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AIM QuTE

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1 Executive Summary

Introduction

Electrical impedance is used in the manufacturing process for electronic components such as resistors and transformers, to analyse touchscreens and fuel gauges, and to calibrate dosimeters for ionising radiation measurement. Impedance is the resistance of an alternating current (AC) electric circuit, and is a measure of the opposition that a circuit presents to the AC when a voltage is applied. An impedance bridge is an instrument used to measure impedance; the units of which are the ohm (Ω), the farad (F) and the henry (H).There are a variety of different types of impedance bridges, and this project looked at two of these – (1) Josephson bridges and (2) automated digital bridges.

This project improved the European capabilities for impedance measurements by developing new standards, methods and traceability routes needed to establish impedance scales at the lowest level of uncertainty (i.e. 10^{-7} between 10 Hz and 20 kHz). The project developed Josephson and digital impedance bridges capable of calibrating impedance at values 'in between' the previously defined set values of impedance standards.

The Problem

Both end users of impedance measurements and instrument manufacturers have identified areas in need of improvement. These areas include the calibration of arbitrary impedance values (rather than the previously set values of impedance), impedance measurement for nanotechnology, improvement of impedance calibration for the frequency range 10 Hz to 20 kHz, and a general requirement to simplify the very complex impedance calibration procedures.

Prior to this project, the lowest uncertainty impedance calibrations used defined ratios, with calibrations performed as comparisons with known predefined impedance standards. These ratios included 1:1, 1:2 and 1:10 ratios of like impedances, and 1:1 ratios for quadrature measurements, which are measurements of AC waveforms out of phase with each other by one quarter of a cycle. The ratios are defined by purpose-built transformers at set values rather than variable impedance values required by modern manufacturers, and many different ratio transformers were required for different impedance ratios. Both the construction of the ratio transformers and 'balancing' of the bridge for the calibrations required highly skilled operators, limiting the availability of the measurements. In addition, for non-standard or arbitrary ratio measurements, there was a substantial increase in uncertainty.

This lack of calibration capabilities at European NMIs for intermediate impedance values, in the range from 10 Ω to 1 MΩ, was an issue for instrument manufacturers. In addition, the accuracy of impedance measurements was restricted by the available traceability of the measurements.

The Solution

This project addressed the existing needs by developing two types of impedance bridges, firstly Josephson bridges which use the Josephson Effect, an electronic phenomenon of supercurrent. Josephson bridges offer an unprecedented combination of low measurement uncertainty, extended frequency range and speed of performance. Secondly, automated digital bridges which reduce the requirement for very experienced operators even for low uncertainty measurements.

Impact

The project has developed automated impedance bridges at the same level of uncertainty than manually operated impedance bridges. Partner NMIs can now reach comparable or better uncertainties than previously achieved but with the advantage of automated impedance bridges making the measurements much easier and removing the requirement for an experienced operator in order to reach the best uncertainties. Eight partner NMIs were expected to be operating automated impedance bridges at the end of the project; five had succeeded during the project.

Automation will also speed up calibration of impedance standards and therefore reduce equipment downtime for customers in their own laboratories. Furthermore, the programmable impedance standard replaces at least five standards in the traceability chain for the calibration of LCR-meters at commercial calibration laboratories.

2 Project context, rationale and objectives

Impedance is used in diverse applications such as the manufacture of passive electronic components or to measure a huge number of other parameters: resistance based temperature metrology, electrochemical impedance spectroscopy for the analysis of battery electrolytes, calibration of dosimeters for ionising radiation, sound and vibration instrumentation, and commercial sensors such as touchscreens or fuel gauges. End users of impedance measurements and instrument manufacturers had identified areas in need of improvement and provided the motivation for this project. The areas requiring further work included the calibration of arbitrary impedance values, not purely resistive/capacitive impedance standards, impedance metrology for nanotechnology, improvement of impedance calibration for frequencies below 100 Hz, and in general to simplify impedance calibration procedures.

Traceability for impedance is established by calibrating impedance standards and a large number of these standards is required for complete coverage of the scales. The lack of calibration capabilities at NMIs for impedance values different from 1, 2, 5, 10 sequence was an issue for instrument manufacturers and their impedance standards. In addition, this limited accuracy propagates through the traceability chain to less demanding applications, such as electrochemical impedance spectroscopy where progress is limited by the available traceability of the measurements or to the large number of impedance-based sensors that cover an extremely wide range of applications. The impedance of these sensors, at least during the development of the product that includes these sensors, is measured with instruments such as those manufactured by stakeholders Agilent, Andeen-Hagerling, Brüel & Kjaer, Fluke, Guildline, Meatest, Newtons4th or Tegam.

Before this project, the lowest uncertainties for impedance calibrations were restricted to previously defined ratios and phase angles between the impedance being calibrated and the reference standard. The ratio is normally defined by a purpose-built transformer. State of the art transformers enable the comparison of two impedances with uncertainties of a few parts in 10^8 or better over a limited frequency range (at best 500 Hz to 5 kHz), but a different transformer is required for a different impedance ratio. The impedance values that can be measured with high accuracy (parts in 10^8) are the decadic values and the quantum Hall resistance (QHR) value. With traditional methods, the uncertainty increases rapidly for impedances that are not purely resistive or capacitive and also at intermediate values. Due to the special construction of conventional impedance bridges, intermediate values essentially means outside a very narrow window (about 2×10^{-4} away from decadic values). The goal of the project was to achieve best in class uncertainties that are independent of the impedances being compared.

One of the paths explored in the project to reach this improvement in uncertainty was to further develop an advance in electrical metrology achieved shortly before the start of the project, an intrinsically referenced measurement for electrical impedances that does not require calibration. This intrinsically referenced method employs quantum standards, which are already well established in voltage and dc-resistance metrology. Quantum standards are independent of time, place and environmental conditions. They allow extremely low measurement uncertainties and highly robust operation while only requiring comparatively simple tests to ensure their quantised behaviour. Similarly, this innovative intrinsically referenced measuring method only requires a simple test to check the correct operation of the Josephson arrays independently of the frequency of the measurements. Josephson bridges offer an unprecedented combination of low measurement uncertainty, extended frequency range and speed of operation for this performance.

When applied in this way, the Josephson arrays "simply" deliver two waveforms of precisely known amplitudes and defined relative phase. The ratio transformer(s) which had been used up to the start of the project for this purpose were no longer required. As a result, the bridge no longer needs to be recalibrated for each signal frequency. The project therefore set out "to realise Josephson based impedance bridges for arbitrary ratios of like impedances (*R:R, C:C* and possibly *L:L*), and 1:1 ratios for quadrature measurements" as one of its three objectives.

Technological advances in semiconductor electronics seemed to allow for transformer-less impedance bridges with uncertainties in the region of parts in 10^7. These bridges could also be operated over a much larger frequency range than transformer-based bridges. In addition to the considerable simplification of the measurement setup, there was also scope for completely automated operation, including the procedures for balancing the impedance bridge. Special equipment beyond commercially available signal sources was required to reach all the goals in the project and two integral research excellence grants from two different

Polish universities developed novel electronic signal generators to fulfil the requirements of the target level of uncertainty in fully digital bridges. The second objective in the project was "to develop automated impedance ratio bridges and perform proof-of-concept tests at an uncertainty level of 10^{-7} covering the frequency range from 10 Hz to 20 kHz".

These two independent measurement methods for determining impedances would significantly extend the coverage of the impedance complex plane, whilst also providing a measurement infrastructure which due to its automated operation would also allow the use of such setups in metrology laboratories that do not have at their disposal extremely highly-skilled metrology personnel. The resulting strengthening of the European metrology infrastructure for impedance metrology would also be supported by the development of a programmable impedance simulator. This instrument is capable of behaving like any impedance in the range 10 Ω ≤ $|Z|$ ≤ 10 MΩ over the audio frequency range from 20 Hz to 20 kHz with an uncertainty of parts in 10^6 and can replace a large number of standards for *R, L* and *C* in order to guarantee the traceability chain from NMIs to accredited calibration laboratories. Furthermore, recent developments in the area of nanotechnology demanded improved reproducibility and traceability of capacitance measurements below 1 fF. All these demands lead to the third objective: "to extend the impedance scales to intermediate values,, within the range for $|Z|$ between 10 Ω to 1 MΩ, along the axes (*R, L* and *C*) to intermediate phase angles and towards values demanded by nanothechnology (capacitances below fF), and to develop the corresponding standards".

3 Research results

3.1 Josephson impedance bridges

In the order listed above, the first objective of this project was "to realise Josephson based impedance bridges for arbitrary ratios of like impedances (*R:R, C:C* and possibly *L:L*), and 1:1 ratios for quadrature measurements". This objective was tackled by CEM, PTB, SP and VTT (previously MIKES), each exploring slightly different subareas of the development of Josephson impedance bridges. This work built on the first proof of concept implementation of an impedance bridge using programmable Josephson arrays for the generation of the waveforms used in the bridge, published before this project, in 2010, as a result of a cooperation between PTB and VTT MIKES[1]. That paper reported the comparison 10 kΩ:10 kΩ over the frequency range from 25 Hz to 10 kHz.

