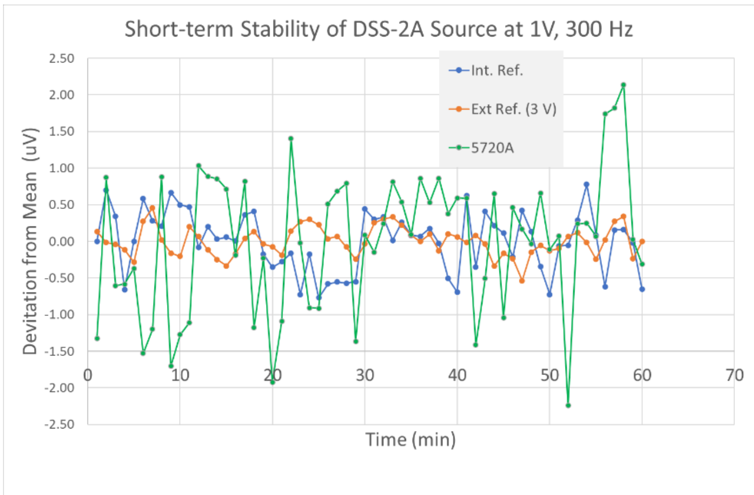


Figure 4.10 Short term stability of DSS-2A (channel 1) for both internal and external reference settings compared with stability of a high-performance AC calibrator

The results of linearity tests, made by UZG using an inductive voltage divider method, are shown in figure 4.11. Linearity measurements made by NSAI using the TWM sampling tool differed from these results and this was attributed to the fact that the UZG method measured the component of the signal at the fundamental frequency only, whereas the NSAI measurements computed the RMS value of the entire signal.

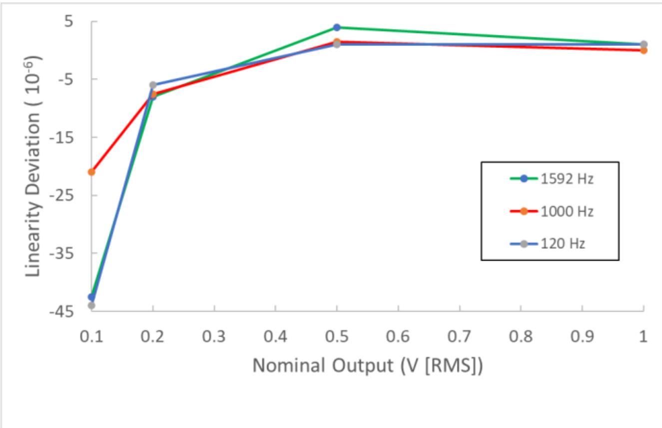


Figure 4.11 Non-linearity error of DSS-2A between channels 1 and 2 by comparison with an inductive voltage divider

Source-based, fully digital bridge constructed by INRIM and POLITO

A schematic of the main bridge network is shown in figure 4.12 and figure 4.13 is a photograph of the bridge set-up. The bridge is fully automated using a control application developed in the LabWindows/CVI environment. The front panel of the control application for the bridge is shown in figure 4.14. The software is freely available to download via the project's website.

