Publishable Summary for 15RPT04 TracePQM
Traceability routes for electrical power quality measurements

Overview

The diversification of electric power generation to include sources with fluctuating output power such as solar and wind, together with the growing number of appliances employing switched-mode power supplies, has led to increased demands for traceable, accurate measurement of electrical power and power quality (PQ) parameters. Conventional power measurement techniques based on thermal converters only provide information about the root-mean-square (RMS) value, which is not sufficient for the determination of the PQ parameters of complex waveforms. Therefore, new measurement setups based on alternative measurement techniques were required. Whilst a few national metrology institutes (NMIs) have developed metrology grade power and PQ measurement systems based on sampling techniques, these systems are not generally available and no NMI can offer accredited calibration services for all the required PQ parameters. This project helped to address these issues by developing and validating a modular metrology grade system for the traceable measurement of power and PQ parameters using digital sampling techniques and equipment that is readily available in many laboratories.

Need

Traceable measurement of PQ parameters entails a complex range of activities. In particular, a successful implementation of a power and PQ measurement system requires knowledge and expertise in at least four fields: (i) Establishment of an appropriate measurement system including the proper, interference-free interconnection scheme of the components of the measurement setup; (ii) Design and implementation of a system capable of controlling the digitizers that will, amongst other things, ensure synchronisation of particular digitizer channels; (iii) Mathematical processing of the sampled voltage and current waveforms in order to obtain the required parameters such as power, power factor, and various PQ parameters including the uncertainty evaluation; and (iv) Validation of the performance of the measurement system to ensure traceability to the SI system. Such a complex range of activities for each required PQ parameter is generally beyond the capacity of individual institutes in particular smaller or emerging NMIs/DIs, universities, calibration laboratories and manufacturers of PQ instrumentation etc. Furthermore, independent development of all parts of the sampling power and PQ measurement system from scratch in every institute would result in duplication of existing designs and devices and hence a waste of resources.

The design of a modular metrology grade measurement setup needed to be flexible and allow new digitizers or PQ algorithms to be easily incorporated in order to cater for continuously developing customer's needs and to reflect documentary standards defining requirements for PQ meters. Ideally any solution needed to focus on maximising the use of the capabilities of existing hardware components and on simple integration of new components without the need to rebuild the entire system.

In addition, the traceability of the measuring devices and transducers can be problematic over their entire operating ranges and at the required level of accuracy, therefore harmonised and validated calibration methods were required.

Objectives

The overall aim of this project was to develop and validate a modular metrology grade system for the measurement of power and PQ parameters using digital sampling techniques. The specific scientific and technical objectives of the project were:

1. To design a modular, metrology grade measurement setup for sampled electrical power and PQ parameters measurements, including a review of existing measurement and calibration methods, associated hardware and software, investigation of the optimum use of equipment already available within the NMIs/DIs and extension of traceability for power and PQ measurements up to 1 MHz.

2. To develop and validate a modular measurement setup for sampled electrical power and PQ parameters measurements, which can be easily established at NMIs/DIs and at other organisations. The target uncertainties of the modular measurement setup are at least four times smaller than the tolerances specified in documentary standards for PQ meters, e.g. the target expanded uncertainties for the amplitude of voltage harmonics of the modular measurement setup are 1.25 % of the measured voltage harmonic for measured values higher or equal to 1 % of the nominal voltage and 0.012 % of the nominal voltage for measured values lower than 1 % of the nominal voltage.
3. To develop an open software tool for instrumentation control, data acquisition and the calculation of electrical power and PQ parameters with full uncertainty estimation.
4. To develop and make available a good practice guide for the assembly and operation of the modular measurement setup including the calibration of all components so as to establish full traceability to the SI of the electrical power and PQ parameters measured. The guide will include the manual for the open software tool to assist users in the extension and modification of the modular measurement setup.
5. For each partner to develop an individual strategy for the long-term operation of the research capability developed during the project, including regulatory support, research collaborations, quality schemes and accreditation, together with a strategy for offering calibration services from the facilities established to customers in their own country and neighbouring countries. The individual strategies will be discussed within the consortium and with other EURAMET NMIs/DIs, to ensure that a coordinated and optimised approach to the development of traceability in this field will be implemented for Europe as a whole.

