Publishable Summary for 19RPT01 QuantumPower
Quantum traceability for AC power standards

Overview

The electrical power industry is undergoing a rapid transformation from fossil fuels to renewable energy generation. Precise and traceable measurements are required to guarantee stable supply, prevent blackouts and ensure a fair electricity market. The aim of this project was to improve quantum traceability for AC power standards. To achieve this, the project designed and built an open-source Quantum Power measurement System (QPS), also known as quantum sampling electrical power standard, for electrical power and power quality (PQ), which is distributed within the metrology community. This provided developing institutes with the best calibration and research capabilities, improved uncertainties in power measurement, ensured a direct link to the new quantum SI, decreased development costs, and reduced the gap in electrical measurement capabilities among the European institutes. The main achievements are the development and use of an open-source multiplexer, algorithms and software that was combined with a quantum voltage standard to allow for reduced uncertainties in calibration of power standards.

Need

Over the last decade, there has been substantial interest in AC quantum voltage references to meet the demand for applied AC measurements, which affect around 70 % of NMIs' calibrations. Additionally, quantum effects play an important role in the redefinition of the SI units e.g., the volt can now be directly realised by the quantum effect. Primary (electrical) power is one of the electrical quantities that has traceability to the volt and the ampere, typically through complicated calibrations of thermal voltage converters, current shunts and digitisers s, which only a few NMIs in Europe can provide with uncertainties approaching a few µV/V. To ensure a secure and robust development of interconnected smart grids in Europe, it is crucial that the developing NMIs increase their competence, capabilities and traceability within the field of electrical power measurements. Commercial Programmable Josephson Voltage Standards (PJVS) are not used for straightforward power measurements due to the complexity of integrating them into a QPS. Although most of the components for this integration were commercially available, a single NMI could not conduct the whole development on this topic, and the power industry needed support and collaboration to assemble a working system and validate it against national standards. An open system for direct quantum traceability for electrical power was therefore necessary as a solid metrological platform for a future smart monitoring of the electrical grids, which can only be achieved by validated methods, developed within the metrological community.

Objectives

The overall objective of the project was to develop a quantum sampling standard for electrical power which would be open to the whole metrology community and would provide direct traceability to the new quantum SI.

1. To design and realise a practical quantum sampling electrical power standard based on programmable Josephson voltage standards, traceable digitizers and transducers. The quantum sampling standard should be able to measure electrical power, power quality (PQ) parameters and phasor. The target uncertainties are better than 20 µW/VA for power measurements and less than 2 µW/VA for the contribution of the digitisers.
2. To develop software for the operation of the quantum sampling electrical power standard developed in Objective 1. The software should enable measurement control, data processing and uncertainty estimation. Additionally, it should be open source and easily modifiable to control different AC quantum systems.
3. To develop new methods and algorithms for the measurement of electrical power using quantum systems, validate these methods and algorithms using a transfer standard and develop a protocol for future comparison of QPSs.
4. For each participant, to develop an individual strategy for the long-term operation of the capacity developed, including regulatory support, research collaborations, quality schemes and accreditation.

Additionally, to develop a strategy for offering calibration services from the established facilities to their own country and neighbouring countries. The individual strategies should be discussed within the consortium and with other EURAMET NMIs/DIs including members of relevant EMNs, JRPs and EURAMET TCs, to ensure that a coordinated and optimised approach to the development of traceability in this field is developed for Europe as a whole.

Progress beyond the state of the art

Practical quantum sampling electrical power standard based on PJVS

The use of quantum standards in sampling of electrical power enables direct traceability not only for power measurements, but also for PQ and phasors. The project developed an open-source hardware multiplexer that was synchronised with the sampling system. It was able to switch the input of the analogue-to-digital convertors (ADCs) between the voltage, current and PJVS channels, to provide real-time calibration of the ADCs and substantially decrease the uncertainties of the power measurements. The multiplexer enabled the use of a single PJVS chip for measurement of both current and voltage components of the electric power using differential sampling, or to provide calibration of ADCs before and after the direct sampling of electric power. This has resulted in a flexible system that will be useful for both industry and NMIs. The newly developed methods will also extend traceability to time-varying signals, which are becoming more relevant for both the electrical power and voltage communities.

Software for the operation of the new quantum sampling electrical power standard

Currently, no commercial products for quantum based electrical power measurements are available, but during EMRP project SIB59 Q-WAVE and EMPIR project 15RPT04 TracePQM, joint algorithms and software for sampling of electrical power were written and verified by the participating NMIs. An open-source approach was considered the best way to spread the load of developing a joint system and reduce the amount of overlapping development. The missing parts in the previous projects were the quantum traceability and real time calibration of the digitisers. This project has built on this earlier research to include the traceability to quantum standards, in a collaboration that has gone beyond what a single NMI could achieve. The PJVS sources has either been controlled by or run in parallel with the quantum sampling software, and a description of the algorithms has been published and made available as open-source plug-and-play software package developed in the project.