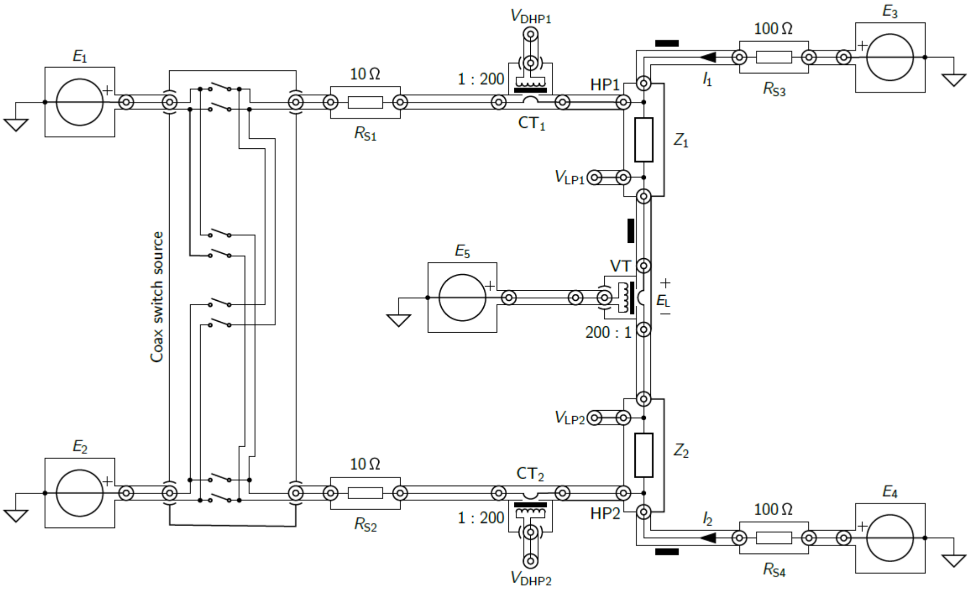


Figure 4.12 Schematic of INRIM 4-TP, source-based, fully-digital bridge

Figure 4.13 Reference model bridge as implemented at INRIM

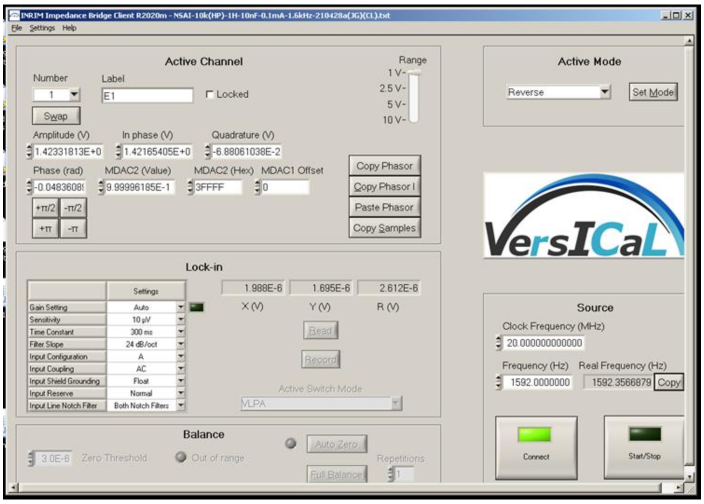


Figure 4.14 Front panel of BClient control programme

A feature of the control software is that its structure allows remote control of the bridge over the internet thus facilitating the operation of a virtual training laboratory (Figure 4.15). The virtual training laboratory was used successfully for training purposes during the project.

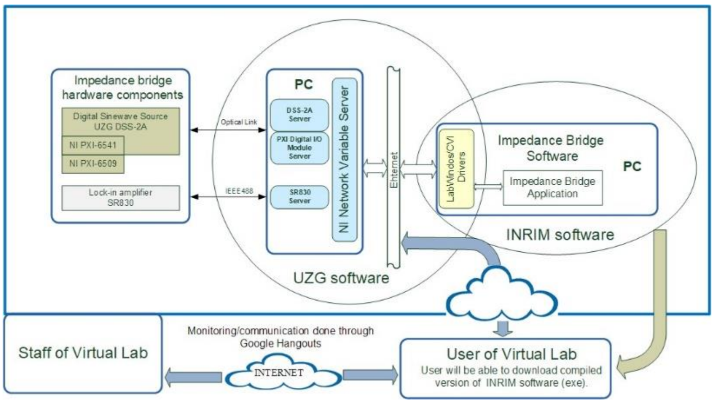


Figure 4.15 Software and hardware structure of the virtual training laboratory

The bridge was validated by a comparison of its measurement results with those obtained using the current Italian national impedance scale for a range of impedances and frequencies. Some typical results are shown in Table 4.2. for the measurement of inductances and capacitances using AC resistors as reference impedances.

Impedance	Frequency	Relative Deviation	Reference Uncertainty
1 mH	1000 Hz	-8×10^{-6}	29×10^{-6}
10 mH	1000 Hz	9×10^{-6}	18×10^{-6}
10 H	120 Hz	-8×10^{-6}	18×10^{-6}
1 nF	1000 Hz	-4×10^{-6}	7×10^{-6}
100 nF	1000 Hz	-13×10^{-6}	41×10^{-6}

Table 4.2 Typical validation results for INRIM 4-TP, Source-based, fully digital bridge

Overall, for impedances in the range 10 Ω to 1 MΩ and frequencies in the range 120 to 1.6 kHz, the bridge can achieve relative standard uncertainties of approximately 1 part in 10^6 for 1:1 impedance ratios and from a few parts in 10^6 to a few parts in 10^5 for impedance ratios up to 1:10. The accuracy is mainly limited by the non-linearity of the generator.

4-TP, sampling-based, fully digital bridge constructed by Trescal

The sampling-based bridge developed by Trescal (figure 4.16) uses a source developed in the AIM QuTE project by the Silesian University of Technology (SUT), two NI PXI-4461 sampling modules and a specially built buffer amplifier.

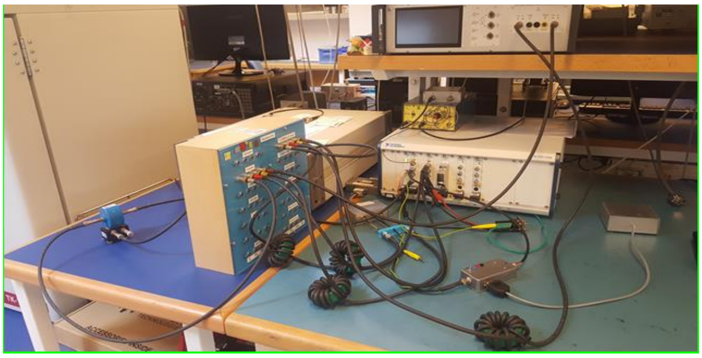


Figure 4.16 4-TP, sampling-based, fully-digital impedance bridge developed by Trescal

A series-parallel capacitive divider was used to determine and correct for non-linearity errors in the samplers (Table 4.3)

Ratio	Linearity Error $\times 10^6$		
	100 Hz	1 kHz	10 kHz
1.000000	-0.1	-0.1	0.0
0.499421	0.9	-0.2	-0.4
0.333215	-1.1	-3.4	-4.3
0.249881	-1.3	-4.1	-4.7
0.199934	-2.4	-4.5	-5.2
0.166621	-3.2	-6.3	-6.5
0.142822	-5.0	-6.9	-7.6
0.124969	-4.7	-8.2	-9.0
0.111080	-6.1	-8.8	-10.2
0.099969	-7.1	-8.5	-11.0

Table 4.3 Linearity errors of NI 4461 using series-parallel capacitive divider

The bridge was validated by measuring impedance standards with a well-known calibration history. The results for the validation of inductance measurements which are shown in Table 4.4 confirm that the bridge can measure at the required level of accuracy. Similar results were obtained for capacitance and resistance measurements.