Progress beyond the state of the art

The project progressed beyond the state of the art by developing a modular measurement system for power and PQ parameters, which made innovative and optimum use of equipment that is commonly available within the NMIs/DIs and high-level calibration laboratories and maximised the capabilities of the chosen hardware components. The possibility of implementing continuous sampling with sampling multimeters for measurements that require long interval waveform records was investigated and a solution that required no external hardware identified. Methods to improve the stability and temperature dependence of wideband digitizers were developed, the temperature coefficients of several digitizers measured and a method proposed to improve short term stability [1]. Traceable methods for the calibration of particular components for frequencies up to 100 kHz were developed together with an investigation of methods for extending the frequency range up to 1 MHz. Measurement setups for the calibration of current shunts and resistive voltage dividers in terms of amplitude and phase up to 1 MHz were developed and validated by comparisons. Moreover, digitizer calibration methods up to 1 MHz were developed and successfully compared using a novel micropotentiometer based travelling standard developed in the project.

An open software tool for instrumentation control, data acquisition and data processing to accompany the modular power and PQ measurement setup was developed enabling the end user community to add functionality for any other digitizer or PQ algorithms by simply adding new modules. The final versions of the open software tools named TWM (based on a LabVIEW platform) and TPQA (based on a LabWindows/CVI platform) were released. A unified system of calibration datasets for every component used in the setup (i.e. digitizers, current shunts and voltage dividers) was proposed for both tools so that adding or interchanging the components only requires calibration datasets to be loaded into the system. The algorithms implemented for the calculation of the PQ parameters were accompanied by a numerical calculator of the measurement uncertainty and, for computationally extensive algorithms, by a quick uncertainty estimator based on a previous Monte Carlo uncertainty analysis. Guidance on the assembly and operation of the modular measurement setup was produced and made available including the calibration of all components to establish full traceability to the SI, together with a manual for the open software tools to assist users in the extension and modification of the modular measurement setup.

In addition, the project extended the research capabilities and calibration services in power and PQ metrology across more European countries. Coordinated activities of the participating NMIs/DIs sped up the research in this field and reduced unnecessary parallel investigations and developments, thus saving resources.

Results

Design of a modular, metrology grade measurement setup for sampled electrical power and PQ parameters measurement

Existing measurement setups, calibration methods and voltage and current transducers for the measurement of power and PQ parameters currently in use in NMI/DIs worldwide or published in the literature were reviewed. The existing measurement setups were categorised based on their measuring principles and/or the hardware used and several candidates for the new system were identified. The contradictory requirements for the setup design (to ensure both the lowest possible uncertainties and the highest possible bandwidth) could not be met by a single measurement setup. Therefore, the new design comprised two setups: (i) a system based on sampling multimeters 3458A for low frequency measurements of the highest accuracy; (ii) a set-up based on NI 5922 digitizers for wideband measurements but with a reduced accuracy. The connection schemes and synchronisation methods of both setups were selected in order to enable multichannel, multiphase measurements which are essential for the PQ analysis.

Traceable calibration methods for the transducers (voltage dividers and current shunts) in terms of amplitude and phase up to 1 MHz were developed, including the development of the new primary phase standards in order to meet the uncertainty requirements. Traceable calibration methods for wideband digitizers for the amplitude and phase angle error up to 1 MHz were also developed. An inter-laboratory comparison of the setups for the calibration of current shunts at 3 laboratories showed good agreement of the results, whilst another comparison of setups for the calibration of resistive voltage dividers was successfully completed by the same three participants, using a travelling standard suitable for comparison of Resistive Voltage Dividers (RVD) calibration methods specifically produced in the project. In addition, the setups developed for the calibration of wideband digitizers were successfully compared by using a novel micropotentiometer based travelling standard developed in the project.