3.1.1 Basic principles and limitations of Josephson impedance bridges

In this project, PTB has completed not only the expansion from 10 kOhm:10 kOhm ratio to other ratios of resistance, but also for capacitance calibrations. Figure 1 shows the schematic diagram of a Josephson impedance bridge with two additional dummy loads. In particular, the voltage level for the measurement was extended in this project from 1 V to 10 V. As in the proof of concept experiment with two 10 kΩ resistors, a complete frequency sweep comparing the two impedance standards in the bridge can be run under complete software control in less than 40 minutes for 20 different frequencies in the range from 25 Hz to 10 kHz. The position of the impedance standards in the bridge is then interchanged in order to remove systematic deviations and a second frequency sweep performed. After two such pairs of sweeps, the comparison of the two impedance standards is completed. In the course of the project, a thorough study of the different contributions to the uncertainty that can be achieved for these measurement was carried out [9], [29]. Different bias electronics were tested, as was the influence of the cables connecting the cryogenically operated Josephson arrays to the impedance standards. The combined uncertainty of the bridge was evaluated to be in the region of parts in 10^8. As an example, the 100 pF:100 pF ratio can be evaluated with a combined uncertainty of 9.6×10^{-9} ($k = 2$).

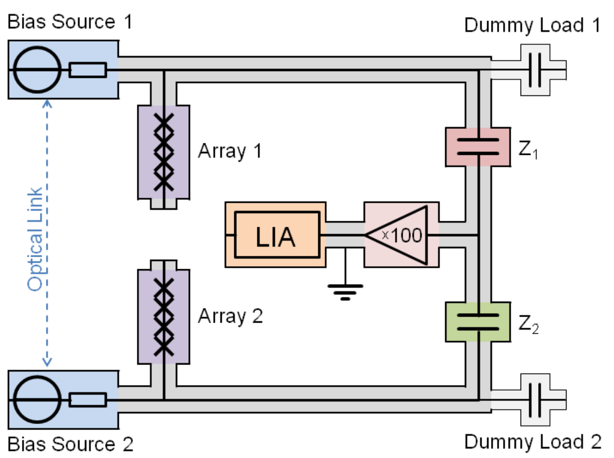

Figure 1 Schematic diagram of a Josephson impedance bridge with additional dummy loads and a null detector made up of a x100 preamplifier and a Lock-In Amplifier (LIA). The two Josephson arrays are operated in liquid helium.

As Josephson impedance bridges were developed by PTB in this project, it became clear early on that square wave signals could not be employed for quadrature measurements such as for the comparison between resistance and capacitance standards. In these bridges, the balance condition can be expressed as $RC\omega = 1$. Traditional bridges use sine wave sources with low harmonic content and filters can be used to improve the signal to noise ratio at the fundamental frequency ω, which is left unaffected by the filter. When using square waves, the amplitude of the odd harmonics 3ω, 5ω, ..., $n\omega$ relative to the amplitude of the fundamental decreases linearly with n. Although the impedance of the resistance standard is largely independent of frequency, the impedance of the capacitance standard follows $|Z| = (C\omega)^{-1}$. As a result, quadrature bridges driven by square waves with a perfect balance at the fundamental frequency show a significant imbalance at these odd harmonics. The resulting comparatively large amplitudes at the input of the detector limit the uncertainty that can be reached

[1] J. Lee, J. Schurr, J. Nissilä, L. Palafox and R. Behr, "The Josephson two-terminal-pair impedance bridge," Metrologia, 47 (2010), pp. 453-459.

for the “zero” amplitude at the fundamental frequency to parts in 10^6. In order to reach uncertainties two orders of magnitude smaller, PTB started the development of pulse driven Josephson impedance bridges, primarily for quadrature measurements. Pulse driven Josephson arrays are routinely used to generate sine waves with very high spectral purity and would therefore be free from these problems. At the same time, it was decided to combine the development of pulse driven Josephson impedance bridges with the operation of these arrays in a cryocooler. This quadrature bridge, was successfully completed by the end of the project and a capacitance standard of 10 nF was measured relative to a Quantum Hall Resistance standard operated at a frequency of 1233 Hz in a direct *R:C* comparison. This preliminary measurement showed an uncertainty of one part in 10^7 and also identified areas of improvement that will be carried out after the end of the project.

SP has developed an automated Josephson impedance bridge based on programmable Josephson voltage standards, but using stepwise approximated sine waves instead of square waves [6], [23]. PTB provided the Josephson arrays for the bridge and further assistance through intensive discussions during the development phase. The bridge was constructed for the comparison of impedance standards, i.e. the ratio of capacitors, inductors and resistors, of impedance values > 1 kΩ. Stepwise approximated sine waves synthesised with these voltage standards have an intrinsic error that is proportional with frequency. The error is small and can be handled at low measurement frequencies but increases with frequency. The bridge at SP is therefore developed for measurements below 400 Hz.

Conventional impedance bridges based on inductive voltage dividers (IVDB) can compare impedance standards, for example the ratio of two capacitors, with very low uncertainty from 400 Hz to 10 kHz. Contrary to Josephson impedance bridges, conventional bridges have the disadvantage of a gradually reduced accuracy below 400 Hz. The measurement principle for the Josephson impedance bridge at SP is to transfer this very good uncertainty of an impedance ratio determined with a conventional bridge measurement above 400 Hz (typically one or a few kHz) down to low frequencies (10 Hz – 400 Hz). This is reached with a measurement method developed for the Josephson impedance bridge [23] (labelled frequency dependence method (FDM) in Figure 2) where the intrinsic error is determined and corrected for via the frequency dependence of the error.

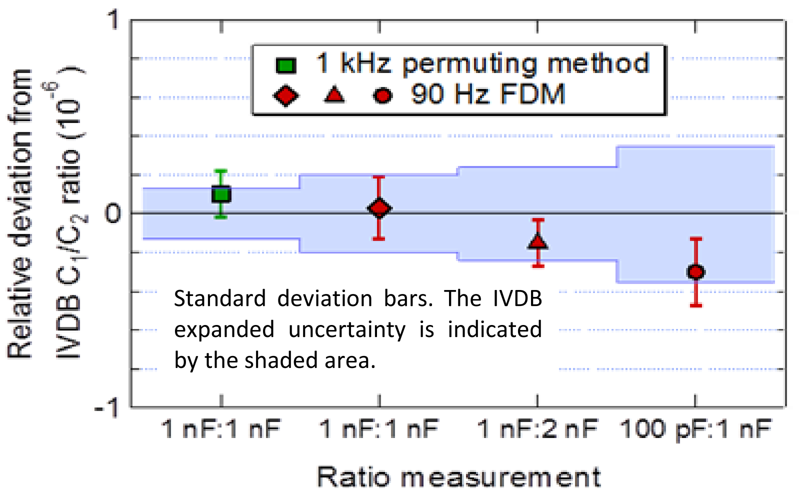

Figure 2 Comparison of the permuting method with a conventional IVD bridge and the frequency dependent correction method (FDM) for different capacitance ratios

The main advantages with Josephson impedance bridges compared to IVDBs are i) the possibility of having better measurement uncertainty at low frequencies, ii) a relatively simple automation and iii) maintained accuracy at arbitrary ratios and phase angles. The Josephson impedance bridge at SP has reached two of these objectives. The bridge is automated and the measurement uncertainty for low frequency measurements has been improved. We also expect improved measurement uncertainties at arbitrary ratio of impedance standards and phase angle differences in the impedance plane but further measurements are needed to confirm this.

Figure 2 shows a comparison of measurements for different capacitance ratios obtained with the Josephson impedance bridge developed by SP and an IVDB. Each point on the graph is the average of more than 4 measurements on different occasions; the Josephson impedance bridge measurements were performed using the FDM measurement method. An alternative measurement method (permuting method) can be used when the two standards under comparison have the same nominal value. This method can be used at frequencies above 400 Hz. Figure 2 shows also a 1 kHz ratio measurement for comparison.

The comparison in Figure 2 gave agreements within the measurement uncertainties. As expected the Josephson impedance bridge measurements have lower uncertainties at 90 Hz compared to the conventional IVDB. The Josephson impedance bridge expanded uncertainty for the 100 pF:1 nF measurement was below 0.3 x 10^{-6}.

The performance of the Josephson impedance bridge has also been validated in the first ever comparison of Josephson impedance bridges. SP researchers transported their Josephson impedance bridge to PTB in June 2015 and the two bridges were compared using capacitance standards. This comparison showed very good agreements within the expected uncertainties [24].

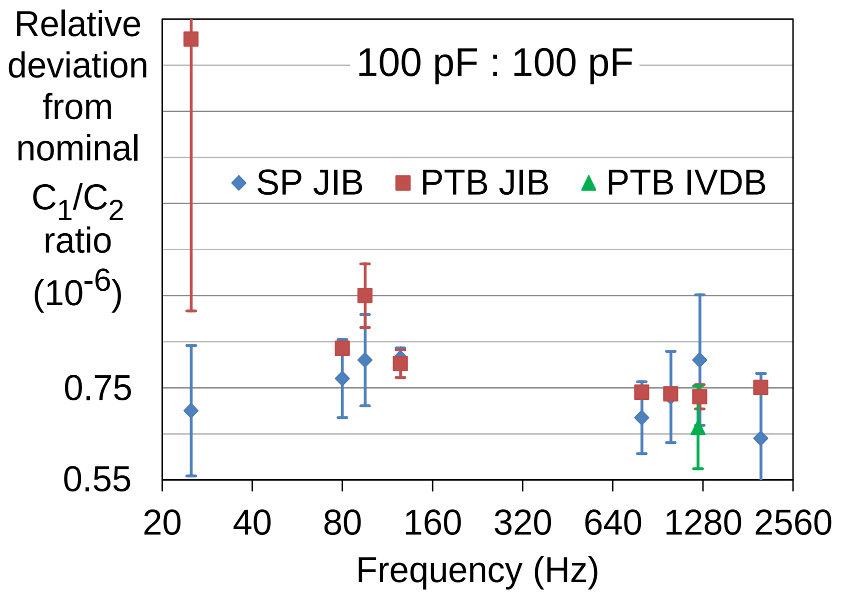

Figure 3 Comparison of the SP and PTB Josephson impedance bridges for the 100 pF:100 pF capacitance ratio.