Frequency	Value	Measured Value (DIB)	Reference Value	Ref. Unc, x 10^6	Difference x 10^6
100 Hz	10 H	9.999 8 H	9.999 8 H	19	0.1
100 Hz	1 H	0.999 98 H	0.999 97 H	21	8.8
1000 Hz	1 H	1.004 59 H	1.004 61 H	19	19.7
100 Hz	100 mH	99.962 mH	99.962 mH	22	4.5
1000 Hz	100 mH	99.978 mH	99.978 mH	20	3.3
100 Hz	10 mH	9.9960 mH	9.9958 mH	24	17.4
1000 Hz	10 mH	9.9951 mH	9.9951 mH	24	-2.7
100 Hz	1 mH	0.99995 mH	0.99996 mH	27	7.7
1000 Hz	1 mH	0.99910 mH	0.99906 mH	25	-40.7

Table 4.4 Trescal bridge – validation results for inductance measurements

4-TP, sampling-based, fully digital bridge constructed by Metrosert

An interesting feature of the sampling-based bridge constructed by Metrosert (Figure 4.17) was the use of commercially available function generators as sources.

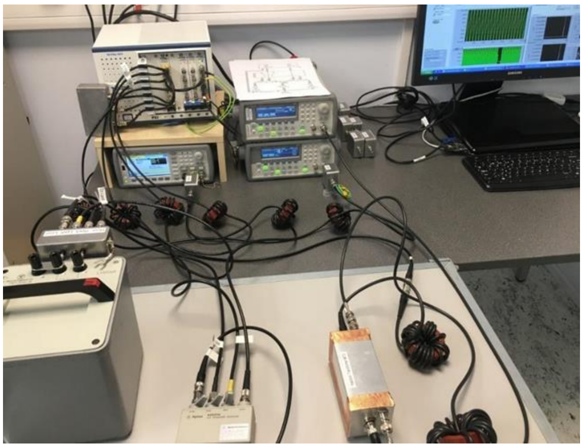


Figure 4.17 4-TP, sampling-based, fully digital impedance bridge developed by Metrosert

The stability of the sources was the limiting factor on the bridge's uncertainty, but it nonetheless performed well within its target uncertainty.

One of the validation tests performed by Metrosert was an RLC triangle consistency test. As shown in figure 4.18, the results for impedances of 10, 100, 1000 and 10 000 ohm showed consistency of better than 10^{-5}.

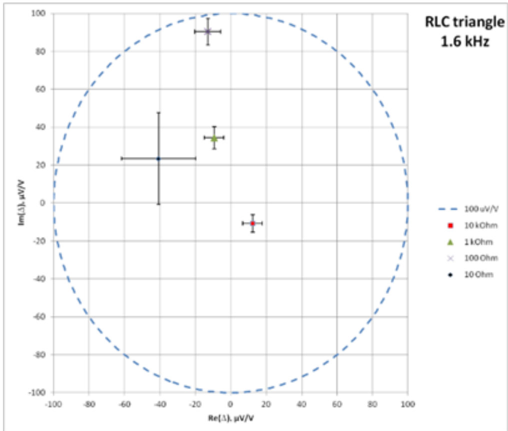


Figure 4.18 Results of RLC triangle consistency checks on Metrosert sampling-based bridge

4-TP, sampling-based, fully-digital bridge constructed by GUM and SUT

GUM, in collaboration with SUT developed the 4-TP, sampling based, fully-digital bridge shown in figure 4.19

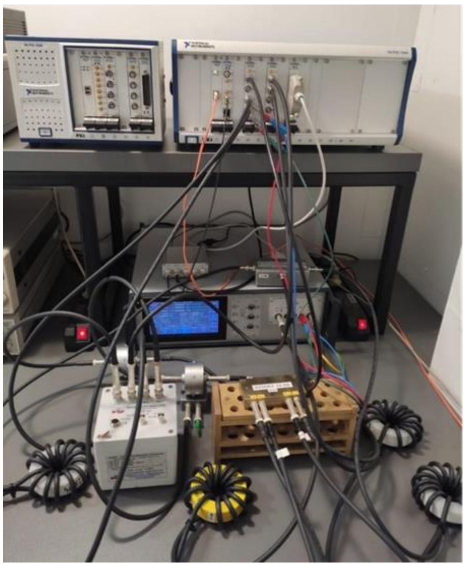


Figure 4.19 4-TP, sampling-based, fully digital impedance bridge developed by GUM and SUT

The bridge is based on the CMI design and uses an SUT source, NI PXI 4461 sampling devices and a digitally controlled multiplexer. The front panel of the control programme is shown in figure 4.20.

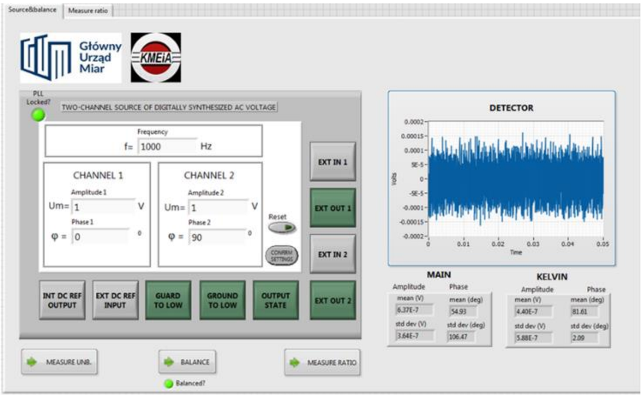


Figure 4.20 Front panel of control programme for GUM/SUT bridge

Triangle RLC consistency checks showed combined errors of less than 10^{-5} for the 10 kΩ-1 H- 10 nF triangle test and better than 3×10^{-6} for the 1 kΩ-100 mH-10 nF triangle test. The former result was significantly affected by the short-term stability of the 1 H inductance standard used for the test. Measurement of the RC ratio at 10 kΩ/10 nF showed agreement with the reference ratio of less than 20×10^{-6}.