Possibilities for extending the record length of the data acquired by a 3458A sampling multimeter were investigated. A solution allowing continuous record was identified and successfully tested up to 16 Megasamples, without the need for any additional hardware. The short-term stability and temperature dependence of NI 5922 digitizers were measured and the methods to compensate for these effects developed.

Development and validation of a modular measurement setup for sampled electrical power and PQ parameters measurements

Based on the design proposed above, the final versions of both the low frequency and wideband setups were developed including the identification of optimal measurement conditions. The verification tests of functionality and accuracy were performed for both low frequency and wideband setups. The target uncertainty goals of the PQ measurements implemented in the modular measurement setup were met, e.g. the target expanded uncertainties for the measurement of the amplitude of voltage harmonics were less than 0.5% of the measured voltage harmonic for measured values higher or equal to 1 % of the nominal voltage and less than 0.01 % of the nominal voltage for measured values lower than 1 % of the nominal voltage. The user friendliness of the test tool was assessed, and a number of improvements were suggested but no important functionality or accuracy errors were detected. The validation of the hardware capabilities showed that both software tools supported the necessary hardware and operated on the modular principle allowing new hardware drivers, transducer correction files and algorithms to be added in the future. The only difference between the capabilities of the two tools is the Application Programming Interface (API) within TWM, which can be used for integrating TWM with a user measurement program.

Development of an open software tool for the modular measurement setups

The low frequency and wideband setup designs were used to propose a concept for the open measurement software tool. LabVIEW and LabWindows/CVI, provided by National Instruments, were selected as the most suitable software environments for the development of the tools (named TWM for LabVIEW and TPQA for LabWindows/CVI). The new software tool comprised two parts: (i) an user interface (GUI) and instrument control module that acquires and stores the digitized waveforms (developed in LabVIEW and/or CVI); (ii) a module for calculation of the power, PQ parameters, and uncertainty in MATLAB or GNU Octave. Both modules are independent of each other so that the calculation of the parameters from the previously recorded or simulated waveform data can be executed manually, if necessary.

Both the TWM tool and TPQA tool were released as open-source projects. The TWM software tool can: (i) digitize using the sampling multimeters 3458A, the digitizers NI 5922, or using an ordinary soundcard (for low accuracy measurements) and simulate a simple composite harmonics signal for testing purposes; (ii) store the digitized waveforms in unified data format that can be read in LabVIEW, C/C++, MATLAB or any other language without excessive effort; (iii) initiate the processing of the recorded data using a selected algorithm from the Q-Wave toolbox (QWTB) including application of correction files for the hardware used or by using raw MATLAB commands (both MATLAB and GNU Octave supported); (iv) display the calculated results either as a table or graph. The TPQA tool features are similar.

Twelve algorithms for the waveform processing were implemented including uncertainty estimators. The algorithms were numerically validated with simulated data, and real data acquired from existing setups were applied to the developed algorithms to assess their performance.

Production of good practice guide on electrical power and PQ measurement

A Good Practice Guide (GPG) was successfully completed and made available on the project website. The document provides guidance to the end user community on the assembly and operation of the modular measurement setup for measurement of sampled electrical power and PQ parameters. The first part of the guide addresses the hardware and includes descriptions of the designs for both, a low frequency, high accuracy setup and a high frequency setup with reduced uncertainty. Commonly used hardware components, such as digitizers, voltage dividers and current shunts are introduced and their performance outlined, together with descriptions of the schemes for interference free connections. Methods for evaluating the measurement uncertainties are provided together with some examples for commonly measured quantities. As the characterisation of the hardware components plays a vital role in establishing the achievable uncertainty of the measuring system, the second section of the GPG describes calibration methods for the various components including extension to high frequencies up to 1 MHz. The document also contains information about the two developed open software tools (TWM and TPQA), which handle the control of the instrumentation, the data acquisition and the data processing. The third section of the guide includes a full description of these two tools including instructions for installing, configuring, and operating the systems.

