22nd IMEKO TC4 International Symposium & 20th International Workshop on ADC Modelling and Testing
SUPPORTING WORLD DEVELOPMENT THROUGH ELECTRICAL&ELECTRONIC MEASUREMENTS
IASI, ROMANIA, September 14-15, 2017

Digital Metrology and Quantum Standards: ACQ-PRO EMPIR Project

Yolanda A. Sanmamed[1], Javier Diaz de Aguilar[1], Ralf Behr[2], Jonathan M. Williams[3], Andrea Sosso[4], Martin Šíra[5], Raúl Caballero[1]

[1]Centro Español de Metrología (CEM), Tres Cantos (Madrid), Spain
yalvarezs@cem.minetur.es, (+34) 9178074768
[2]Physikalisch-Technische Bundesanstalt (PTB), Germany
[3]National Physical Laboratory (NPL), United Kingdom
[4]Istituto Nazionale di Ricerca Metrologica (INRIM), Italy
[5]Český Metrologický Institut Brno (CMI), Czech Republic

***Abstract* – This paper describes the 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.**

Keywords – Analog-to-Digital converter, Digital-to-Analog converter, thermal converter, AC quantum voltage standard, Josephson effect, digital metrology

I. INTRODUCTION

Quantum effects play a fundamental role in the redefinition of the SI electrical units [1], allowing their direct realization. Application of the Josephson effect, as the basis of a quantum DC voltage reference, started 30 years ago. 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. Currently most National Metrology Institutes (NMIs) and some industrial laboratories possess such a quantum standard [2].

Over the last decade, there has been a substantial research activity on AC quantum voltage standards to meet the demand for applied AC measurements in industrial and scientific research [3]. However, established standards need 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. Different approaches have been used to achieve this goal and current systems are complicated to construct and operate. As a consequence, only a few NMIs in Europe have the capability to operate and conduct research in this technical area.

The overall objective of the EMPIR Project ACQ-PRO, jointly founded by the European Union and the participating countries, 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. The first two years of project activity have provided the following results: A complete set of training material available at the project website [4], those related to several research activities with AC quantum standards applications and a new simplified AC quantum voltage design to cover the most demanding applications. These early results are the basis to prepare a Good Practice Guide on the use and applications of AC Quantum (ACQ) standards and also to prepare a coordinated smart strategic plan for the future development of ACQ standards in Europe.

In section II the application of Quantum standards in AC metrology is described. Section III deals with the description of the method and underlines the need and overview of this project. Early results related to training material, research activities and the new design are reported in section IV, and finally, in section V, the conclusions are presented.

II. QUANTUM STANDARDS ON AC METROLOGY

The Josephson effect as a quantum standard of DC voltage is widely used, however for AC measurement the situation is different. Although much effort has been devoted to the development of AC quantum voltage standards [5, 6], they are very complex systems [7], difficult to develop and operate and accessible to only a few institutes. Thus, the current state of art of AC quantum metrology research in Europe illustrates the huge gap between different NMIs. While some of them are among the most advanced in the world, others lack not only AC but also DC quantum voltage standards. This project will facilitate an increase in the number of AC quantum voltage infrastructures in Europe as a result of the collaboration between NMIs.

Two different ways have been investigated to obtain an AC quantum voltage based on the Josephson effect: the so called Programmable Josephson Voltage Standard (PJVS) [8] and the Josephson Arbitrary Waveform Synthesizer (JAWS) [9]. The PJVS system is a Digital-to-Analog converter (DAC) that can produce selectable, stable, dc voltages or step-wise approximated waveforms whose accuracy is enhanced because the steps are defined by quantum-accurate constant-voltages. Both the root mean square (RMS) accuracy and output frequency of this approach, however, are limited, because the transition time between steps is finite and biasing and timing errors affect the time spent on the voltage steps. The PJVS system is presently used in applications that required rapidly programmable, stable, constant voltages and for low-frequency applications, such as power metrology at 50 Hz to 60 Hz. The second quantum-based AC voltage source is the JAWS and it consists on Josephson junction series arrays operated by short current pulses, the pulse frequency varies to generate the required arbitrary waveforms. Although there are a number of NMIs operating AC quantum voltage standards, the majority of NMIs still relate the AC measurements to DC using thermal converters which equate the electrical heating power of a DC and an AC input. Uncertainties for these devices are in the order of 1 part in 10^6 for low frequencies and 10 parts in 10^6 at MHz, but they are very far from the reproducibility of quantum standards (2 parts in 10^{16} at 4 K). Besides, the thermal converters only provide information on the RMS value whereas industry and science need information on phase and harmonic content.

For power measurements, most of the NMIs that previously based their standards on thermal converters have changed to digital sampling wattmeters due to the industrial development of high accuracy and sampling rate of Analog-to-Digital converters. However, new standards based on AC quantum voltage references are needed for the calibration of precise Analog-to-Digital converters in amplitude and phase.