4-TP, digitally assisted bridge constructed by TUBITAK

TUBITAK constructed a coaxial 4-TP digitally assisted bridge (Figure 4.21) based on a CMI design with the main objective of reducing the uncertainty for capacitance to resistance transfers.

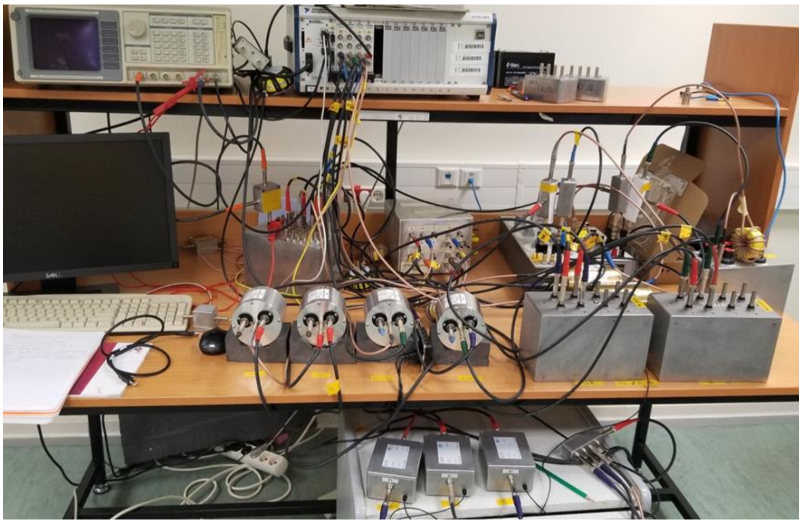


Figure 4.21 4-TP digitally assisted impedance bridge developed by TUBITAK

A self-built, two-stage ratio transformer, constructed so as to minimize the effects of cross capacitance between the shields, is used to provide the reference ratio for the bridge. The ratio transformer was calibrated using the primary level IVD calibration system available at TUBITAK. The control software was developed on the LabView platform. The user can choose manual or fully automatic balancing.

To validate the bridge, its capacitance ratio measurement results in the range 1 nF to 1 µF were compared with those obtained using a manually operated coaxial transformer ratio bridge. Results are shown in Table 4.5.

Ratio	Δ(ratio) Transformer - DA Bridge (120 Hz)	Δ(ratio) Transformer - DA Bridge (500 Hz)	Δ(ratio) Transformer - DA Bridge (1 kHz)	Type A Uncertainty (10^{-6}) (DA Bridge)
1000 nF / 100 nF	< 20 µF/F	< 15 µF/F	< 10 µF/F	< 1 µF/F
100 nF / 10 nF	< 1 µF/F	< 2 µF/F	< 2 µF/F	< 0.1 µF/F
10 nF / 1 nF	< 10 µF/F	< 2 µF/F	< 1 µF/F	< 0.1 µF/F

Table 4.5 TUBITAK bridge – validation results for capacitance ratio measurements

4-TP, Source-based, fully digital bridge constructed by NSAI

The 4-TP, source based, fully digital bridge constructed at NSAI is shown in figure 4.22.

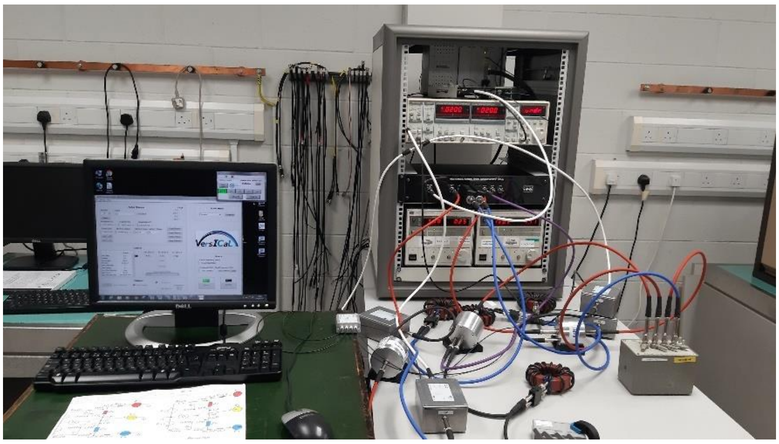


Figure 4.22 4-TP, source-based, fully digital impedance bridge constructed by NSAI

The bridge is a copy of the reference model bridge developed by INRIM. The bridge was validated using impedance standards with well know calibration histories or by comparison with a commercially available digital capacitance bridge (Andeen Hagerling 2700A). The results for the capacitance validation are shown in Table 4.6.

Z_1	Z_2	Frequency	Test Current	$\left(\frac{\Delta Z_2}{Z_2}\right) \times 10^6$	$\left[\frac{u_A(Z_2)}{Z_2}\right]$	ϑ
100 kΩ	1 nF	1000 Hz	0.01 mA	+8	0.1	2
100 kΩ	1 nF	1592 Hz	0.01 mA	+5	0.4	2
10 kΩ	10 nF	1000 Hz	0.1 mA	-6	0.9	2
1 kΩ	100 nF	1000 Hz	1 mA	+17	3	3
100 Ω	1 µF	1000 Hz	10 mA	-17	4	-

Table 4.6 NSAI bridge – validation results for capacitance measurements

Bridge Designs developed by IPQ and BRML

Both IPQ and BRML drew up designs for 4-TP sourcing impedance bridges that followed closely the design of the reference model bridge. IPQ initiated a cooperation with a local SME for the construction of some of the bridge components. BRML were unable to begin the construction of the bridge due to procurement problems.