Figure 3 shows one result from the PTB – SP comparison of the two Josephson impedance bridges. In the range 80 Hz to 2 kHz this example from the comparison shows an excellent agreement of 0.07 x 10^{-6}. The figure shows also one conventional inductive voltage divider bridge (IVDB) measurement.

3.1.2 Simpler setups for Josephson impedance bridges

Both CEM and VTT undertook the simplification of the setup used in the proof-of-concept experiment that introduced Josephson impedance bridges. VTT targeted the operation of two programmable Josephson arrays in a cryocooler to decouple these bridges from the availability of liquid helium. CEM pursued the concept of using a single Josephson array to generate both waveforms required for an impedance bridge. Significant progress has been achieved in both directions, although the challenges have proved to be more demanding than anticipated and neither of the impedance bridges could be validated in the lifetime of the project.

3.1.2.1 Josephson impedance bridge based on a cryocooler

The first Josephson impedance bridges (*see footnote 1*) were based on cooling two programmable Josephson arrays in two separate liquid helium dewars. Disadvantages of this approach are for example dependence on liquid helium (expensive and prone to availability problems) and long cables leading to non-idealities in the measurement. VTT took the challenge to investigate if a Josephson impedance bridge could be based on a cryocooler to cool the voltage standard components down to 4 K operating temperature without any liquid helium. This was known to be challenging, since researchers had earlier reported problems in extracting heat from the Josephson junctions to the cold head of the cryocooler via solid metallic contacting. PTB provided Josephson junction arrays and sample holders with a new design with improved thermal contacts. After a set of unsuccessful trials with a dry cryostat VTT redesigned a cryostat which combines the advantages of liquid helium as a heat transfer medium and a cryocooler with compact dimensions.

Figure 4 depicts the design of a cryostat with in-built helium liquefier. It describes a system where condensing copper elements and a helium liquefying sleeve have been mounted to a pulse tube cryocooler [4]. Helium gas from an external reservoir is supplied into the liquefier at a constant pressure (1 bar) and after initial cool down of the gas, helium starts to condense on the bottom of the sleeve. The Josephson junction arrays are located below the sleeve bottom and the copper enclosures around them become filled with liquid He via separate tubing. The evaporating helium is returned to the upper part of the liquefier to be recondensed.

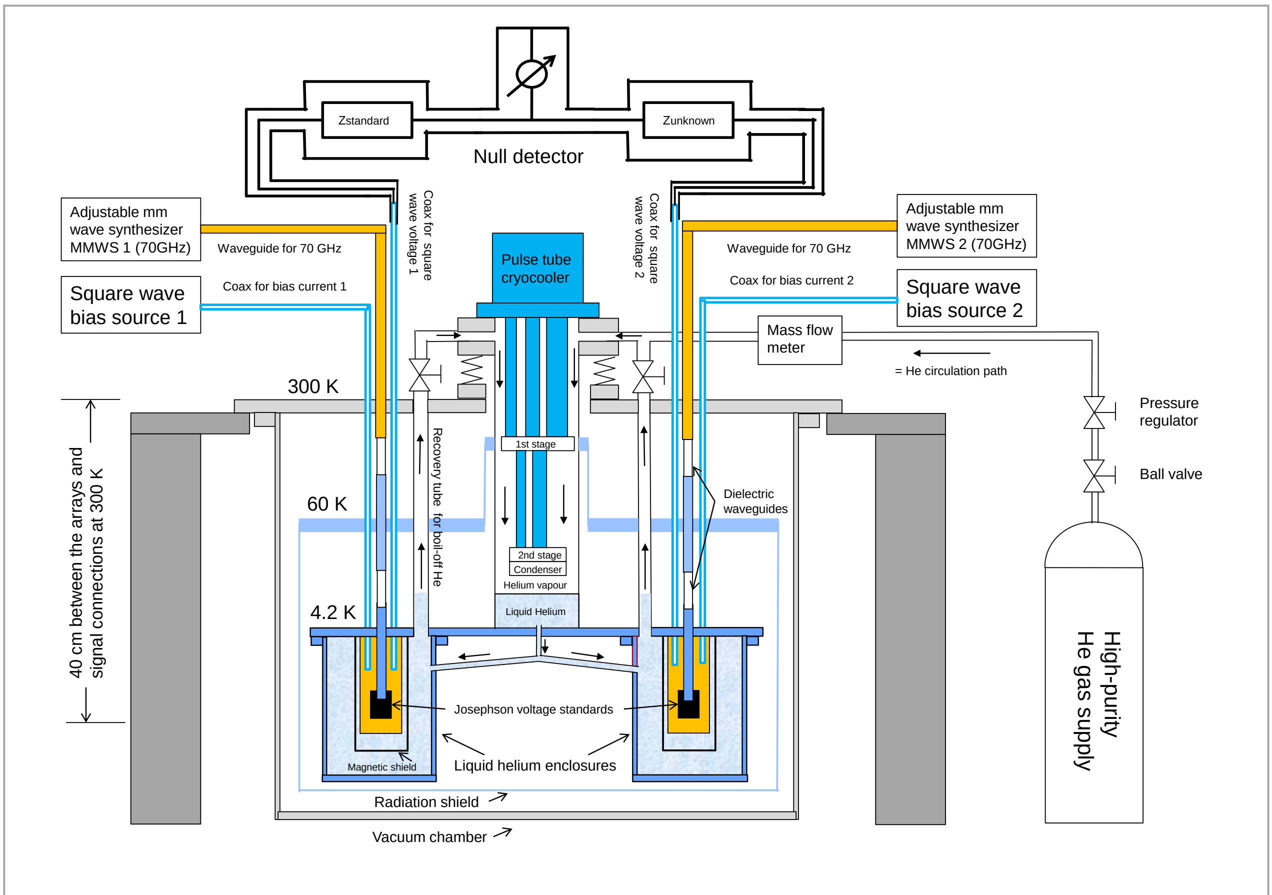

Figure 4 Schematic diagram for the VTT Josephson impedance bridge.

The relatively compact dimensions of the cryostat should allow using much shorter cables than typical when using liquid He dewars. This is expected to improve the performance of the Josephson bridge. Unfortunately, the setup could not be completed by the end of the project. In the future, besides bringing the Josephson bridge into operation, an interesting option would be to try to integrate a quantum Hall standard (likely a graphene-based one) for impedance into the same experimental space.

3.1.2.2 Development of a Josephson impedance bridge using a single array

CEM developed a new impedance bridge based on a single array, as a simpler and cheaper alternative to multiple array bridges being developed in other NMIs.

A single array bridge has a fundamental limitation due to the impossibility of exactly balancing the bridge because only ratios of integer numbers can be generated. In order to overcome this limitation and be able to measure in-between impedance ratios, a method of calibration of phase sensitive detectors (PSD's) has been developed. It is based on a phase controlled ac voltage source and a high accuracy ac-dc resistive divider. The first results show that it is possible to calibrate this type of instruments with uncertainties lower than 20 nV for the greatest unbalanced voltage in the single array bridge (½ Josephson step or about 70 μV). For the very first time, it is possible to calibrate PSD's with this order of uncertainty. This has made possible, in particular, to characterise the behaviour of these instruments in phase, showing a greater dependence on frequency than expected [32].

A first simple version of the single array bridge was set up as a two terminal-pair bridge during a secondment to PTB. PTB provided a new programmable Josephson array for these investigations and also helped CEM modify the cryoprobe in order to optimize the transition times between quantized voltage levels. First measurements showed an agreement of the order of parts in 10^7 in the comparison of capacitors against a high accuracy commercial bridge [31].

A second, four terminal-pair, version of the bridge has been developed and set up, but no measurements could be made in the term of the project, due to the delayed reception of fundamental components. VTT MIKES provided the electronics for biasing the two parts of the Josephson array individually.

3.1.3 Conclusion

Josephson impedance bridges have been studied and extended to resistance ratios beyond 10 kΩ: 10 kΩ, to capacitance ratios and to quadrature measurements (*R:C* comparisons). Considerable advances have been achieved in the understanding of this type of impedance bridge, in what situations its performance is comparable to previous state-of-the-art impedance bridges and what the limitations to their performance are. The first ever intercomparison of Josephson impedance bridges, between PTB and SP, has been carried out in the project. Also for the first time, a Josephson impedance bridge has been able to measure a capacitance standard relative to the Quantum Hall resistor operated at 1233 Hz directly. Furthermore, the pulse driven Josephson impedance bridge used by PTB for these measurements was operated in a cryocooler.

The Josephson impedance bridges developed in the project are partially or fully automated. Compared to traditional impedance bridges, the burden on the operator has been considerably reduced, simplifying impedance calibrations at the top level of uncertainty.

3.2 Digital bridges

The second objective in the project was "to develop automated impedance ratio bridges and perform proof-of-concept tests at an uncertainty level of 10^{-7} covering the frequency range from 10 Hz to 20 kHz."

Beyond the results for automated Josephson bridges reported in the previous section, several digital impedance bridges have been developed within the project. Digital means that the electrical signals, voltages and currents in the bridges are generated by digital synthesis of the waveforms.

