Final Publishable JRP Summary for SIB53 AIM QuTE Automated Impedance Metrology extending the Quantum Toolbox for Electricity

Overview

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.

Prior to this project, it was only possible to calibrate impedance at certain predefined set values, by comparison with a standard with a known impedance. However, this was an issue for end users and manufacturers, who need to measure impedance at arbitrary values.

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.

Need for the project

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.

This project addressed these 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.

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Scientific and technical objectives

The overall aim of the project was to improve the European infrastructure for metrology by developing the tools and methods needed to establish impedance scales at the lowest level of uncertainty and their dissemination to calibration laboratories. The aim was to meet user requirements for reliable impedance measurements in the frequency range between 10 Hz and 20 kHz.

The project was structured around three technical objectives:

1. to develop Josephson based impedance bridges for arbitrary ratios of like impedances, and 1:1 ratios for quadrature measurements, in order to establish their performance,
2. to develop automated digital 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
3. to extend the impedance scales to intermediate values, within the range 10 Ω to 1 MΩ, along the axes, to intermediate phase angles and towards the small values of capacitance demanded by nanotechnology.

Results

Development of Josephson based impedance bridges for arbitrary ratios of like impedances, and 1:1 ratios for quadrature measurements

Josephson impedance bridges were introduced shortly before the start of this project, and hence the project investigated their measurement benefit. For the first time ever, the project demonstrated that a pulse driven Josephson impedance bridge could be used to measure a capacitance standard relative to the Quantum Hall resistor operated at 1233 Hz (a primary standard for impedance). The project also performed the first ever comparison of Josephson impedance bridges using two different waveforms – stepwise approximated sinewaves and square waves. The project also investigated two developments for simpler set ups for Josephson impedance bridges: firstly VTT used two Josephson arrays in a cryocooler and secondly CEM explored the limits of a Josephson bridge with a single array. However, both these developments proved more demanding than anticipated and could not be completed in the lifetime of the project.

In conclusion, 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.

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

Previous attempts to automate impedance ratio bridges had resulted in an increase in uncertainty of at least ten times. During the project partners CMI and INRIM developed digitally assisted automated impedance bridges that can measure impedance ratios in the range 0.1-10, for impedances from 10 Ω to 100 kΩ over the frequency range 50 Hz – 20 kHz with an uncertainty of 10^{-7}. In addition, the automated bridge at CMI can also be configured as a fully digital bridge that can reach uncertainties of 10^{-5} and 10^{-6} depending on the magnitude of the impedances being compared (10 Ω – 10 MΩ).

INRIM developed a separate fully digital impedance bridge for two terminal-pair impedances that reaches 10^{-7} for the more favourable impedance comparisons. The robustness of INRIM's bridge was successfully tested at the commercial calibration laboratory of unfunded partner esz AG. The bridge and control software were designed following a modular concept. As a result, digital signal sources, such as those developed by researcher excellence grants (REG) at SUT and UZG or a custom one built at CMI, can be used with in the bridge. These two digital signal sources are now available commercially and allow performance levels beyond those previously available. The operation of these impedance bridges is completely automated. Therefore, end users of NMI calibration services will benefit from the increased flexibility offered by these novel automated impedance bridges as well as the reduced calibration times.

In summary, the project 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.

To extend the impedance scales to intermediate values, within the range for impedance between 10 Ω to 1 MΩ, along the axes, to intermediate phase angles and towards the small values of capacitance demanded by nanotechnology

The flexibility of the impedance bridges developed in objectives 1 and 2 opened up the possibility of measurements at intermediate impedance values using the bridges. During the development phase of these novel bridges, their performance was routinely validated against existing impedance bridges present at the NMI partners where the development took place. However, no impedance standards with adequate performance were available at the start of the project and as a result, a number of impedance standards were developed by TUBITAK. As no standards were available with the required performance TUBITAK developed two sets: (i) six pairs of resistance standards were built for intermediate resistance ratios, and (ii) six temperature controlled impedance standards for intermediate phase angles of ±30º and ±60º. The standards were measured with the novel digital bridges developed by CMI, INRIM and METAS and the results of the comparison showed that these bridges are not only more flexible than those previously operated at the NMIs, but they are also completely automated and hence remove the requirement for an experienced operator.

Traceability was established for very small values of capacitance, as demanded by nanotechnology. LNE developed new impedance standards below 100 fF (femto Farad) and also a system for their combination into a programmable capacitance standard, tested between 10 aF (atto Farad) and 10 fFs with an uncertainty of 0.14 aF. This programmable standard was used to calibrate commercial capacitance bridges in these low ranges.

Further to this an impedance simulator for LCR-meters (a type of electronic test equipment used to measure the inductance (L), capacitance (C), and resistance (R) of an electronic component) from METAS was validated and tested at the commercial calibration laboratory of partner esz AG. The LCR-meter 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.

Actual and potential 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.

Dissemination activities and stakeholder engagement

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.

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.

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.

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.

List of publications

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JRP-Partner 3 CMI, Czech Republic	JRP-Partner 9 RISE, Sweden
JRP-Partner 4 INRIM, Italy	JRP-Partner 10 Trescal, Denmark
JRP-Partner 5 LNE, France	JRP-Partner 11 TUBITAK, Turkey
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