Key outcomes and conclusions

By designing, constructing and validating six operational digital impedance bridges, it has been shown that it is feasible to realise an inductance scale over the range 1 mH to 10 H with a relative uncertainty of the order of 10^{-5} and a capacitance scale in the range 1 nF to 10 µF with a relative uncertainty of the order ot 10^{-6} over the frequency range 120 Hz to 1592 Hz by means of digital impedance bridges. These bridges provide a practical and economic alternative to traditional manually operated coaxial transformer ratio bridges. The design and construction details of the model reference bridge, as well as its control software, have been made freely available with the intention of providing newcomers to the field with the resources needed to fast track the development of a digital impedance bridge. A virtual training laboratory has been set up as an associated training resource.

The main factor that contributed to the bridges being operational and validated within the timeframe of the project was the high degree of co-operation and knowledge sharing among the partners. The objective was successfully completed.

4.3 Measurement uncertainty tool and good practice guide

Objective 3

To develop a good practice guide for application of the digital impedance bridges and the realisation of inductance and capacitance scales and a software tool for modelling uncertainties.

Relevance to project's needs and objectives

One of the key performance parameters of an impedance bridge is the uncertainty of the measurement result that it delivers. Since electrical impedance is a vector quantity the evaluation of its uncertainty is not a straightforward matter. Identifying the error sources, deriving the associated measurement equations and propagating the uncertainty components is a significant task. Clear guidance is needed on these topics and an evaluation tool which uses a numerical method to evaluate the uncertainty would be of great assistance to users of digital impedance bridges.

An underlying aim of the project is to promote the use of digital impedance bridges and to provide a distributed network of capability in the field of impedance measurement. A practical guide containing information on design principles, component parts, interconnections, operating methods and uncertainty evaluation provides a valuable tool to those intending to develop a digital bridge. The case studies contained in the guide show “real world” examples of bridge development.

Measurement Uncertainty Tool

POLITO, with input from INRIM, CMI, Trescal, UZG, SUT and NSAI prepared a paper on error sources in electronic fully digital bridges which was published in the IEEE Transactions on Instrumentation and Measurement. The paper presents a comprehensive analysis of both types of electronic fully digital bridges. The sources of measurement error are analysed in detail and expressed by explicit mathematical formulae which can be used to optimise the design and operating parameters of the bridge and to evaluate the measurement uncertainty.

The main error sources described for source-based bridges were identified as generator nonlinearity, channel crosstalk, generator loading, low unbalance error and high unbalance error. Those for sampling-based bridges are digitizer nonlinearity, multiplexer switching errors, and low unbalance error. As examples, these error analyses were applied to the source-based bridge developed at INRIM and the sampling-based bridge developed at Trescal. The nonlinearity errors for the DSS-2A source, as determined by UZG and NSAI were used to estimate the associated nonlinearity uncertainty component of the INRIM bridge. Similarly, the nonlinearity uncertainty component for Trescal's digitizing bridge was estimated using the nonlinearity errors determined by Trescal using the capacitance build-up method. Similarly, the uncertainty components due to the other error sources were evaluated for both bridges.

A software uncertainty tool, based on the error modelling reported in the published paper, was produced by POLITO. The uncertainty propagation is performed using a Monte Carlo simulation method to evaluate the uncertainty. While it is designed to work with the data files generated by the control application for the model reference bridge, it can easily be adapted to cater for other bridge designs. The tool was developed under the numerical computing environments MATLAB and GNU/Octave and was tested under Octave 5.2.0, MATLAB R2019b, and MATLAB R2020a.

Figure 4.23 represents the architecture of the software tool. The script takes three files as input, the measurement data file generated by the bridge control application, a file containing data on the reference impedance standards used with the bridge, and a file containing data on the bridge parameters (source non-linearity, crosstalk coefficients etc.).

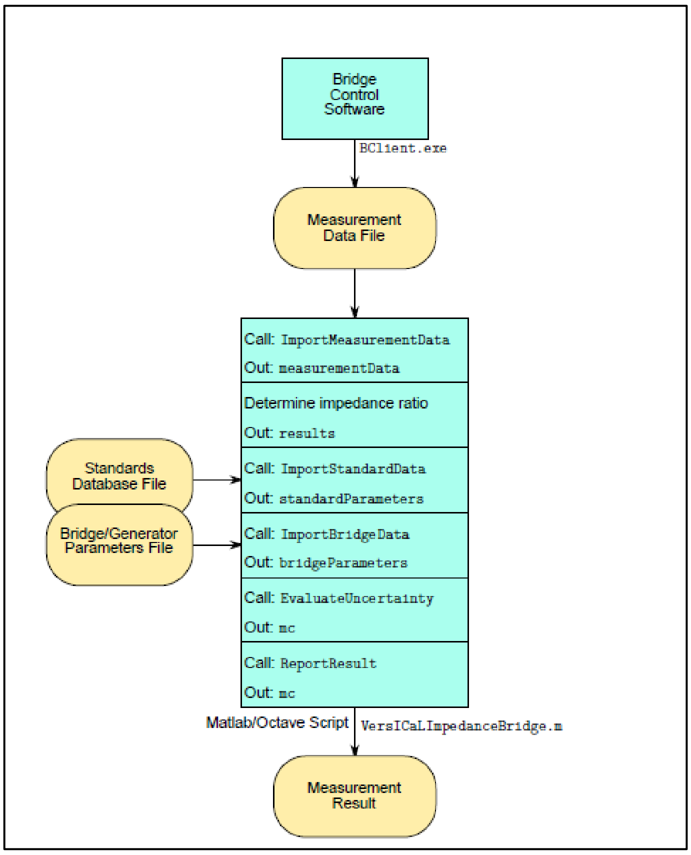


Figure 4.23 Schematic structure of the uncertainty software tool

The Monte Carlo simulation is performed by using random samples extracted from the assumed distributions of the various input quantities. The user is prompted to choose the output format for the result (figure 4.24). The best estimates of the chosen measured quantities and their associated expanded uncertainties are displayed.