The bridges are intended to cover the audio frequency range between 20 Hz and 20 kHz, and to be able to measure impedances with arbitrary values and arbitrary phase angles over the entire complex plane, with primary accuracy: that is, an uncertainty orders of magnitude lower than commercial impedance meters, and therefore suitable for their calibration through appropriate impedance transfer standards. This is the frequency range of interest for most users such as calibration laboratories for the dissemination of impedance units.

The motivation for developing several bridges stems from the need to compare competing technologies and bridge topologies. Digital bridges can be broadly classified in *digitally-assisted* bridges, which include electromagnetic components (transformers, inductive dividers, current comparators) that provide the necessary accuracy; and fully-digital bridges, where the bridge accuracy is directly dependent on the accuracy of the mixed-signal electronic components (digital-to-analogue converters, analogue-to-digital converters) that generate and measure the electrical signals in the bridge network.

Impedance standards can be defined as two terminal-pair or four terminal-pair entities, depending on whether shared or separate connections are used for carrying current and voltage into and out of the standard. The two-terminal pair definition of impedance is suitable for medium- to high-value impedances, and the bridges which adopt such definition are relatively simpler. The four terminal-pair definition makes negligible the contribution to the measurement uncertainty due to the measurand definition, and is suitable for any nominal value of impedance. On the other hand, achieving a full four terminal-pair definition complicates the bridge network and requires a number of auxiliary balances in the bridge to perform a measurement.

3.2.1 Signal sources for digital impedance bridges

Digitally-assisted and fully-digital impedance bridges are modular in nature. One important module is the signal source, which in fully-digital bridges is also the provider of the bridge accuracy. An important activity within the project was the development of new sources, achieved by two university partners from Poland, the Silesian University of Technology (SUT) and the University of Zielona Góra (UZG) and the characterization of commercial sources, in collaboration with a Aivon Oy, a Finnish industry stakeholder. The development of two separate digital signal sources (DSS) responded to the different requirements for the types of digital bridges developed in the project. Both DSS allowed the digital bridges in the project to achieve performance levels beyond the possibilities of commercial DSS, such as isolation between channels, superior stability in amplitude and phase, and carrying out changes in amplitude and phase values without step changes. As part of the development, UZG also built a test system for testing parts of its source and the complete DSS. This test system was validated during a one week visit to GUM. The prototype of the medium stability 7-channel DSS from UZG was then tested with the validated test setup at UZG, at GUM and during a visit to CMI and at INRIM. These tests provided valuable input for the final version of the 7-channel source, which was again tested at GUM and INRIM. These tests resulted in INRIM committing funds from its national programme to purchase its own version of this 7-channel DSS for future work in impedance.

SUT developed a high stability 2-channel DSS, after an initial exhaustive evaluation of commercially available signal generators. The evaluation was carried out during guest working periods at VTT, METAS – together with Trescal – and INRIM. The results of this evaluation influenced the design of the prototype 2-channel high stability DSS from SUT. During its testing, the influence of the output impedance on the measurements became larger than anticipated and delayed the completion of the final version of the DSS. However, the performance targets of 0.1 µV/V for amplitude adjustment and 1 µradian resolution for the adjustment of the relative phase between the two signals have been comfortably met. Trescal decided to commit funds from their national programs in order to buy an additional version of the SUT source for future use in their digital bridges.

3.2.2 The INRIM current comparator, three-arm digitally-assisted bridge

The most accurate current ratio bridges are based on the current comparator (CC) principle. In a CC, a ferromagnetic core defines a closed flux path of high permeability, and the currents to be compared flow through windings linked to the core. The resulting magnetomotive force generates a magnetic flux in the core: in the ac regime, the flux is sensed by a suitable detection winding. Whenever the detection winding sees no flux, the flux from the input currents is compensated; in the case of two currents, $0 = n_1 \cdot I_1 + n_2 \cdot I_2$, $(n_2/n_1) = (-I_1/I_2)$ to a very good approximation. In a CC impedance bridge, the currents being compared by the CC are generated by the impedances under comparison, when excited by the same voltage, so $(n_2/n_1) = (-Z_2/Z_1)$. Typical CC bridges have *two* main arms and compare like impedances (*R:R*, *C:C* or *L:L*).

Within this project, INRIM introduced the concept of *three-arm* current comparator impedance bridge, where three unlike impedances are involved in the measurement. The measurement outcome provides a relation between the complex values of the three impedances. The aim of the three-arm CC bridge is the calibration of impedances having arbitrary phase angles, with traceability to pure impedances (that is, having phase angles near 0 or +/- 90 degrees) as are the resistance and capacitance scales maintained in national metrology institutes and calibration centers.

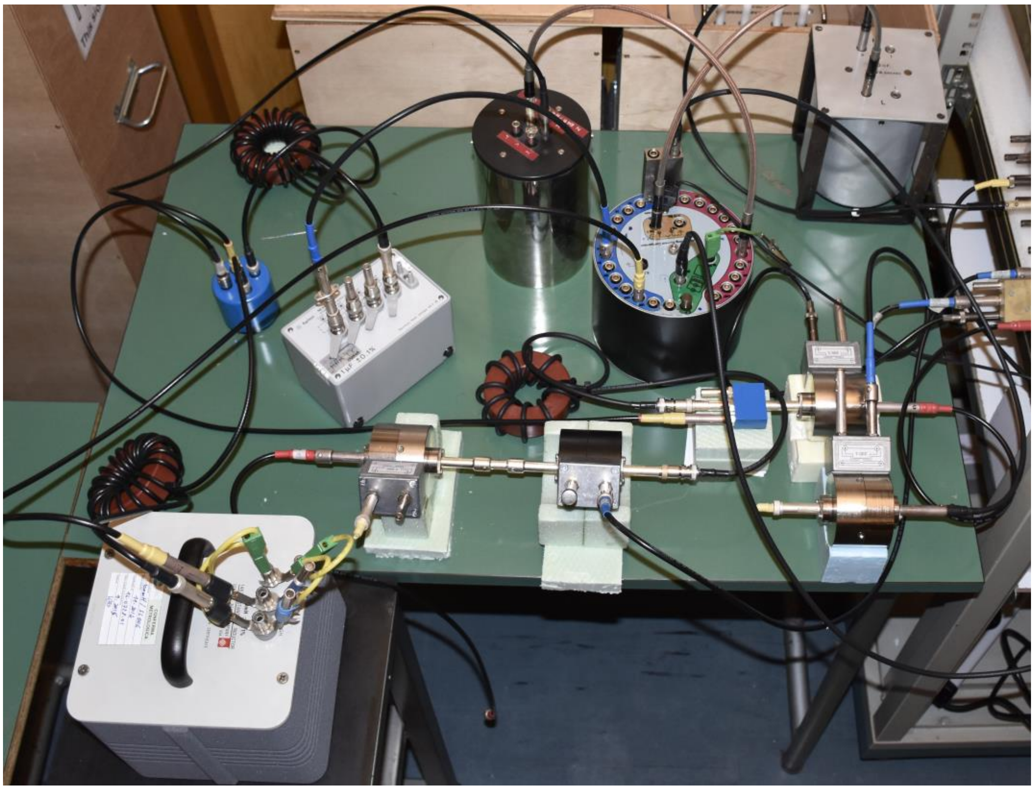

Figure 5 The three arm, four terminal-pair digital current comparator bridge from INRIM.

In the course of the project, the bridge evolved from a simpler version, where the three impedances under comparison were defined as two terminal-pair standards, to a more complete version which implements an approximate four terminal-pair definition of the impedances being compared (Figure 5). The bridge maintains a very simple network, and can be balanced easily. The approximate definition allows accurate measurements in the audio frequency range with impedance magnitudes in the 10 Ω - 1 MΩ range, with a relative accuracy in the parts per million (ppm) range to be performed.

The most important components of the bridge are:

- the current comparator, which was constructed for this purpose at INRIM;
- the digital source. Two different sources have been tested with the bridge: the first one is based on a commercial DAC board and custom amplifier/filters. The second one was realized for this purpose within the project by UZG as a specific deliverable.
- detector and injection/detection transformers, which are standard components in impedance metrology laboratories.
- the control program, which includes a dedicated high-speed bridge equilibrium strategy.

An important development is the extension of the bridge to the four terminal-pair definition. The typical approach would have required a very complex network and needed about 7 digital source channels and a similar number of detectors; the automation of its balancing process would also be matter of research. The approximate four terminal-pair definition used in the bridge follows the principle of maximum network simplicity and allows to employ a 3-channel source instead. It is not limited to the particular topology of the three-arm bridge developed in the project, but is more general and can be adopted in other digital bridges too, including Josephson bridges.

The bridge has been extensively tested, first in a two-arm configuration by measuring the ratio of calibrated AC resistance standards developed within the project, and then by calibrating standards developed within the project having positive and negative phase angles versus the Italian national standard of ac resistance and capacitance.

3.2.3 The INRIM two terminal-pair, fully-digital bridge

INRIM has developed a coaxial fully-digital voltage ratio bridge, suitable to perform comparisons between two impedance standards having arbitrary ratio (in magnitude and phase) and defined as two terminal-pair standards.

The schematic diagram of the bridge, shown in Figure 6, is of outmost simplicity and includes a two-channel digital source, the standards being compared, a detector and coaxial current equalizers. Equilibrium is achieved automatically by reprogramming the magnitude and phase of the sine wave generated by one channel of the source.

