Towards the propagation of AC quantum voltage standards, the EMPIR ACQ-PRO Project

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Abstract. The ACQ-PRO is an EMPIR Project, jointly founded by the European Union and the participating countries. The overall objective of the project is to provide trans-European access to AC quantum voltage standards, to increase research capacity and to establish the basis for future collaboration between metrological institutes working on AC quantum voltage standards. With this in mind, project tasks were designed. This paper describes the objectives and the first outcomes of the project. The most remarkable achievement are the results of experimental research visits working on ACQ voltage standards. The design of a new AC quantum voltage standards easier to integrate and operate that with the BIPM participation will be validated by a pioneering intercomparison. Besides a Good Practice Guide on the use of AC quantum voltage standards is under preparation. Two working groups on ACQ voltage standards and on cryogenics applications will be created within the activities of the project. Finally, the participant Institutes are establishing the strategic plans to ensure the coordinated developing of future AC Quantum Standards.

1 Introduction

Quantum effects play a fundamental role in the redefinition of the SI electrical units [1], allowing their direct realisation. The maintained unit of voltage and resistance depends on two fundamental constants, the elementary charge (e) and the Planck constant (h) and have an uncertainty in the SI. However, when the forthcoming redefinition of the SI takes place, h and e are expected to be given exact values allowing quantum standards of voltage and resistance to be realised directly in the SI.

Since more than 60 years, the AC standards refer to DC throw transfer techniques, mainly by thermal converters. An immediate consequence of this is that the most accurate instruments for current AC measurement and generation are limited to providing the root mean square RMS value. This is clearly insufficient to meet the current metrological needs of Research and Industry. Most measuring instruments are based on sensors that convert the measured quantity into a related electrical signal. Dynamic measures are fundamental in many applications where the RMS value does not provide the required information. This should be obtained by sampling and processing the signal. Analog digital converters are essential for this function. The industry has been able to develop converters capable of covering a wide range of industrial and research needs. Research in metrology allows us to have quantum standards capable of characterizing these converters. All this will make the analog digital converters progressively replace the thermal converters in a larger frequency range. Together, the development of analog digital converters will contribute to the gradual transformation of “conventional” to “digital” metrology.

Application of the Josephson effect, as the basis of a quantum DC voltage reference, started 30 years ago. However, the use of the Josephson effect as an AC quantum voltage reference is much more complicated and several research studies have been done in this topic during the last decade [2, 3].

The T4.J03 JOSY project, funded under the iMERA plus program, investigated new technology for the manufacture of "arrays", which lead to the improvement of the AC standards.

The SIB59 Q-WAVE project, financed within the EMRP call, has been a great advance in the European development of AC quantum standards, achieving the milestone of generating spectral high purity alternate signals up to 1 V voltage [4], it established the bases of the metrology of sampled signals, a fundamental step for the transformation of "conventional" to "digital"

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metrology. As support for these standards, a great deal of work has been developed in the evaluation of algorithms for the treatment of the signal and for the calculation of uncertainties. An analog digital converter has been designed that will be fundamental to transfer the traceability of the ac quantum standards to the next levels of the traceability chain. This project, in turn has been a great advance in the investigation of the use of photodiodes to increase the number of "arrays" in parallel that can be illuminated with radiofrequency pulses, the main limitation of the pulsed systems.

However, this improvement in AC quantum standards [5, 6], these systems are complicated to construct and to operate [7]. As a consequence, only a few NMIs in Europe have the capability to operate and conduct research in this technical area.

This paper describes the objectives, activities and early results of the EMPIR Project ACQ-PRO, jointly founded by the European Union and the participating countries. The overall objective of the project is to provide trans-European access to AC quantum voltage standards, to increase research capacity and to establish the basis for future collaboration between metrological institutes working on AC quantum voltage standards. A new simplified AC quantum voltage design to cover the most demanding applications is presented.

2 Lifetime and partners

The RPT *Towards the propagation of AC Quantum Voltage Standards* is an EMPIR project selected in the 2014 Research Potential call. As a research capability project it is focused on the development of the scientific and technical research capability of several NMIs in the topics of AC quantum voltage standards.

The lifetime of the Project is 36 months starting in June 2015.