New methods and algorithms for the measurement of electrical power using quantum systems

Over the last decades there has been a rapid development of analogue-to-digital converters and implementation of digital measurements of electrical power, but the community is not yet widely utilised quantum voltage standards in their technologies. This project has made significant advances in power measurement systems and implementation of the quantum systems traceable to the new quantum SI, where the fundamental electrical units are now defined by physical constants and realised by quantum standards. This was achieved through the development of new methods and algorithms for the measurement of peak amplitude and phasor tailored to PJVSs. This project was built on the work in previous iMERA, EMRP and EMPIR projects such as ProVolt, SIB59 Q-WAVE, 14RPT01 ACQ-PRO, SIB59 Q-WAVE, 15SIB04 QuADC, 17RPT03 DIG-AC, 15RPT04 TracePQM, ENG04 SmartGrids and 15NRM04 ROCOF.

The project went beyond the previous state-of-the-art available for electrical power traceability by using the verified algorithms for power, developed in 15RPT04TracePQM, and incorporating a multiplexer and direct traceability to the SI through PJVS. New algorithms for sampling and sorting the PJVS, voltage and current channels was developed, and ensured that voltage/current signal used for power calculations are directly traced to the SI. This expands the usefulness of the sampling software platform developed in EMRP project SIB59 Q-WAVE and EMPIR project 15RPT04 TracePQM for power measurements as well as voltage waveform analysis, where quantum traceability is needed.

Results

Practical quantum sampling electrical power standard based on PJVS

All NMIs in this consortium had acquired their own PJVS and set them up to produce periodic stepwise voltage waveforms as a quantum reference to calibrate the digitisers in these QPSs.

A modular open-source multiplexer has been designed based on early specifications developed in the project. Circuit board files have been designed and distributed among the partners based on a 4-1 slave board design. This enables switching of 4 inputs to 1 output (4-1 design), and the multiplexer can operate with up to 12 inputs switched to 3 outputs. Complete assemblies of the multiplexer have been tested at 6 partner institutes. Initial tests suggested that the multiplexer operates within the required uncertainty contribution with amplitude stability of (0.231 ± 0.340) µV/V at a nominal value of 7 V. The phase delay is linear through the frequency range 0-5 kHz with a delay through the multiplexer of about 320 ps. This is within the specified performance listed in objective 1. Information about the open hardware, testing and results are described here. An uncertainty of less than 0.5 µV/V contribution from the multiplexer (together with results presented at CPEM2022 showing that the gain and offset of the digitisers can be calibrated in real time to within 0.5 µV/V), means that the combined uncertainty for the two channels of the digitisers, which is needed for power measurements, is below the target uncertainty of 2 µW/VA. The target combined uncertainty of 20 µW/VA for power measurements, are thus on track, as the other components in the uncertainty stem from the contributions of the stability of the power source, and the transducers, which can perform better than 10 µW/VA in available instrumentation. The open hardware description, firmware, bill of material and built instructions can be found at https://github.com/rjiuzzol/QuP.

By piecing together these QPSs consisting of up to 3 digitisers, a PJVS, multiplexer, software and algorithms (from previous projects and objectives 2 and 3) and current and voltage transducers, power sampling was made possible with uncertainty of ≤2 µW/VA for the digitisers and ≤20 µW/VA for the overall QPS (except for the 60° capacitive phase at 24.4 µW/VA) for 5 A and 240 V inputs at 53 Hz. These results were obtained during the comparison carried out within the project, and thus, this objective was achieved on all points except for 60° capacitive phase.

Software for the operation of the new quantum sampling electrical power standard

The firmware and software driver for the multiplexer was developed and incorporated into the control software for the sampling system and has been tested for three methods of triggering the multiplexer. A successful demonstration workshop was held online for the project consortium in February 2022. The list of components and user manual was finished as part of the delivery of a summary report on the development of an open hardware multiplexer based on a single Josephson chip. The multiplexer must be sufficiently wideband to cover the required frequency range (20 Hz to 1 kHz).

During the workshop at PTB in June 2022 a schematic for a new stand-alone software, QPScontrol (https://github.com/KaeroDot/QPsw) was discussed and later written by CMI with help from JV. The software communicates with the stand alone TWM software (https://github.com/smaslan/TWM) to control all digitisers and multiplexers, samples the waveforms and interacts with the toolbox QWTB (https://github.com/qwtb/qwtb) where algorithms for calculations of results and uncertainty analysis are made.