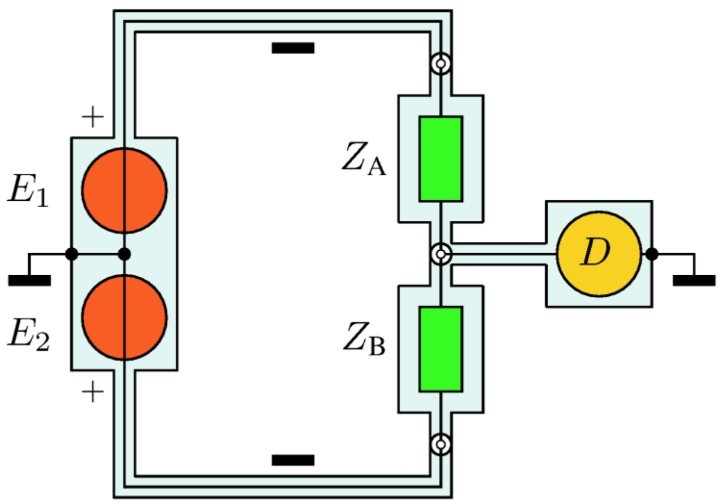

Figure 6 The electrical schematics of the INRIM fully-digital bridge, showing its extreme simplicity. The two voltage generators represent the two output channels of the digital source employed.

In the course of the development, the bridge network has been modelled in detail. The model shows that if the bridge is operated by performing two measurements in sequence, by exchanging the impedances being compared, and using as ratio estimate the complex geometric mean of the two bridge readings, several systematic errors caused by the source properties can be corrected.

In particular, the model shows that even a significant but setting-independent gain tracking error between the source channels is totally compensated by the exchange measurement procedure. On the other hand, the error caused by the non-zero output impedance of the channels is not compensated, but a correction can be derived from the model if the source is characterized.

The bridge, shown in Figure 77, includes a commercially available source, developed by a project stakeholder in consultation with VTT. The amplitude and phase of each channel are adjusted by recalculating and uploading new waveform samples; the voltage ratio is calculated from the Fourier expansions of the quantized waveforms. The bridge balance is automated, and the total adjustment time is typically less than one minute. An expression of the bridge measurement uncertainty was carried out in the context of the supplement 2 of the guide to the expression of uncertainty in measurement. The base accuracy is in the ppm range.

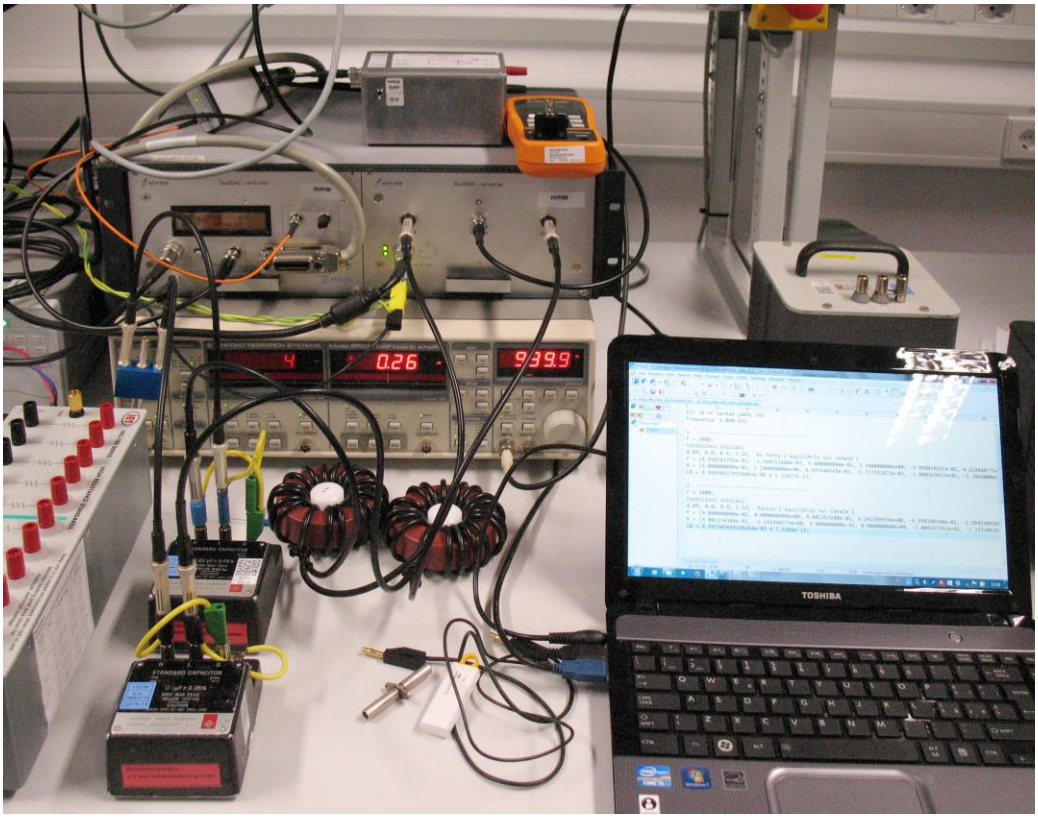

Figure 7 The INRIM fully digital bridge. Picture taken during the on-site demonstration at esz AG.

The bridge was extensively tested with impedance standards available at INRIM, and then with the special standards developed by TUBITAK. Measurements were performed in the frequency range 159 Hz – 15920 Hz. The limitations of the source have been identified by the measurements performed, and will enable to improve the source properties.

The superposition in range of the measurement bridges developed by INRIM made possible to mutually validate the performance claims of each bridge, by performing internal comparisons, both with traditional impedance standards (“pure“ resistors, capacitors or inductors) and with the specially-developed impedance ratio and phase standards built by TUBITAK.

3.2.4 The CMI four-terminal-pair, fully-digital bridge

Two-terminal-pair bridges, where reference sources have to energize the network consisting of the impedances under comparison and the connecting cables, suffer from systematic errors and limitations of the bridge usability to mid-range and high-range values of impedance magnitude. Therefore, CMI extended two-terminal-pair bridge to four-terminal-pair type, where the measurement current flowing through the impedances under comparison is energized from auxiliary sources, as shown in Figure 8. Such a circuit arrangement allows performing calibrations of low-value standards with improved accuracy, while maintaining high accuracy for mid-range and high-range valued impedance standards too.

Introduction of additional sources in the bridge places demand on more complex balancing procedure of the bridge. Due to the self-balancing procedure implemented in the control program and automated switching of the null detector between measurement points, the whole balance of the bridge is performed within a few minutes, while base accuracy on the ppm level is maintained.

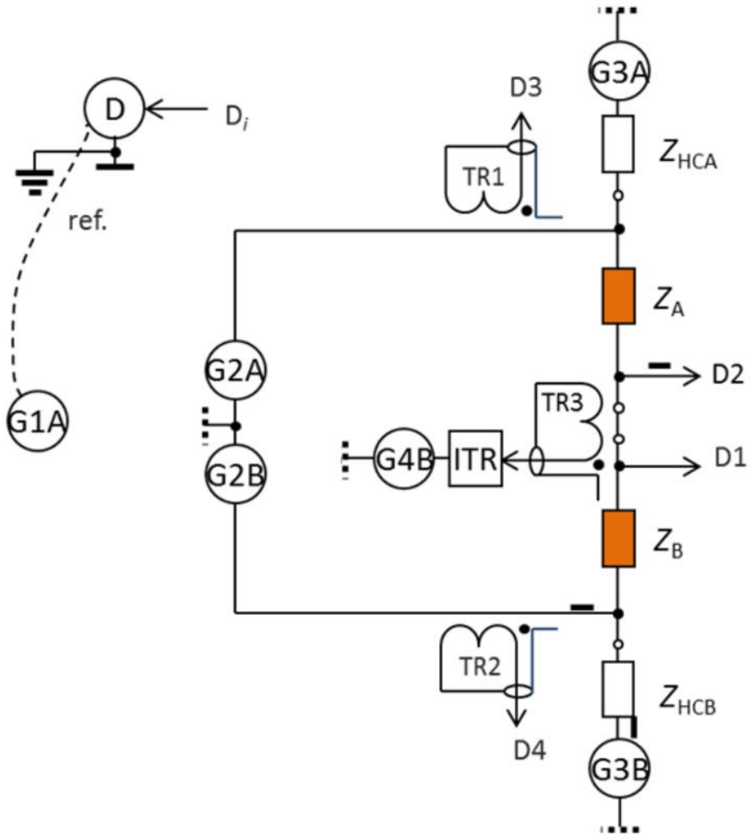

Figure 8 Schematic diagram of the reconfigurable CMI bridge when set up as a fully digital four terminal-pair bridge to compare Z_A and Z_B.

The bridge was designed as modular and reconfigurable and it can be easily rebuilt to a digitally assisted bridge, for a reduced region of the complex impedance plane, but the accuracy is improved for those predefined ratios. The fully digital bridge, as shown in Figure 10 consists of isolated sources, injection and detection transformers, a coaxial multiplexer developed at CMI and a commercial null detector equipped with isolated synchronization. Both internal or external reference clock signals and voltage references can be used during operation of the bridge. The bridge is designed for measurements in the impedance range $|Z|$ = 10 Ω – 1 MΩ.

The bridge and control software (Figure 9) have been designed following a modular concept. As a result, different types of sources, such as those developed by SUT and UZG in the project or a custom one built at CMI outside of the project, can be used in the bridge. Extensive testing of sources and bridge parts during the project led to overall improvements of the hardware used.

As shown in Figure 10 the four-terminal-pair bridge was tested by means of comparison measurements of impedance standards, which reference values were derived from reference measurements with other equipment at CMI or from their calculable frequency dependence. Then, nearly pure impedance standards and passive impedance standards for intermediate angles developed by TUBITAK were used for testing the bridge capabilities for impedance magnitude ratios varying from 0.07:1 up to 15:1.

