Publishable Summary for 14RPT01 ACQ-PRO
Towards the propagation of AC Quantum Voltage Standards

Overview

Quantum effects play a fundamental role in the redefinition of the SI electrical units, allowing their direct realisation. Currently, most NMIs and some industrial laboratories possess a quantum standard but these needed to be improved and their metrological applications extended to other voltage levels and frequencies, so that their use can also be extended to industrial calibration laboratories and further levels of the traceability chain.

This project tackled that problem by providing European National Metrology Institutes (NMIs) the access to AC quantum voltage standards, therefore contributing to spread the capacity to countries or regions in Europe where access to these facilities was limited. The project also established the basis for the future collaboration between metrology institutes working on AC quantum voltage standards.

Need

At the beginning of this project, infrastructure and level of knowledge presented a barrier for most of the NMIs to develop their own AC quantum voltage standards, the consequence being that only a few institutes in Europe had access to these standards and the technological gap between NMIs was increasing. Furthermore, existing AC quantum voltage standards systems are complicated to construct and operate. As a consequence, only a few NMIs in Europe had the capability to operate and conduct research in this technical area, Traceability to AC quantum voltage standards could only be provided by a few NMIs and the dimension of the European research capacity on AC quantum voltage metrology was not large enough to keep up with the societal challenges associated with energy, environment and health. In addition, when raising the profile of basic scientific metrology, knowledge and technology transfer into industry and pre-/co-normative research, not even the most established institutes in Europe were able to exploit the full potential of their AC quantum voltage standards. The European research capacity in AC quantum voltage metrology needed therefore to be improved.

Objectives

The overall objective of the project was to develop the European measurement and research capacity. The specific scientific and technological objectives of the project were to:

- Transfer experience and expertise in different and specific technologies to enable the integration, operation and modification of AC quantum voltage standards. The purpose is not only to provide the infrastructure but also the capacity to improve the measurement technology through continuing research and development
- To design a new practical AC quantum voltage infrastructure accessible to all NMIs, which is easy to implement and operate, maintaining the potential research capacity. The design should be for a consolidated AC quantum voltage standard based on the knowledge acquired in previous research projects, where different types of approaches were followed.
- To produce a Good Practice Guide on the use of AC quantum voltage standards including guidance on development and validation of measurement methods for different specialised applications.
- To establish the basis for future cooperation between European NMIs working on AC quantum voltage standards research and the further propagation of their use.
- To create an individual strategy for the long-term development of the research capability in AC quantum voltage metrology for each NMI/DI partner developing capability in project. Individual strategies will include priorities for collaborations with the research community in the respective country, the establishment of appropriate quality schemes and accreditation. The future plans will

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consider the possible cooperation of some NMIs to build and use shared AC quantum infrastructures depending on the particular needs of each country.

Progress beyond the state of the art

The state of art of AC quantum metrology research in Europe at the beginning of the project illustrated the huge gap between different NMIs. While some of those NMIs were among the most advanced in the world, others lacked not only AC but also DC quantum voltage standards. This project narrowed this gap by the integration of new AC quantum voltage infrastructures and by transfer of knowledge and expertise from more experienced NMIs to other institutes by means of workshops and research activities on AC quantum voltage standards. The collaboration made smart specialisation possible, not only in the new infrastructures but also in the research carried out, thereof improving the European research capacity.

Results

Transfer of experience and expertise in different and specific technologies

All project activities contributed to the transfer of experience and expertise but two were specifically planned to achieve this objective: a workshop on quantum based voltage measurements and the development of research capability on AC quantum voltage measurement systems. A workshop on quantum based voltage measurements was held at PTB, in Braunschweig, in June 2015. The workshop was an overview of different aspects of Josephson voltage standards used for AC applications: different types of Josephson voltage standards namely the programmable Josephson voltage standard (PJVS) and the pulse-driven standard, usually called Josephson Arbitrary Waveform Synthesiser (JAWS), cryocoolers, Josephson standards for power measurements and associate instrumentation. The workshop also included hands-on training in practical systems.