With a successful comparison carried out within this project, this software has been verified, and thus this objective has been achieved.

New methods and algorithms for the measurement of electrical power using quantum systems

A review of the available methods for making a quantum power measurement system was conducted early in the project, and published on the project website and has later been expanded with instructions on how to turn a PJVS into a QPS. Advantages of the various techniques were discussed and provided the basis for the selection of slow switching technique and direct sampling within the consortium.

The development of new algorithms for the analysis of measured data is being published online at the open GitHub site https://github.com/KaeroDot/QPsw as part of the project's adaptation of existing software so it can be used in quantum systems to measure electrical power.

The validation of the new QPS has been divided into two parts. The first part is the comparison of QPS method and the differential method. The differential method is taken as reference and the difference with the QPS method is the deviation produced by this new method. Experimental results show an average difference of 0.30 µV (0.33 µV/V). This small difference confirms that the multiplexer does not add an appreciable error to voltage measurements. The digitisers contribution to uncertainty is accomplished (≤2 µW/VA).

The second part comprises of the QPS and a transfer standard. The transfer standard is taken as reference and the difference with the QPS is the deviation produced by this new method. Experimental results show a deviation within objective (≤20 µW/VA) in all cases, except when the phase difference is 60°, that is a little bit higher (24.4 µW/VA). Power source stability assessment shows good short-term stability.

As this is the first full test of the system, results are considered as satisfactory. Partners will be working on methods to improve uncertainties and optimize the system out of this project. The method developed here can be used to validate any future QPS. Still, with the achievement of producing measurement results within the target uncertainty in all but one phase difference this objective is mostly achieved.

Development of individual strategies for the long-term operation of the capacity developed, including regulatory support, research collaborations, quality schemes and accreditation.

All the individual strategies were gathered and combined into a document with a summary. The strategy has been discussed within the consortium before it was finalised in October 2022. Each individual plan includes identification of current and future user needs, priorities for collaborations, future applications of the quantum sampling electrical power standard and development of a comprehensive long-term plan. The strategies consider the integration of the common hardware and software developed for electrical power sampled measurement based on PJVS, that will improve and shorten the existing traceability chain of electric power quantities in the new SI. Further, integration of PJVS in the field of Power Quality (PQ) and Phasor Measurement Units (PMU) for monitoring electrical grids and calibration services with associated CMCs for the most relevant and high demand power parameters. For most of the NMIs, the main target of the plan is the adoption of existing and/or novel PJVS into existing sampling power standard. This will improve and provide a direct link to the existing traceability chain of electrical power quantities in the new SI. Therefore, this objective has been fully achieved.

Impact

The project website was developed to share information about the project's objective and developments, and news events and results, such as the publication of the deliverable report on the multiplexer, the method developments and presentations held within the TC-EM community have been shared with the project's stakeholders. A YouTube Channel was set up to post promotional and training videos about the project and instructions for installing and using the developed software.

Two papers have been presented at the 23rd International Workshop on ADC and DAC Modelling and Testing IMEKO TC-4 2022 which was held in Brescia, Italy on September 12-14, 2022, on the topic of Simple method for calibration of PMU calibrators as well as how to turn a PJVS into a QPS. Two posters were presented in the Conference on Precision Electromagnetic Measurements (CPEM) 12 - 16 December 2022, Michael Fowler Centre, Wellington, New Zealand on the topic of multiplexing schemes for quantum power systems as well as an SSR-based multiplexer for power measurement.

Impact on industrial and other user communities

This project has enabled industrial stakeholders to establish direct traceability of electrical power measurements to the new quantum SI, by providing an open design system that will connect commercial products together to provide direct quantum traceability to the SI. The collaboration with European manufacturers of quantum standards and high precision DACs and ADCs, represented as stakeholders in the project and within the EURAMET European Metrology Network for Smart Energy Grids (EMN SEG) and EURAMET European Metrology Network for Quantum Technology (EMN-Q), ensured that the project was aligned with industrial needs from the start. The project has been included in the repository for finished and on-going projects within the EMN SEG, and work must be included on the website at the EMN SEG and EMN QT have been conducted. By sharing the knowledge gathered in numerous EMRP/EMPIR projects and making quantum traceability for electrical power widely available, this project will ensure that high quality type approval (certification) and calibrations can be offered more widely.

As a result of the modular and open-source approach has been developed in this project, many calibration laboratories and DIs will be able to use results of the project independently and incorporate validated hardware or software into their quantum systems and services. This will expand the number of NMIs and calibration laboratories with the ability to provide very low uncertainty calibration of electrical power.