In conclusion, a new four-terminal-pair fully digital bridge for the calibration of impedances with arbitrary ratios and phase angles was developed together with control software; sources of uncertainties were identified and a procedure for evaluation of the uncertainty budget was implemented. This bridge operates in the frequency range from 20 Hz to 20 kHz and can measure impedances in the range $|Z|$ = 10 Ω – 1 MΩ with a maximum current of 200 mA. The accuracy varies between just under 1 ppm and a few parts in 10^5 for the extreme ratios 0.07:1 and 15:1 in the fully digital configuration. As a digitally assisted bridge, flexibility for the ratio and for the phase angle between the impedances being compared is sacrificed for a lower uncertainty in the range between 1 ppm and parts in 10^8.

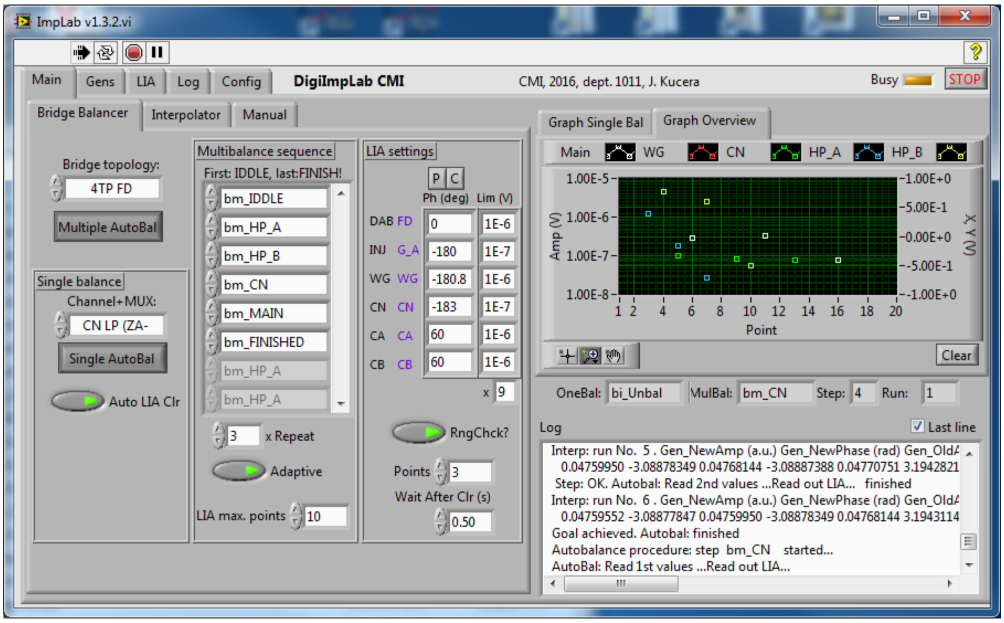

Figure 9. Example of balancing program run, where sequential balancing is adaptively performed on multiple balancing conditions to achieve overall accuracy of the measurement better than 1 ppm.

Figure 10. Four terminal-pair fully digital bridge operating at CMI.

3.2.5 Conclusion

Digitally assisted and fully digital bridges have been completed and validated not only for “pure” resistance, capacitance or inductance standards, but also for intermediate values and phase angles far away from these three axes. These bridges are modular in design, as shown for example by the CMI bridge, which can be configured as a digitally assisted bridge or a fully digital bridge by removing a few components. In common with the fully digital bridges developed by INRIM, a base uncertainty of parts in 10^7 over the frequency range between 159 Hz and 16 kHz has been achieved. Digitally assisted bridges have achieved uncertainties in the range between parts in 10^6 and 10^8, depending on the magnitude of the impedances being compared.

The digital impedance bridges developed in the project are partially or fully automated. Compared to traditional impedance bridges, the burden on the operator has been considerably reduced, simplifying impedance calibrations at the top level of uncertainty. The performance of the novel digital bridges for intermediate phase angles has been validated using the standards built for this purpose by TUBITAK. The bridges from CMI; INRIM and METAS showed very good agreement and the results of this novel intercomparison will be published in the coming months. As opposed to the situation before the project, these novel bridges can be built exclusively from commercially available equipment.

3.3 Extension of the impedance scales

Both Josephson and digital impedance bridges can extend the impedance scales with their novel measurement capabilities. During the development phase of these novel bridges, their performance was routinely validated against the existing impedance bridges present at the NMI where the development took place. However, no impedance standards with adequate performance were available at the start of the project in order to establish the performance previously unavailable. As a result, a number of impedance standards were developed by TUBITAK. Six pairs of resistance standards were built for intermediate resistance ratios and six temperature controlled impedance standards for intermediate phase angles were also constructed. Two additional activities in response to the needs identified at the start of the project were also directed at fulfilling the third objective: “to extend the impedance scales to intermediate values, within the range for |*Z*| between 10 Ω to 1 MΩ, along the axes (*R*, *L* and *C*) to intermediate phase angles and towards values demanded by nanotechnology (capacitances below fF)”: the impedance simulator and the development of capacitance standards for very small capacitances, as demanded by nanotechnology.

3.3.1 Passive standards for intermediate ratios and phase angles

After initial discussions among the partners, the values for the intermediate resistance ratio standards and for the impedance standards with phase angles of – 60 °, -30 °, +30 ° and +60 ° were decided. TUBITAK then started not only the procurement of the electronic components required, but also the construction of the enclosures for the impedance standards and the temperature controllers for the intermediate phase standards.

The capability to measure intermediate ratios without loss of uncertainty can be demonstrated by measuring resistance ratios different from the traditional 1:1, 1:2, and 1:10. The selected ratios were 1:3, 1:7 and 1:15, with two “ratio standards” built for each ratio (see Table 1). Each of the ratio standards allowed access to both resistances as a four terminal-pair impedance standard, as can be seen in Figure **11**.

Table 1 Resistance values in the ratio standards.

Ratio	R1	R2
1:3	1 kΩ	3 kΩ
	10 kΩ	30 kΩ
1:7	1 kΩ	7 kΩ
	10 kΩ	70 kΩ
1:15	1 kΩ	15 kΩ
	10 kΩ	150 kΩ

Figure 11 One of the six ratio standards built by TUBITAK.

The standards for intermediate phase angles were built as combinations of a resistor and a capacitor, for negative phase angles, or a resistor and an inductor, each accessible as a four terminal-pair impedance. Six temperature controlled negative phase standards as given in Table 2 were constructed by using ceramic capacitors with NPO dielectric and Vishay S102 model resistors. The stability of the temperature controlled system is better than 5 mK. The values for the components in the standards are listed in Table 2 and one of the three enclosures can be seen in Figure 12 with its associated temperature controller.

Table 2 Values for the negative phase standards

Phase	C	R
-30 °	1 nF	91.9 kΩ
-30 °	10 nF	9.2 kΩ
-60 °	27 nF	10 kΩ
-60 °	2.7 nF	102.7 kΩ
-60 °	274 pF	1 MΩ
-30 °	92 pF	1 MΩ

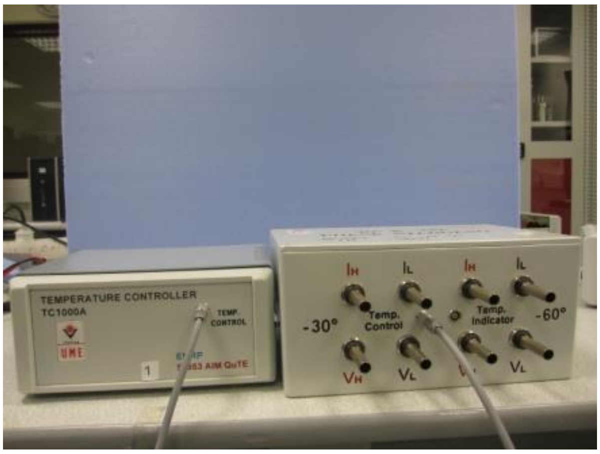

Figure 12 Temperature controlled negative phase standard

Six temperature controlled positive phase standards as given in Table 3 were constructed by using QuadTech 1482 type Standard inductors and Vishay S102 model resistors. The stabilities of the temperature controlled system were better than 5 mK.

Phase Standards with 1 H and 10 mH were constructed by TUBITAK. No commercial components with suitable temperature coefficient could be found for the 100 mH inductor, so a temperature controlled inductance standard from INRIM was used as phase standard. TUBITAK made two resistors to add to this inductor to turn it as phase standard. One of the phase standards for positive phase angles is shown in Figure 13.

Table 3 Values in the positive phase standards

Phase	L	R
+30 º	1 H	10 kΩ
+60 º	1 H	3.6 kΩ
+30 º	10 mH	10 Ω
+60 º	10 mH	36 Ω
+30 º	100 mH	361 Ω
+60 º	100 mH	1088 Ω

Figure 13. Temperature controlled negative phase standard

3.3.2 Impedance simulator

The classical calibration procedure of commercial LCR-meters is a manual, time consuming task that requires the use of a large set of different calibrated impedance standards. Moreover, only a small fraction of the measurement capabilities of the LCR-meter is tested since the reference standards have usually decadic value and phase angles close to -90 degrees (capacitors), 0 degree (resistors) or 90 degrees (inductors).

To improve and automate the calibration procedure of LCR-meters, an impedance simulator, called iSimulator, has been developed [1], [4]. The basic principle of the iSimulator is to independently supply the current and the voltage to the LCR-meter using external voltage sources. By adjusting the amplitudes and the relative phase of the sources, the synthesized impedance can cover the entire complex plane.