There are 13 partners involved in the Project (BEV-PTP (Austria), CEM (Spain), CMI (Czech Republic), FCT-UNL (Portugal) , FER (Croatia), GUM (Poland), INRIM (Italy), IPQ (Portugal) , JV (Norway), NPL (United Kingdom), PTB (Germany), SIQ (Slovenia), TUBITAK (Turkey)) and 2 collaborators (BIPM (Bureau International Weights and Measurements) and SUPRACON (Germany)).

3 Scientific and technical objectives

The overall objective of the project is to develop the European measurement and research capacity by providing European NMIs and DIs the access to AC quantum voltage references, therefore contributing to spread the capacity to countries or regions in Europe where access to these facilities is currently limited. The project will also establish the basis for the future collaboration between metrological institutes working on AC quantum voltage standards. This will allow the European NMIs to provide direct traceability to the future definition of the SI, to improve their CMCs to the quantum level and to build a research capacity with European dimension.

The specific scientific and technological objectives of the project, according its protocol, are:

1. To transfer experience and expertise in different 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.
2. 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.
3. To produce a Good Practice Guide on the use of AC quantum voltage standards describing the use of AC quantum standards and including guidance on development and validation of measurement methods.
4. To establish the basis for future cooperation between European NMIs working on AC quantum voltage standards research and the further propagation of their use (e.g. working group, web pages, training courses).
5. To create an individual strategy for the long-term development of the research capability in AC quantum voltage metrology for each partner developing capability in project. This will include a strategy for offering calibration services from the established facilities to their own country and neighbouring countries.

4 Results and achievements so far

4.1. Research visits

During the first two years of the project, and to address the first objective, several research visits were carried out at the NPL and PTB. Some institutes are still analysing the data from these visits to present the results in the near future. These are some of the topics of these researches:

4.1.1 Evaluation on the gain dependence with in frequency and aperture time of ADCs

Frequency response and stability of Anolog–to–Digital Converters (ADC) using the Josephson Arbitrary Waveform Synthesizer (JAWS) and the Programmable Josephson Voltage Standard (PJVS) were carried out and both methods were compared. This characterization will significantly improve the AC metrological application of the ADC.

4.1.2 Specific waveform to calibrate digitizers

A special waveform has been prepared with the aim of calibrating several digitizer parameters at once. Parameters of the waveform were based on the properties of the JAWS system at PTB. The waveform has been generated by JAWS using three different configurations of chips to get different ranges of waveform amplitudes. JAWS is the only device capable of generating such a waveform with sufficient precision and stability. The waveform was sampled by selected digitizers. After an extensive data processing of sampled data, several digitizer parameters have been obtained and stability and correlations factors of these parameters were estimated.

4.1.3 AC Quantum Voltmeter as a standard

An AC Quantum Voltmeter was used as a standard to calibrate directly an AC source [9, 10]. The AC source was compared to the Josephson voltage by a differential sampling process measured by a commercial ADC. The measurements were conducted to explore different parameters configuration of the setup (i.e. the sampling rate) to observe repeatability of the results.

4.1.4 PJVS as a standard

PJVS was used to calibrate directly a voltmeter. As transfer standard, a commercial DAC was used to be compared to the Josephson voltage by sampling the voltage difference. The signal of the referenced DAC was used as standard signal to be applied to the voltmeter.

4.2 New design

The second objective of the project is related with a new design of the AC quantum standards based on the Josephson effect. The objective of the present work is to define a simplified subsystem that could be used for all AC quantum voltage applications (i.e. thermal voltage calibration, digital impedance bridge). The interoperability of this subsystem is a key requisite. In addition, the requirements to use common software for the AC quantum voltage infrastructures will also be defined. The new design is focused on the currently most available systems, the Programmable Josephson Voltage Standard (PJVS) and it is based on an ultra stable Digital–to–Analog Converter (DAC) [8] directly corrected by a PJVS to form a quantum traceable waveform generator. The new design will cover the most demanding applications, calibrating ADCs at µV/V accuracy level, i.e. for power and power quality parameter measurements, digital multimeters, thermal converters, or DACs itself.

Thanks to the collaboration of BIPM in the project, a pioneering intercomparison of AC quantum voltage standards has been arranged. The comparison, in which participates BIPM, NPL and PTB, will be used to validate the AC quantum voltage standard design. This will serve as a basis for future worldwide comparison of AC quantum voltage standards.