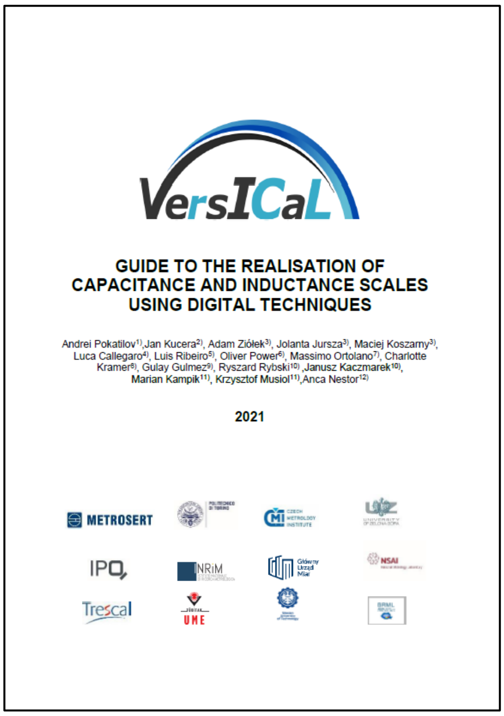
Output format	Parameter definition
L_S, R_S	$L_S = \mathrm{Im}\, Z_2/(2\pi f)$ $R_S = \mathrm{Re}\, Z_2$
L_S, Q	$L_S = \mathrm{Im}\, Z_2/(2\pi f)$ $Q = \lvert \mathrm{Im}\, Z_2 / \mathrm{Re}\, Z_2 \rvert$
C_p, G_p	$C_p = \mathrm{Im}\, Y_2/(2\pi f)$ $G_p = \mathrm{Re}\, Y_2$
C_p, D	$C_p = \mathrm{Im}\, Y_2/(2\pi f)$ $D = \lvert \mathrm{Re}\, Y_2 / \mathrm{Im}\, Y_2 \rvert$
R_S, τ	$R_S = \mathrm{Re}\, Z_2$ $\tau = \mathrm{Im}\, Z_2/(2\pi f R_S)$
R, X	$R = \mathrm{Re}\, Z_2$ $X = \mathrm{Im}\, Z_2$
G, B	$G = \mathrm{Re}\, Y_2$ $B = \mathrm{Im}\, Y_2$

Figure 4.24 Available output formats for the results produced by the uncertainty tool

NSAI installed and successfully tested the uncertainty tool on their version of the model reference bridge. The software is freely available to download via the project's website.

Good Practice Guide

A good practice guide entitled "Guide to the realisation of capacitance and inductance scales using digital techniques" was produced and is available to download from the project's website. All project partners contributed to the guide which was edited by Metrosert.



GUIDE TO THE REALISATION OF CAPACITANCE AND INDUCTANCE SCALES USING DIGITAL TECHNIQUES

Andrei Pokatilov[1],Jan Kucera[2], Adam Ziółek[3], Jolanta Jursza[3], Maciej Koszarny[3], Luca Callegaro[4], Luis Ribeiro[5], Oliver Power[6], Massimo Ortolano[7], Charlotte Kramer[8], Gulay Gulmez[9], Ryszard Rybski[10] ,Janusz Kaczmarek[10], Marian Kampik[11], Krzysztof Musiol[11],Anca Nestor[12]

2021

Figure 4.25 Front page of good practice guide

The guide is primarily intended as a practical resource for those who need to develop a digital impedance bridge from scratch. The guide contains the following sections (contributing partners are given in parentheses):

1. Introduction and Overview (Metrosert, NSAI): This describes the purpose and target audience of the guide and summarizes its contents.
2. Realisation of inductance and capacitance scales (Metrosert, IPQ, INRIM, POLITO, UZG, CMI, TUBITAK, BRML, Trescal, GUM, NSAI), : This section begins with an overview of the traceability chain for electrical impedance quantities with particular reference to the important role played by impedance bridges. The operating principles of digital impedance bridges are outlined, and the reference model impedance bridge is fully described. A comprehensive list of the main bridge components that are currently available (sources, digitisers, artefact impedance standards) is given. Guidance on interconnection schemes, including the use of adapters, is provided. The section concludes with information on validation methods.
3. Measurement Uncertainty (Metrosert, POLITO, INRIM, UZG, NSAI, CMI): Models for the principal errors in both source-based and sampler-based brides are provided. The uncertainty evaluation tool is fully described.
4. Case Studies (GUM, Trescal, Metrosert, TUBITAK, NSAI): Each partner that had developed a bridge provided a full description of the development process including motivation for the work, bridge design, construction details, bridge operation, and validation tests.
5. Bibliography (POLITO with assistance from all other partners): A comprehensive bibliography of books, papers and conference proceedings on the subject of digital impedance bridges.

Summary of key results and conclusions

Contributions from all project partners, based on previous knowledge and expertise and on experience gained during the project formed the basis of a good practice guide on the realisation of inductance and capacitance scales using digital impedance bridges.

The paper on error modelling in fully digital bridges is an important contribution to the topic of uncertainty evaluation in this field. The software uncertainty tool uses these models as a basis for evaluating the uncertainty of results produced by digital bridges. The tool has been tested successfully. It may be readily adapted for use with any design of fully digital bridge. The objective was successfully completed.

4.4 Draft CMCs

Objective 4

To develop new and/or improved draft Calibration and Measurement Capabilities (CMCs) in the context of the CIPM Mutual Recognition Arrangement for the new inductance and capacitance capabilities.