Impact

The partners have presented the project’s results and progress at scientific conferences (e.g. CPEM, CIM and IMEKO), international and European technical committees, and legal metrology organisations. Additionally, three open peer-reviewed papers and one conference proceeding were published in highly influential journals (e.g. IEEE Transactions on Instrumentation and Measurement and IOP Measurement Science and Technology). We organised and held various courses and workshops with good attendance from industry, calibration laboratories and NMIs. A half day workshop related to the power quality organised by SIQ in Slovenia provided training to more than 30 participants from Slovenian electricity distribution companies and producers of PQ instruments. Presentations from the initial workshop (held for the consortium only) were collated and published on the project website. An additional one-day workshop open to all interested parties was held at the end of the project with 28 attendees from industry, metrology and scientific communities to promote the uptake of the project’s outputs by potential end-users. Moreover, presentations from this workshop were made available to download on the project website. All these activities, in addition to the contributions to standardisation, metrology and regulatory bodies (see section below) aimed at promoting the uptake of the project’s results.

Impact on industrial and other user communities

A stakeholder committee was created to ensure the project addressed the end-users’ needs. Fifteen organisations from different fields of activities related to power and PQ (PQ test instruments manufacturers, distribution service providers, universities, test laboratories, etc.) joined the stakeholder committee and were regularly consulted. The project was so well received amongst user communities, that the collaborators offered additional assistance with instrumentation, experts’ knowledge, feedback on the design of the setup, and input into the discussion of the strategies and comparison protocol.

The traceable measurement capabilities for power and PQ quantities improved in this project are now available to calibration laboratories, European electricity distribution companies and producers of PQ instruments, therefore contributing to the growth and development of the energy infrastructure necessary to underpin more effective monitoring of the electrical grids. The modular design and open software tool will enable future expansion of the measurement setup to include customers’ upcoming needs.

One of the stakeholders expressed that particular algorithms developed within the project will be internally used for validation of the commercial PQ meters’ installation.

Impact on the metrology and scientific communities

The project aimed at early phase knowledge transfer from experienced to less experienced NMIs. For this, a half day workshop on power and power quality metrology was organised in conjunction with the kick-off meeting providing the partners with the necessary knowledge to progress with the activities of the project. The active participation of less experienced NMIs in the development of the new system extended their knowledge.

The open software tools and GPG are publicly available on the project website to all interested parties, i.e. NMIs/DIs, calibration laboratories, industry, universities and individual practitioners. They serve as a quick starting point for the establishment of an expandable modular sampling power and PQ measurement system, and as a reference design to speed up the design of new systems. These features, together with the easy-to-implement modular design of the power and PQ measurement setup will lead to the improvement of the power and PQ measurement capabilities within Europe.

One of the partners, Metrosert, established a new accredited calibration service in electrical power measurements with an expanded measurement uncertainty below 150 µW/VA. This was recently improved to start from 70 µW/VA and total harmonics distortion can be now measured with an expanded measurement uncertainty of 0,03 %. The TWM software tool is being tested in several institutes within and outside the consortium. For example, BEV-PTP and CMI are using the TWM software in the K5 international comparison on power. Additionally, CMI and SIQ are using the TWM tool to replace several older calibration sampling systems for regular and high accuracy calibration of power and PQ parameters. JV is exploring the software package with the aim to offer customer service in new areas in the future. The TWM software is a core tool of the new digital sampling impedance bridge for ultra-low frequencies and impedances that was developed within EMPIR project 17IND10 LiBforSecUse. Furthermore, the TWM tool was also used to improve a control and measurement software developed in EMPIR project 15SIB04 QuADC. In EMPIR project 17RPT04 VersICaL, several of the designs for digital impedance bridges under development are based on multichannel signal sources whose level and phase stability have a significant effect on the performance of the bridges. The consortium of 17RPT04 VersICaL project is investigating the suitability of the TWM tool developed in this project for this application.