For impedance measurement the units of AC resistance, capacitance and inductance are derived by the use of coaxial AC bridges based on transformers. These bridges are very complicated and laborious to implement and operate and only a few NMIs in Europe are able to carry out impedance measurement at the highest level. Some institutes have already replaced the transformers with Digital-to-Analog sources, easy to integrate and operate.

For AC measurement the uncertainty can be reduced to parts in 10^7 and it will be possible to provide traceability to the industrial laboratories replacing thermal converters by Digital-to-Analog and Analog-to-Digital converters (ADCs). AC quantum standards will enable the realization of sampling measurement at the highest level in a wider number of European NMIs. In general, the measurement capabilities created and improved in previous European projects (SIB59 Q-WAVE and SIB53 AIM-QuTE) can now be extended to a larger number of NMIs.

III. DESCRIPTION OF THE METHOD

A. Need

The availability of AC quantum voltage standards would improve the electrical measurement capabilities of the European NMIs and industrial laboratories: For AC voltage and current measurement the uncertainty can be reduced from several ppm to the sub-ppm level. For power measurements, the calibration of the digital power measurement systems using AC quantum voltage standards will enable uncertainties to be achieved at the ppm level. In addition, AC quantum voltage standards will allow the precise calibration in amplitude and phase of Analog-to-Digital converters, which can be used to develop accurate measurement systems of power quality parameters and provide metrological support to the "Smart Grid" concept. For impedance measurements, the use of automated bridges based on quantum standards will significantly reduce the measurement times and therefore will reduce the cost.

B. Overview of the method

Based on the measurement capabilities and knowledge acquired in previous European research projects, this project addresses the objective of developing the European measurement and research capacity by providing the access to AC quantum voltage standards. The project will also establish the basis for the future collaboration between metrological institutes working on AC quantum voltage standards and it 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.

IV. RESULTS AND DISCUSSIONS

A. Training Material

At the beginning of the project a workshop on quantum based voltage measurements has been held for the project partners at PTB as a first step in transfer of experience and knowledge. After the workshop a collection of training materials was compiled and is available to any interested party on the project website [4]. This collection gives an insight into the problem of

AC Josephson standards, its applications and cooling techniques.

B. Research Activities

With the aim of transferring experience and expertise in different and specific technologies of AC quantum voltage standards, several research activities to be carried out by the partners developing research capability in this project were defined. In order to optimise efforts, the electrical quantities that share similar systems have been grouped in two areas, the first related with digital and the second with analogue systems: 1) Analog-to-Digital converters and Digital-to-Analog converters, power measurements and impedance measurements, and 2) thermal converters calibration, AC voltage source calibration, AC voltmeter calibration.

Some examples of the research activities carried out are:

- Specific waveform to calibrate digitizers. The objective of this research activity was to use unique properties of Josephson Arbitrary Waveform Synthesizer (JAWS) to calibrate several digitizer parameters at once. Parameters of the waveform were based on the properties of the JAWS system (Fig. 1). The waveform has been generated by JAWS using three different configurations of chips to cover different ranges of waveform amplitudes. JAWS is the only device capable of generating such a waveform with enough 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 correlation factors of these parameters were estimated.

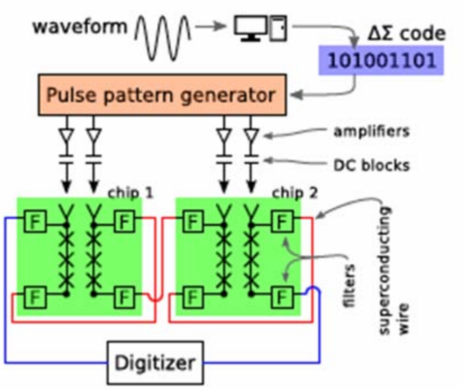

Fig.1. Schematic of JAWS system at Physikalisch-Technische Bundesanstalt (PTB)

- Evaluation of the gain dependence with frequency and aperture time of ADCs. The aim was the evaluation of frequency response and stability of Anolog–to-Digital Converters (ADC) using the two different ACQ voltage standards, Josephson Array Waveform Synthesizer (JAWS) and the Programmable Josephson Voltage Standard (PJVS) (Fig. 2). Several measurements were carried out and both methods were compared. This characterization will significantly improve the AC metrological application of the ADCs.

Fig. 2. DAC characterization at National Physical Laboratory (NPL)

C. New Design

Based on the knowledge and expertise acquired during the research activities and in previous research projects (i.e. SIB59 Q-WAVE, SIB53 AIM-QuTE and T4.J03 JOSY) a new design (Fig. 3) using the currently most available systems, the PJVS, was decided to cover the most demanding applications. This system is based on an ultra-stable Digital to Analogical Converter (DAC) directly corrected by a PJVS to form a quantum traceable waveform generator. Depending on the applications, the DAC can be replaced for another source, as i.e. a calibrator.