Relevance to the project's needs and objectives

The drafting of calibration and measurement capabilities (CMC) for the bridges constructed within the project shows that the bridges are operational and have been validated to some extent. CMCs, expressed as expanded uncertainties, provide a convenient "figure of merit" for the performance of a measurement set-up. By drafting CMCs for the digital bridges developed during the project their performance can be assessed against the target uncertainties obtained from the stakeholder survey.

Work undertaken

At the beginning of the project a review of existing CIPM MRA CMCs for impedance measurements was carried out by INRIM, CMI, Trescal, Metrosert, GUM, TUBITAK, BRML and NSAI. All of the internally funded partners already had approved CMCs under the CIPM MRA for categories 4.2 (capacitance) and 4.3 (inductance) although there were some gaps in the coverage for some partners. For the emerging NMIs that participated in the project, these CMCs were entirely dependent on external calibration of sets of impedance standards. As a result of participating in the project those partners who constructed and validated digital impedance bridges (Trescal, Metrosert, GUM, TUBITAK, NSAI) were in a position to draft new CMCs based on semi-independent realisations of local scales of capacitance and inductance.

The draft CMCs were based on preliminary uncertainty evaluations which, in turn, used the error models produced by POLITO, documented in the published paper and, in some cases, the performance data of the multichannel source which had been generated by UZG. The validation test results were used to check the reliability of the uncertainties. The draft CMCs cover the range 1 mH to 10 H for inductance and 1 nF to 10 µF for capacitance for frequencies in the range 60 Hz to 2 kHz. The capabilities of the bridges extended beyond these limits so that partners were able to draft additional CMCs, such as those for category 4.1 (AC resistance), beyond the targets set out in the project objectives.

The CMCs were produced in a spreadsheet format (including uncertainty matrices) suitable for direct uploading to the Key Comparison Data Base (KCDB) website. A summary of the draft CMCs (excluding those outside the target ranges set down in the project objectives) is shown in Table 4.6.

NMI	Draft CMC		
	Impedance Range	Frequency Range	Relative Expanded Uncertainty (95% CP)
TUBITAK	1 nF – 10 µF	120 Hz - 1 kHz	1×10^{-6} to 20×10^{-5}
GUM	1 nF – 10 µF	120 Hz – 1.6 kHz	2×10^{-6} to 30×10^{-5}
GUM	1 mH – 10 H	1 kHz	2×10^{-5} to 5×10^{-5}
Trescal	1 nF – 10 µF	100 Hz – 10 kHz	2×10^{-6} to 30×10^{-5}
Trescal	1 mH – 10 H	100 Hz – 10 kHz	5×10^{-5} to 40×10^{-5}
NSAI	1 nF – 10 µF	60 Hz to 2 kHz	2×10^{-5} to 10×10^{-5}
NSAI	1 mH to 10 H	60 Hz to 2 kHz	5×10^{-5}

Metrosert	1 mH to 1 H	1 kHz to 1.6 kHz	2 x 10^{-4}

Table 4.6 Summary of draft CMCs based on digital impedance bridges

These CMCs feature improvements related to reduced uncertainties, extended ranges, and amended traceability routes. They are based on preliminary uncertainty budgets and are subject to change according as the users gain further experience with bridge operation.

When the CMCs are submitted, information on the participation of the NMI in the VersICaL project and contributions made to the project outcomes (publications, reports, good practice guide) will be useful evidence to show competence in the measurement field. Additional evidence to support the CMCs, in particular the results of participation in an approved measurement intercomparison, will be required prior to submission.

Summary of key results and conclusions

The key outputs were the draft CMCs produced by those partners who constructed and validated digital impedance bridges. This demonstrated clearly that laboratories with limited resources and expertise can, using digital techniques, develop semi-independent realisations of capacitance and inductance scales to meet the demands of their customers within a reasonable timeframe and at a reasonable cost. The objective was successfully completed.

4.5 Individual strategies to exploit the project outcomes

Objective 5

For each partner, to develop an individual strategy for the long-term operation of the capacity developed, including regulatory support, research collaborations, quality schemes, and accreditation. Each participant will also develop a strategy for offering calibration services from the established facilities to their own country and neighbouring countries. The individual strategies will be discussed within the consortium and with other EURAMET NMIs/DIs, to ensure that a coordinated and optimised approach to the development of traceability in this field is developed for Europe as a whole.

Relevance to the project's needs and objectives

The improved measurement capabilities developed within the project need to be put on a sound footing so that they can be used to efficiently deliver calibration services that are of a high quality. Plans to produce operating procedures and incorporate the set-ups into the laboratory's quality system are needed. Further work on the validation of the bridges, including participation in a formal measurement intercomparison, needs to be planned. The project aimed to improve the research potential of the partners. A strategy to further develop and exploit this research capacity is required.

Work undertaken

NSAI, CMI, GUM, INRIM, POLTO, IPQ, Metrosert, TUBITAK, Trescal and UZG developed strategies for the long-term operation of the measurement and research capabilities developed during the project and drafted a 4-year plan for the implementation of the strategies. Due to internal operational reasons BRML were unable to prepare a strategic plan. The plans can be considered under two broad headings: (1) improved measurement capabilities for impedance quantities and (2) improved research capacity in the field of impedance metrology.

Table 4.7 summaries the plans relating to category (1). Note that UZG is not an NMI/DI but does plan to establish an accredited calibration service.

NMI	Bridge Status	Development Plans			
		Participation in international comparison	Improved CMCs	New Traceability Scheme	New Calibration Services
NSAI	Operational	√	√	√	√
CMI	Operational	√	√	√	
GUM	Operational	√	√	√	√
INRIM	Operational	√	√	√	
IPQ	Planned	√	√	√	√
Metrosert	Operational	√	√	√	√
Trescal	Operational	√	√	√	√
TUBITAK	Operational	√	√	√	
UZG	Planned				√

Table 4.7 Summary of plans based on improvement measurement capabilities.