Impact on the metrology and scientific communities

The new QPS developed in this project has been used as basis for workshops which members of EURAMET technical committees has been invited to, for disseminating the work to the European metrology community. A close collaboration between this project and EURAMET EMN-SEG has ensured that the knowledge is spread to stakeholders within the field and that the increased capacity for high-quality electrical power measurements will benefit end-users. Once the first demonstration of the Quantum Power measurements System was ready, promotional videos were taken and uploaded to the project's Youtube Channel and subsequently were distributed via the Stakeholders and EMN SEG and EMN QT to widen the uptake to further laboratories. Members of the EMN SEG are invited to the planned workshop at CMI, Brno during the combined TC-EM SC meetings for LF and DC&QM that took place in May 2023, and information about the project has been distributed to the members both through direct contact and by promoting the project on the EMN SEG website. A presentation of the project results was done during the 17RPT03 DIG-AC dissemination meeting at CEM, Spain in May 2022. Additionally, this project increased capacity and decreased the existing technological and scientific gap in power measurements among the different NMIs of the consortium. The demonstration of quantum electrical power sampling, which is accessible to all NMIs and calibration laboratories, will promote the development of PJVS systems across Europe, and will lead to more robust traceability, not just for electrical power, but also DC and AC voltage and impedance measurements. As a result of this project, some of the participating NMIs are now able to deliver power measurements with lower uncertainties than before.

Impact on relevant standards

The project engaged with relevant technical committees of regional metrology organisations such as i) EURAMET TC-EM (Technical Committee for Electricity and Magnetism), ii) EURAMET TC-EM SC Low Frequency, iii) EURAMET TC-EM SC DC Quantum Metrology, iv) EURAMET TC-EM SC Power and Energy and v) BIPM-CCEM (Consultative Committee for Electricity and Magnetism) to ensure knowledge transfer and exchange with the community primarily responsible for maintaining references for electrical power. The documentation of the open-source software and hardware multiplexer was disseminated to the community, to ensure that emerging NMIs can benefit from the work developed in the project. Furthermore, the reduced uncertainties for power measurements will support the MID (Measuring Instruments Directive) mandated under EU directive 2014/32/EU which has been challenged by recent electromagnetic interference (EMI) issues with approved smart meters and investigated in the EMPIR project 17NRM02 MeterEMI.

The project has been presented at the EURAMET TC-EM Power & Energy and DC & QM meetings in 2021, at the annual TC-EM meeting at BIM, Bulgaria in October 2022, at CPEM 22 in New Zealand, at 25th IMEKO TC4 at the EMN SEG meeting in April 2023 and on a workshop held between the TC-EC SC DC & QM and LF meetings in May 2023. Several stakeholders from NMIs were recruited after these presentations, which focused on the benefits of utilising the PJVS for traceability for electrical power.

Longer-term economic, social and environmental impacts

This project will significantly enhance the development of a coordinated European electric power metrology infrastructure, which will support EU power industry, estimated to have been approximately €155 billion in 2017. Extending cutting-edge research technologies to the European NMIs and calibration laboratories, by publicly releasing the project results, will lead to higher efficiency in measurement services, which will contribute to increasing economic welfare in Europe. Measurement of electric power is essential to the management of power quality and stability through the balance of variable demand and variable distributed generation caused by renewable sources.

List of publications

1. M. Šíra, and S. Mašlán, "Simple method for calibration of PMU calibrators", 25th IMEKO TC4 Int. Symp., 12-14 Sept. 2022, p. 39-44, https://doi.org/10.21014/tc4-2022.08
2. B. Trinchera et al., "Towards a novel programmable Josephson voltage standard for sampled power measurements", 25th IMEKO TC4 Int. Symp., 12-14 Sept. 2022, p. 1-6, https://doi.org/10.21014/tc4-2022.01
3. B. Trinchera et al., "Development of a PJVS system for quantum-based sampled power measurements", Measurement, 13 July 2023, https://doi.org/10.1016/j.measurement.2023.113275
4. B. Trinchera et al., "Quantum sampling modular setup for practical power measurements based on a programmable binary Josephson voltage standard", IMEKO TC-4 International Symposium", https://metrica.inrim.it/handle/11696/77819

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

19RPT01 QuantumPower

Project start date and duration:	01 September 2020, 36 months	
Coordinator: Bjørnar Karlsen, JV Tel: +47 64 84 84 32 E-mail: bka@justervesenet.no Project website address: http://quantumpower.cmi.cz/		
Internal Funded Partners: 1. JV, Norway 2. CEM, Spain 3. CMI, Czechia 4. INRIM, Italy 5. PTB, Germany 6. VTT, Finland	External Funded Partners: 7. INTI, Argentina 8. UMA, Spain (withdrawn from February 2022)	Unfunded Partners:
RMG: IPQ, Portugal (Employing organisation); CMI, Czechia (Guestworking organisation)		