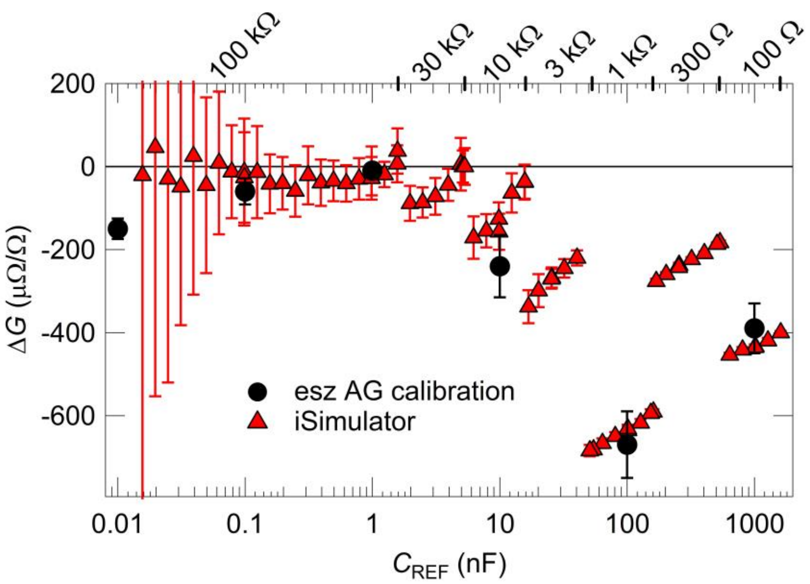

Figure 14 Gain error of commercial LCR-meter (Agilent 4284A) measured at 1 kHz along the -90 degrees axis of the complex plane (capacitance scale). Circles: using the artefact-based procedure of esz AG. Triangles: using the iSimulator. The error bars correspond to *k*=1. The different impedance ranges of the LCR-meter are indicated on the top of the figure.

The fully automated impedance simulator developed by METAS can be used to simulate impedances ranging from 1 Ω to 10 MΩ, at arbitrary phase angle, over a large frequency range (from 50 Hz to 20 kHz) [21], [34].

The validation of the iSimulator has been performed during an on-site demonstration. The measuring setup has been moved to a calibration laboratory (esz AG Calibration & Metrology, Eichenau, Germany) and used to calibrate an LCR-meter (model Agilent 4284A) at a frequency of 1 kHz. The results have been compared to those obtained using the calibration procedure of esz AG (using capacitance standards) and to the values from the

INRIM fully digital bridge that was being tested at the same time in the same laboratory and are presented in Figure 14.

The difference between the two calibration methods is smaller than the combined standard uncertainty (k=1). That clearly demonstrates the ability of the iSimulator to perform calibration of LCR-meters. Additional features that can be observed in Figure 14 are the discontinuities in the gain error measured with the iSimulator. In fact, these discontinuities appear at the transition between the various ranges of the LCR-meter. The range transitions are also represented in the top part of Figure 14.

An important point to note is that some ranges (300 Ω, 3 kΩ and 30 kΩ) are simply not tested using the traditional method based on capacitance standards while the use of the iSimulator allows the characterization of every range of the LCR-meter.

3.3.3 Development of a programmable standard of ultra-low capacitance values

To extend the range of traceable capacitance measurements to very small values, several capacitance standards have been developed (Figure 15) at LNE using different techniques, namely Zickner air capacitors and lithographed capacitors. A digitally programmable coaxial multiplexer has also been developed, which together with these capacitors is capable of generating a set of predefined values ranging from 10 aF to at least 100 fF.

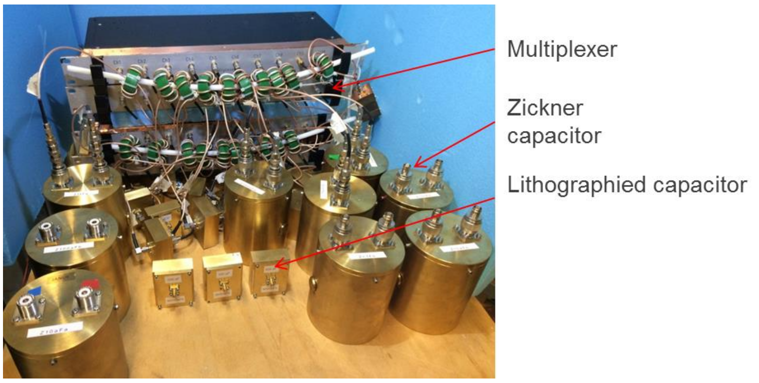

Figure 15. The digitally programmable capacitance standard which incorporates capacitors (from 10 aF to 100 fF) together with a 20-channel coaxial multiplexer

The Zickner air capacitors were constructed by interposing a screen with a small predefined aperture between its active electrodes. The aperture in the screen controls the amount of electric field lines between these electrodes, thus defining the value of the capacitance standard. At LNE, Zickner air capacitors were developed with a plane geometry. Physical dimensions of the capacitors and the diameter of the aperture were determined by finite element modelling. A micrometric screw was integrated on one of the active electrodes in order to achieve a fine adjustment of the nominal value of the capacitor. The two electrodes and the electrical screen were separated by ceramic rings. These capacitors were entirely fabricated in brass, which facilitates their thermal stabilization during the measurements. Finally, capacitors of values 10 aF, 100 aF, 1 fF, 10 fF and 100 fF have been fabricated by this technique.

Capacitance standards of relatively smaller sizes, facilitating their integration, have been developed by optical lithography. Like Zickner air capacitors, the geometry of these capacitors is also determined by finite element modelling. These capacitors have been fabricated on a fused silica substrate where the patterns of the electrodes and a part of the electrical screens have been deposited by gold pulverization on each face of the substrate. The substrate was then enclosed in a brass shield. The annular design permits only few field lines to interact between the electrodes, thus defining the small value of the capacitor. Several capacitors of values 10 aF, 20 aF, 50 aF, 100 aF, 200 aF, 500 aF, 1 fF, 2 fF, and 5 fF have been developed using this technique.

A multiplexer has been designed in order to be able to generate every parallel combination of the Zickner and lithographed capacitors fabricated and connected to it. It possesses 20 channels and can then connect up to 20 capacitors in parallel. Due to its architecture, the multiplexer has minimum influence on the capacitance generated. The system of multiplexing consists of multi-layered printed circuit boards (PCB). Special care has been taken in the design and manufacture in order to minimize leakage and the cross capacitances. Each PCB is stacked in such a manner that the signal plane is covered by grounded planes almost from all the four sides in order to maintain a coaxial geometry, as far as possible, for the signals passing through the multiplexer. Moreover, the multiplexing of each terminal (high (H) and low (L)) takes place on different PCBs, which reduces significantly the cross capacitances. The relays used are shielded and of latching type. So, once the commutation is done, the circuit piloting the relays is shortened and connected to the ground in order to limit the leakage current and to avoid further perturbations during the measurements.

The characterization of the programmable capacitance standard at 1 kHz was carried out with the LNE's two terminal pair capacitance bridge. It has been found that the multiplexer possesses very small and reproducible foot-print which could be easily corrected. This capacitance standard has been used to calibrate commercial capacitance bridges at 1 kHz with comparatively low uncertainties (<0.3 aF with the 20 channels connected). Three different units of a commercial capacitance bridge have been calibrated for their ranges below 100 fF using the programmable capacitance standard.

3.3.4 Verification of the novel impedance measurement capabilites

The Josephson and digital impedance bridges developed in the project allow the extension of primary impedance metrology to measurements of impedance standards having arbitrary magnitude and phase, with accuracy at the primary level and sufficient for the calibration of commercial impedance standards and meters, in the audio frequency range which is the most relevant for dissemination. The standards developed by TUBITAK were crucial for testing these novel measurement capabilities. At the same time, each partner in the project concentrated its efforts in one area, leading to combined progress much more quickly than could have been possible otherwise.

Intermediate ratios were tested by PTB and INRIM using the resistive ratio standards. Unfortunately, delays in the project prevented a full intercomparison of all Josephson bridges using these standards. Only the bridges of PTB and SP were operational during the lifetime of the project. These two Josephson impedance bridges, one using square waves and the other stepwise approximated sine waves, were compared using capacitance standards, as detailed in the first section. The comparison of the bridges showed excellent agreement and ratified the excellent uncertainties that Josephson impedance bridges can achieve for measuring capacitance standards below 400 Hz.

These very good uncertainties for capacitance measurements were also confirmed in a comparison with LNE. The frequency dependence of different temperature controlled capacitance standards was determined using an impedance bridge based on an IVD at LNE and a Josephson impedance bridge at PTB. LNE supplied the 10 pF and 100 pF fused silica standards, which were measured in the sequence LNE-PTB-LNE. For maximum stability, the standards were transported with their temperature control units switched on. Figure 16 shows the measurements for the 100 pF: 100 pF ratios as a function of frequency. The error bars show the combined uncertainty with a coverage factor of $k = 2$. The agreement of the frequency dependence was excellent.

A major extension to the impedance measurement capabilities in NMIs was for intermediate phase angles. As described above, new standards were required to verify this extension and were built by TUBITAK. Both sets of phase standards were measured by INRIM and METAS. After those measurements, the phase standards for negative angles were sent to PTB and the standards for positive phase angles to CMI. PTB tried to measure the standards using its Josephson impedance bridge with square waves, but these proved unsatisfactory for intermediate phase angles. Nevertheless, the measurements from INRIM, METAS and CMI showed very good agreement and will be submitted for a peer reviewed publication after the end of the project.