The development of research capability, which covered different configuration and applications of AC quantum voltage standard, was reported and the knowledge shared within the consortium. The knowledge transfer and experience gained by the less experienced NMIs during the workshop and the guest research visits have been very useful for collaborating in the definition of the new configuration for a general AC quantum voltage standard. This experience was also fundamental for an active participation on the preparation of the Good practice guide and for elaborating the individual strategies for the development of AC quantum voltage standards. Overall the research activity outcomes were successful for the ACQ PRO project and they led to a strengthening of connections between scientists all over Europe.

In conclusion, the objective was achieved.

Design of a new practical AC quantum voltage infrastructure

A new design based on a PJVS, currently the most feasible AC quantum standard was chosen to cover the most demanding applications. This new AC quantum voltage standard combines the best approaches towards hardware and software configuration based on experience of project partners and a review of available literature. This design is based on an ultra-stable Digital to Analogical Converter (DAC) directly corrected by a PJVS to form a quantum traceable waveform generator. This generator can be used for the calibration of Analog-to Digital Converter (ADC), for example for power and power quality parameter measurements, Digital Multimeters (DMMs), thermal converters, or DACs itself to provide traceability to digital impedance bridges. The description of the new design was included in the Good practice guide.

The design was validated by a pioneering comparison with the BIPM, the international organization charged with the maintenance and dissemination of the SI under the Convention of the Meter, as they have recently established a transportable system for the purposes of international comparison. Two validation exercises carried out at NPL and at PTB have demonstrated that the reference design is capable of achieving measurement uncertainties at the 1 μV/V level. These comparisons will serve as a basis for future worldwide bilateral and pilot comparisons of ACQ standards. A common software requirement to facilitate the integration and collaboration within NMIs have been described.

In conclusion, the objective was achieved.

Good Practice Guide

A good practice on Quantum Voltage standards was agreed within the consortium that focused on instruments, configuration, cryogenics and hands-on instructions on how to use the different components. .

This Good Practice Guide is targeted at NMIs and industry who wish to develop a quantum standard for alternating voltage based on the Josephson effect. It gives a detailed description of the components required to construct a practical system as well as information on measurement techniques, uncertainty estimation, software tools and safe operation of cryogenic equipment. Specific issues that were not detailed on the available referenced papers were also included. The guide is available on the project website and has been submitted to the TC-EM to be considered as a TC-EM document. The guide was also made available on "ResearchGate", and has got over 200 reads in the first month of publication.

In conclusion, the objective was achieved.

Establish the basis for future cooperation between European NMIs

A group was created to work on AC Quantum Voltage standard Development and Cooperation. This group is aimed at establishing the basis for the European cooperation on AC voltage quantum standards and coordinate European NMIs working on AC quantum voltage standards, supporting propagation of their use in research and application.

The terms of reference of the group were approved within the consortium and the members were selected among experts from the field of arrays fabrication, cryogenics, software development, AC measurements, impedance measurements, uncertainties estimation and quantum standards. This group included consortium partners that are willing to develop AC Quantum standards. The first meeting of this group was held and a further meeting was arranged as a satellite meeting at CPEM 2018. To continue beyond the project, the group has been proposed as a Working Group of TC-EM, in cooperation with the EURAMET Subcommittees: DC and quantum metrology, Low frequency and impedance, Power and Energy. The decision will be taken during the next meeting of the Strategy planning working group to be held in Croatia on September 2018

Taking into account that cooling systems are very important and diverse in quantum standards, a new group related to cryogenics was formed by some project partners and is open to all interested parties. The aim of this group is the development of a European research network on Josephson Voltage Standards cryogenics to exchange know-how and experience in this field. This project promoted this group by uploading information to the project website.

In conclusion, the objective was achieved. The working group has been stablished, the first members were selected, the terms of reference have been approved and the convener for the first two years was elected. The group have been proposed as a working group of the TC-EM.

Impact

The results of this project were presented at 7 conferences and submitted for publication as two peer-reviewed papers. The project was presented to EURAMET Technical Committee for Electricity and Magnetism (TC-EM) and a Good Practice Guide on the operation of AC quantum voltage standards which was written by the consortium was submitted to TC-EM to be considered as a TC-EM document. Three articles aimed at general public and calibration laboratories were published in journals EspacoQ and Revista Medições e Ensaios.