4.3 Good Practice Guide

The consortium is working to prepare a document on the use of AC quantum voltage standards that will include guidance on the development and validation of measurement methods and the design for a consolidated AC quantum voltage standard for different specialised applications. A complete bibliography on this topic was elaborated and the outline of the document is ready. This document will include details about the instrumentation and configuration (for binary-divided arrays and pulse-driven arrays), software requirements, details about the use of cryocoolers, measurement procedures (calibration of thermal converters, voltmeters and AC sources; characterisation of ADC, impedance ratio, power and power quality).

4.4 Future collaboration

4.4.1 Working group on ACJVS

The aim of this working group is the future cooperation between European NMIs working on AC quantum voltage standards. The members will include the project partners but also potential collaborators and experts in this topic. This working group will work in close collaboration with the relevant existent TC groups (EURAMET TC-EM "DC & Quantum Metrology, "Low Frequency" and "Power and Energy").

4.4.2 Working group on ACJVS Cryogenics

This group is aimed at the development of a European research network on JVS cryogenics and applications of cryocoolers to JVS. This group will be helpful to share experiences, "tricks" and know-how in this topic.

4.5 Individual strategic plans

One of the long-term research objectives defined in the EURAMET "Science and technology Roadmap for Metrology" is to make AC quantum voltage standards the basis for AC metrology. The necessary research to achieve this started 20 years ago, and the work will continue for several years. The project will contribute to this overall objective by making cutting–edge knowledge accessible to all the European NMIs working on AC quantum voltage standards and by establishing a basis for future cooperation.

With the knowledge acquired in the research visits, in the elaboration of the Good Practice Guide and in the design of a new practical AC quantum voltage standard, some NMIs will develop their individual strategic plans for the development of AC quantum voltage standards in the next five years. These strategies will consider the development of either individual or collaborative quantum standards, or an agreement to the future use of other NMI standards. The individual strategies will be further discussed with the other participant institutes to ensure a coordinated development of the European research and measurement infrastructure from the early beginning. The plans will also include a strategy for offering calibration services in the established facilities to their own country and neighbouring countries.

For this purpose, an early survey was already filled by the partners to understand motivations, measurement capabilities, cooling techniques and cooperation setup. The survey results provide an essential snapshot of the present perspectives of European NMIs: with 13 institutes involved, the questionnaire gives up-to-date information on topics that are fundamental for the management of the project, like number and type of quantum standards operated in each NMI (Fig 1), and their being part of the traceability chain for routine calibrations (Fig 2). NMIs replies to questions related to cooperation expressed interest in collaboration with other institutes and sharing facilities, if possible. Finally, directions for the best practice guide approach were addressed, with more than 80% of the replies in favour of considering mainly practical issues: setting up and using a Josephson AC quantum standard.

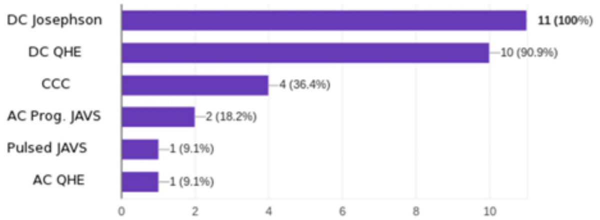

Fig. 1. Number and type of quantum standards operated in each NMI.

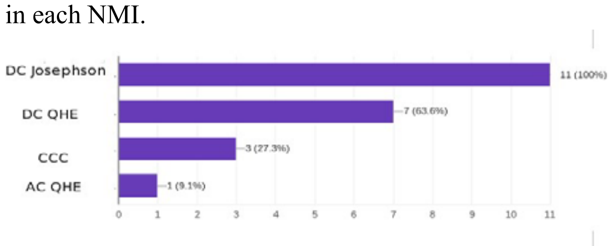

Fig. 2. Use of quantum standards for routine calibrations.

5 Conclusions

The results of this project will have a direct impact on the participating NMIs that will be able to provide traceability for AC quantum voltage metrology over the range already established and develop new measurement capacities. AC quantum voltage standards affect most the electrical measurements activity and the intermediate impact will spread across the European industry.

A new design has been proposed using the currently most available systems, the Programmable Josephson Voltage Standard (PJVS). To cover the most demanding applications the new design is based on an ultra stable Digital–to–Analogical Converter directly corrected by a PJVS to form a quantum traceable waveform generator.

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