INRIM measured both the resistive standards for intermediate ratios and the positive and negative phase standards from TUBITAK. CMI and METAS also measured some of the phase standards standards from TUBITAKand the results validate the different bridges developed in the project for intermediate phase angles with a relative accuracy level of a few parts in 10^5 A peer reviewed paper after the project will report this first ever comparison for impedances with intermediate phase angles.

Outside of the resistance axis, the magnitude of an impedance depends on the measurement frequency. As a result, expressing the uncertainty of the bridge as a function of the impedances being compared becomes very difficult and demands advanced mathematical methods to cover the whole complex plane. INRIM has chosen METAS. MatLab.UncLib, which implements the Guide on Expression of Uncertainty

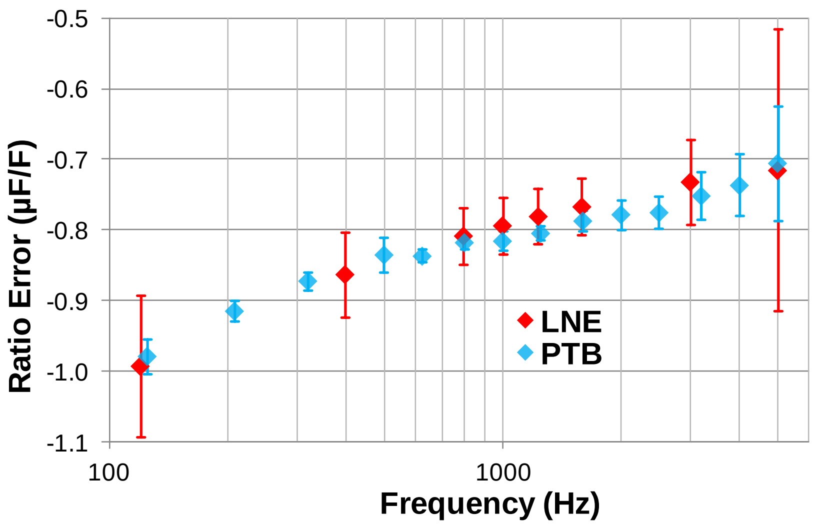

Figure 17. Measurement of the ratio between two 100 pF capacitance standards measured at LNE with an IVB based impedance bridge and at PTB with a Josephson impedance bridge.

Supplement 2 and allows uncertainty calculations in the complex domain, for the expression of uncertainty of its measurements. One example for the representation of the uncertainty is shown in Figure 17.

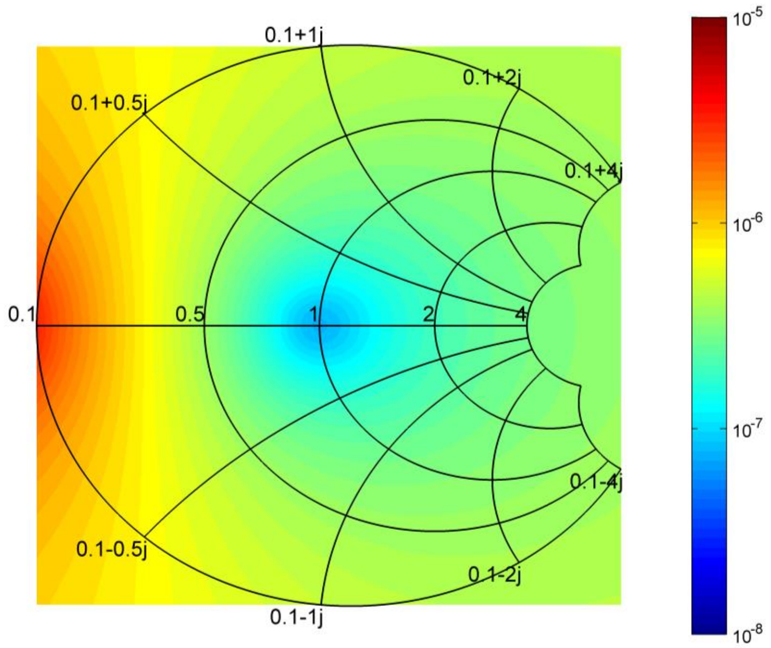

Figure 16 An example of uncertainty expression in the whole complex plane for the INRIM fully-digital bridge. The colour scale represent the measurement uncertainty as a function of the complex ratio between the impedance being measured, plotted as a Smith chart.

3.4 Summary of the results

The project has advanced the state of Josephson impedance bridges. This type of bridge can now measure at levels of uncertainty comparable to the best conventional impedance standards at NMIs, but cover a wider frequency range. The Josephson impedance bridges developed in the project are partially or fully automated. Compared to traditional impedance bridges, the burden on the operator has been considerably reduced, simplifying impedance calibrations at the top level of uncertainty.

The project also succeeded in developing automated impedance ratio bridges and completing proof-of-concept tests at an uncertainty level of 10^{-7} for the frequency range from 50 Hz to 20 kHz. As opposed to the situation before the project, these novel bridges can be built exclusively from commercially available equipment.

The flexibility of the impedance bridges developed in this project opened up the possibility of measurements at intermediate impedance values using the bridges. Traceability was established for very small values of capacitance, as demanded by nanotechnology. An impedance simulator for LCR-meters was validated and tested, which can be programmed to simulate any impedance in the range 10 Ω to 1 MΩ and thus replaces at least six impedance standards required for the calibration of LCR-meters, which are commonly used in calibration laboratories.

4 Actual and potential impact

4.1 Dissemination activities

33 presentations about the work of the project were given, at conferences such as the Conference on Precision Electromagnetical Measurements (CPEM) 2104 and 2016 and the XXI IMEKO World Congress Measurement in Research and Industry. Articles were also published in 32 peer reviewed publications and at least five further papers have been or are in the process of being submitted.

An invited article with the title “Traceable measurements of electrical impedance” was published the IEEE Instrumentation and Measurement Magazine.

A stakeholder committee with 32 members from other NMIs, BIPM, universities, research institutes, instrument manufacturers and industrial users of impedance measurements was set up by the project and they were kept informed of the development in the project through newsletters and at meetings e.g. CPEM 2014 and 2016

Two workshops were held at PTB about Josephson impedance bridges: one for calibration laboratories over two days in June 2015 and two hands-on demonstrations.The final workshop for the project was held in Prague hosted by CMI, together with the projects SIB51 GraphOhm and SIB59 Q-WAVE, which covered other aspects of electrical metrology. Representatives from many European NMIs and collaborators NIST and KRISS, from Korea, also attended, as well as companies from the stakeholder committee.

A training course on Josephson Impedance Bridges was run at PTB, and attended by the scientific community in higher education and public research organisations.

4.2 Contribution to standards

The partners in the project made a joint request to the BIPM committee to add another option for the realisation of the henry (the unit of inductance) in the mise en pratique for inductance. A mise en pratique is a set of instructions that allows the definition of a unit to be realised at the highest level. As a result, a new realisation of the henry will be included as part of the future mise en pratique for electrical units.

4.3 Early impact

- LNE is now able to calibrate commercial capacitance bridges for very small values of capacitance, below 100 fF. These low values of capacitance are important for nanotechnology devices such as those with touch screens, and there is commercial interest in the calibrations and the standards developed. A semiconductor manufacturer has shown interest in purchasing individual standards for low value capacitance.

- REG(SUT) and REG(UZG) developed two types of digital signal sources with performance targets beyond what was commercially available at the start of the project. INRIM has bought an additional signal source, developed by UZG, from its national program funds for future impedance work. Trescal is completing the process of buying the source developed by REG(SUT), also from its national budget, in order to complete its own fully digital bridge a few months after the end of the project.
- INRIM and collaborator KRISS signed a contract for the delivery of a system for the realisation of the Farad (the unit of capacitance) with an uncertainty of 64 parts in 10^9. The system includes two digitally assisted coaxial bridges and four impedance standards. This was reported in the news on the website of Science and Technology of the Italian news agency (ANSA).
- KRISS has purchased a digitally assisted impedance bridge from partner CMI.
- As far as digitally assisted and fully digital impedance bridges are concerned, three partner NMIs, CMI, INRIM and METAS, have developed these types of bridge and can now offer calibrations for intermediate phase angles. In addition a new capability for measurements at intermediate phase angles has been established using the impedance standards.
- Two partner NMIs in the project, PTB and RISE, are running three different types of Josephson impedance bridges. Simpler setups, using a cryocooler for the two Josephson arrays at VTT or just one Josephson array at CEM, are expected to be completed after the end of the project.
- A collaboration between NIST in the USA and METAS has developed a Josephson impedance bridge.

4.4 Potential impact

The two types of impedance bridges (Josephson and digital) developed in the project now allow the calibration of impedance standards with intermediate values along the three impedance axes, which are important for modern manufacturers. As a result of the work of this project, the road towards establishing traceability at intermediate phase angles has been started and the project has also highlighted the need for more stable standards in order to improve the uncertainty that can be reached away from the “pure” impedance values traditionally used.

Finally, manufacturers of passive electronic components, instrumentation manufacturers for impedance measuring equipment and their users will benefit greatly from the automated operation of the bridges developed in the project. These impedance bridges provide easier and faster calibrations, without a penalty in terms of uncertainty.

5 Website address and contact details

A project website has been set up and can be found here:

www.ptb.de/emrp/aimqute.html

The address of the project coordinator:

Dr. Luis Palafox-Gámir

Physikalisch-Technische Bundesanstalt (PTB)

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