The plans and strategies for future research activities were more diverse. Some examples of future research plans are as follows:

- TUBITAK plans to use calculable resistors to link capacitance measurements to the resistance unit.
- CMI, INRIM and POLITO are participating in project 18IB07 GIQS.
- IPQ and NSAI intend to use the developed capacity to investigate the measurement of non-ideal impedances such as these encountered in material testing applications.
- Trescal will investigate possible improvements in the electronic parts of their bridge.
- UZG plan to continue with further development of the multichannel sinewave source and intend to construct a digital impedance bridge which will be used as a teaching and research tool.

Summary of key results and conclusions

Long-term strategies on the use and development of impedance measurement set-ups using digital techniques have been drawn up by 10 partners. The measurement services based on these set-ups will no longer be entirely dependent on the external calibration of sets of impedance standards. The distributed network of capability will strengthen the European measurement infrastructure in this important field of measurement. Most of the partners are now in a position to take part meaningfully in an official international measurement intercomparison. There will be additional opportunities for partners to take part in future joint research projects which involve high accuracy impedance measurement. Due to the inability of BRML to contribute the objective was partially successful.

5 Impact

Information about the project and its results have been disseminated via a project website. Presentations on the project were given at three national conferences (Italy, Denmark and Turkey) and at five EURAMET technical committee meetings. Three presentations relating to the project were made at the CIM2019 conference (Sep 2019) and two associated papers have been published. Two presentations were presented at the IEEE Conference on Precision Electromagnetic Measurements conference (CPEM2020) and a paper associated with one of the presentations has been published in the IEEE Transactions on Instrumentation and Measurement. A presentation was made at the NCSLI2020 conference and an associated paper included in the conference proceedings. The latest version of the control software for the reference impedance bridge and the uncertainty evaluation tool have been made available on a public repository with links provided on the project's website

Impact on industrial and other user communities

The measurement of electrical impedance, or the detection of small changes in electrical impedance play a vital role in a wide array of everyday technologies, such as the study of polymer dielectrics, supercapacitors, and solar materials in electrical engineering, tissue impedance analysis in the life sciences, and thin-film and nanostructure characterisation in materials research. Impedance spectroscopy is also used in a whole array of diagnostic techniques ranging from medical imaging to the monitoring of agricultural product quality.

The development of digital bridges to realise impedance scales at the reference level, which is the core objective of this project, will improve the traceability chain, in terms of accuracy, accessibility and economic cost, available to users of impedance measuring devices. Once the new CMCs based on the newly developed bridges have been submitted and approved, calibration services for impedance measuring instruments and devices will be improved from the point of view of accuracy, range, accessibility and efficiency.

A project partner has initiated a collaboration with a start-up SME which involves the fabrication of bridge components. Participation in the project will strengthen the SME's research and development capability.

Impact on the metrology and scientific communities

A programme of short secondments of staff from the project partners with less experience in the use of digital impedance bridges (BRML, GUM, Metrosert, TUBITAK) to the laboratories of more experienced partners (INRIM, CMI, Trescal) has had a positive impact on improving the knowledge and developing the necessary skill set of the former laboratories. As well as facilitating the development of digitally based measurement set ups in the laboratories of the participating partners, this knowledge transfer will enable the partners to offer training and consultancy on impedance measuring methods to interested users.

The Silesian University of Technology (SUT, Poland) collaborated with one of the project partners in the design and construction of a digital impedance bridge based on a sampling method. The collaboration will also improve the quality of education in the area of metrology at SUT and has strengthened its cooperation with the Polish national metrology institute.

Interaction with stakeholders through a stakeholder committee helped the project to focus on the end-user's needs. The committee comprised organisations from different fields of activities related to impedance metrology including NMIs, academic institutions, accredited calibration laboratories and industry.

A copy of the reference impedance bridge has been constructed and operated at a developing NMI (NSAI) thus demonstrating the feasibility of using digital impedance bridges to realise local scales of impedance without the necessity for external calibration of sets of impedance standards. Improvement in the research capacity of the less experienced partners has been demonstrated by their contributions to joint presentations and publications. Three other NMIs who were not part of the consortium are in the process of developing digital impedance bridges, one of which is based on the reference model bridge

Impact on relevant standards

Posters and presentations describing the project objectives, progress and outcome were presented to the EURAMET Technical Committee for Electricity and Magnetism (TC EM) meetings in September 2018, October 2019 an October 2020 as well as at the TC-EM Sub-committee on Low Frequency in May 2019.

Longer-term economic, social and environmental impacts

The long-term impacts of this project will follow from the improvement, both in quality and in geographical spread, of the impedance metrology infrastructure in Europe. As a result of the project outcomes, several developing NMIs are in a position to offer local, high level calibration of the artefact impedance standards used as working standards in their own laboratories and in accredited calibration centres. Measuring systems that rely on trustworthy measurements of electrical impedance will be impacted indirectly. Such systems are to be found in the areas of health (medical diagnostics and imaging, safety of implantable measurement devices), energy (characterisation of supercapacitors) and environment (air quality sensors).

6 List of publications

J. Kucera et al., "Characterization of a precision modular sinewave generator", Meas. Sci. Technol., 33(6), Jan 2020, 10.1088/1361-6501/ab6f2e

M. Ortolano et al., "A Comprehensive Analysis of Error Sources in Electronic Fully Digital Impedance Bridges," IEEE Transactions on Instrumentation and Measurement, vol. 70, pp. 1-14, 2021, 10.1109/TIM.2020.3034115

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/