The DAC (5) generates a smooth sine wave with the same period and amplitude as the step-wise waveform from the Josephson waveform synthesizer. The Josephson array high frequency bias is supplied by the RF bias source (2), operating at 20 GHz or 70 GHz, depending on the type of Josephson array. The DAC is frequency-locked to the Josephson synthesizer using a synchronisation oscillator (8) operating at 10 MHz or, in case of using another source, the synthesis frequency, f_w depending on the type of voltage source. The difference voltage between the DAC source and the Josephson synthesizer is measured using the digitizer (6) at the high potential terminals. There is an option of using a second digitizer (7) at the low potential terminals. The digitizer (6) is synchronised from the oscillator using either a 10 MHz frequency or the sampling frequency, f_s, of the Josephson synthesizer, depending on the model of the digitizer. The second digitizer (7) is synchronised in a similar way.

Furthermore, the new design will be validated by means of an inter-comparison. The inter-comparison arranged will take place in the second half of 2017 and will include the participation of the project collaborator BIPM, and project partners NPL and PTB. This will serve as a basis for future worldwide bilateral and pilot comparisons of ACQ standards. For this inter-comparison, the DAC selected has been designed and built by VTT MIKES Metrology together with Aivon Ltd for producing multitone waveforms in the audio frequency range up to 20 kHz [10].

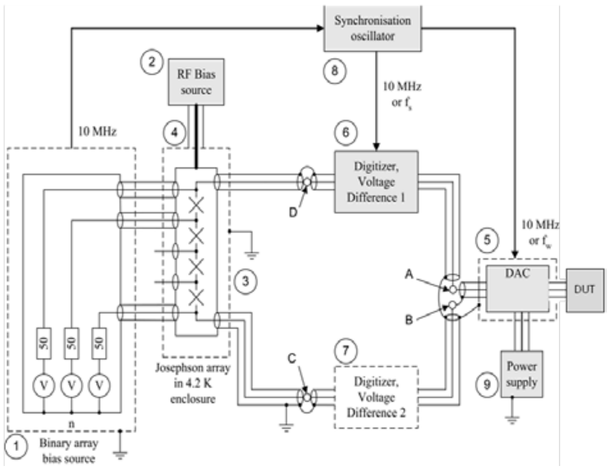

Fig .3. New AC quantum voltage design

V. CONCLUSIONS

The outcomes of this project will directly impact on the participating NMIs since it will enable them to provide traceability for AC quantum voltage metrology over the range already established and to develop new measurement capacities. AC quantum voltage standards affect the majority of the electrical measurements activity and the intermediate impact will spread across the European industry.

First results of the project have been presented in this paper. A collection of training materials was compiled and is publicly available on the project website. Besides, several research activities related with AC quantum standards applications were carried out with promising results and significant steps have been made in relation with the new simplified AC quantum voltage design.

VI. ACKNOWLEDGMENT

This project has received funding from the EMPIR programme co-financed by the Participating States and from the European Union’s Horizon 2020 research and innovation programme.

REFERENCES

[1] Resolution 1, 24th meeting of the General Conference on Weights and Measures, 24_CGPM_Resolution_1, 2011.

[2] Jeanneret, B. and Benz, S.P., *Application of the Josephson effect in electrical metrology,* Eur. Phys. J. Special Topics 172, pp. 181-206, 2009.

[3] Lipe, T., *Quantum AC Voltage Standards,* IEEE Trans. Instrum. Meas., 61 (8), pp. 2160-6, 2012.

[4] http://www.acqpro.cmi.cz.

[5] Behr, R. , Williams, J.M. ,Sosso, A., M. Starkloff, M., Kieler, O., Bauer, S., Palafox, L. , Lee, J. , Möhring, T. and Hagen, T., *Workshop on AC Quantum Voltage Standards*. PTB, Braunschweig, Germany. http://acqpro.cmi.cz. 2015.

[6] Kohlmann, J., Behr, R., and Funck, T. *Josephson Voltage Standards*, Meas. Sci. Technol. 14, pp. 1216-28, 2003.

[7] Behr, R., Kieler, O., Kohlmann, J., Muller, F., and Palafox, L., *Development and metrological applications of Josephson arrays at PTB,* Meas. Sci, Technol. 23, 124002, 2012.

[8] Waltrip, B.C. et al., *AC power standard using a programmable Josephson voltage standard*, Trans. Instrum. Meas., 58, April 2009, pp 1041-1048.

[9] Kieler, F., Behr, R., Wendisch, R., Bauer, S., Palafox, L. and Kohlmann, J. "*Towards a 1 V Josephson Arbitrary Waveform Synthesizer*," IEEE Trans. Appl. Supercond. 25 (2015) 1400305 (5 pp).

[10] Nissila, J.; Lee, J.; Sira, M.; Ozturk, T.; Arifovic, M.; Diaz de Aguilar, J.; Lapuh, R.; Behr, *Stable arbitrary waveform generator as a transfer standard for ADC calibration*, Conference on Precision Electromagnetic Measurements (CPEM) Proc., Ottawa, Canada, July 10-1, 2016, pp. 1-2.