The training material used in the first workshop was collected, assembled and, after agreement for guarding the intellectual property rights of the partners, it was published on the project public website so that it is accessible to any interested party.

The project website contains all information and output documents that could be released publicly. In addition, a project page was created on ResearchGate to increase the visibility and ensure the documents are available for longer. An overview of the publically available material was sent to metrological technical committees of all Regional Metrology Organisations.

Impact on industrial and other user communities

During the project, a pioneering intercomparison of PJVS has been arranged among BIPM, PTB and NPL. This intercomparison took place from 2017 to 2018 and it was beneficial for BIPM to establish the comparison protocol, given the three different designs used. Such a protocol is a prerequisite for key comparisons of AC voltage using quantum systems and thanks to this activity a key comparison can be started and traceability initiated. Comparisons are a main prerequisite for the use of AC quantum voltage standards in accredited laboratories and industry, and therefore this activity will have worldwide impact.

Results of the project were discussed with and presented to BIPM, Supracon AG and eszAG.

Impact on the metrology and scientific communities

With the knowledge acquired in the project, 9 NMIs developing capabilities in the field have prepared individual strategies for the development of the research capabilities in AC quantum voltage metrology. These strategies are the result of activities carried out within this project and cover at least the next five years. The strategies considered the development of either individual or collaborative quantum standards, or an agreement to the future use of other NMI standards. In addition, the strategies included a plan for calibration services in the established facilities which will comply with quality schemes and accreditation and will ensure a coordinated appropriate development of traceability in the field of AC quantum voltage metrology in Europe. The individual strategies were discussed within the consortium, to ensure a coordinated development of the European research and measurement infrastructure from the early beginning. According with these strategies in a few years most of the NMIs that participated in this project will have AC quantum standards, providing direct traceability to the new future SI definition.

Training material on AC quantum voltage systems and measurement methods were collated and made publically available. This material is being used as teaching material at the Department of Physical Electronics, Masaryk University, in Brno. The course on Low temperature physics, which is using this material is attended by many students every year.

AC quantum standards cannot be driven without a software. However, contrary to expensive hardware or know-how, software can be often easily transferred to other institutes thus decreasing time to acquire the new device. This can be usually done only if the software is open-source because some modification of the source code is almost always required. INRIM developed an open source software for operation of PJVS, which allows future improvements. This initiative has the potential to save other institutes significant time that otherwise would be spent in the development of software for ACQVS.

Impact on relevant standards

Two papers have been submitted for publication in peer-reviewed journals which address the issues of present standards for calibration of analogue to digital converters, namely IEEE Std. 1057-2017 and IEEE Std. 1241-2010. The problems of aperture time, stability of digitizer and uncertainties were studied in detail and are advancement compared to the actual standards.

A new group was formed and was proposed as a working group of EURAMET TC-EM. This group will be crucial for sharing and developing knowledge on AC voltage quantum standards after the end of the project and therefore will contribute to the establishment of a basis for a future European cooperation on the area. Because of the knowledge gained in this project, even less experienced NMIs were able to join this group.

Longer-term economic, social and environmental impacts

ACQVS have become the primary standards in the field of electrical power. Therefore, the acquisition of ACQVS by the less experienced NMIs which participated in this project will have a long term impact on CMCs related to power measurement, which are required for development of smart grids. This will lead to a decrease in the wasting of electrical power, which in turn will have direct economic and environmental impact.

List of publications

Javier Díaz de Aguilar, Raúl Caballero, Yolanda A. Sanmamed, Martin Šíra, Patryk Bruszewski, Andrea Sosso, Vitor Cabral, Luís Ribeiro, Helge Malmbekk, Jonathan M. Williams, Ralf Behr, Oliver Kieler, Recep Orhan, Grégoire Bonfait, Good practice guide on the operation of AC quantum voltage standards, ISBN: 978-80-905619-2-2, 2018.

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