The strategies for the long-term development and use of partners' capabilities, which are available at the NMIs, will enable fast uptake and maximum use of the project's results leading to the establishment of new calibration services and improving existing measurement capabilities in participating countries. The project prepared a protocol for a flicker comparison, which will be implemented as optional part in EURAMET comparison K13 and will support the establishment of CMCs at less developed NMIs after the end of the project.

Moreover, an RMG researcher from BEV-PTP was trained in sampling technology, enabling the measurement of phase angle on current shunts. As a result of the comparison between shunts calibrated at NMIA, CMI and BEV-PTP, BEV-PTP started a new CMC claim for phase angle measurements. BEV-PTP is also using the GPG developed in this project to set up a circuit for high frequency measurements on voltage dividers.

Impact on relevant standards

The partners have disseminated the results to a range of technical subcommittees and regulatory bodies: CIPM CCEM (Electricity and Magnetism), EURAMET TC-EM (Electricity and Magnetism), EURAMET TC-EM SC Power and Energy, EURAMET TC-EM SC Low Frequency, OIML TC 12 and WELMEC.

Additionally, the consortium contacted IEC TC77, WG9 "Power Quality Measurement Methods" to determine if the results of the research can be of use to the working group.

Longer-term economic, social and environmental impacts

The project will indirectly influence energy consumers by providing a metrological foundation for more secure energy supply, to reduce losses, dips, flickers and unexpected blackouts by more careful monitoring of power and PQ in Europe. This will improve industrial efficiency and competitiveness, increase employment, and ultimately improve the quality of life.

Joint effort in power and PQ metrology will reduce duplicate developments and save costs and time resources of the NMIs, universities and producers of power and PQ related instrumentation that can be invested more effectively. Expanded power and PQ measurement capabilities over Europe will indirectly help to reduce bad PQ in the electrical grids and therefore will have an influence on reducing the energy wastage and increasing energy efficiency. The open modular power and PQ measurement setup developed in the project will speed up measurements by remote control and automated data processing, reducing calibration time and costs. In addition, the wider distribution of measurement capabilities over Europe will reduce the transportation of calibrated devices, and therefore calibration cost. It will also reduce the travel cost of manufacturers who need to cooperate with the NMIs during development of the new equipment.

The project will have an indirect impact on secure energy supply thanks to the enhanced measurement capabilities in PQ throughout Europe. Increased accessibility of the calibration services over Europe will reduce the transport distance for calibrated equipment which will have a positive influence on air pollution.

List of publications

[1] V. Nováková Zachovalová, et al. "EMPIR project TracePQM: Traceability routes for electrical power quality measurements", 18th International Congress of Metrology (2017), EDP Sciences, https://doi.org/10.1051/metrology/201704001

[2] Javier Diaz de Aguilar, J. R. Salinas, Oliver Kieler, Raúl Caballero, Ralf Behr, Yolanda A. Sanmamed, and Ángel Méndez "Characterization of an analog-to-digital converters frequency response by a Josephson arbitrary waveform synthesizer", IOP Measurement Science and Technology (2019), https://doi.org/10.1088/1361-6501/aafb27

[3] Stanislav Mašláň, Martin Šíra, Tereza Skalická, and Tobias Bergsten "Four-Terminal Pair Digital Sampling Impedance Bridge up to 1 MHz ",IEEE Transactions on Instrumentation and Measurement (2019), https://doi.org/10.1109/TIM.2019.2908649

[4] Tobias Bergsten and Karl-Erik Rydler "Realization of absolute phase and ac resistance of current shunts by ratio measurements", IEEE Transactions on Instrumentation and Measurement (2019), https://doi.org/10.1109/TIM.2018.2882927

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 June 2016, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Věra Nováková Zachovalová, CMI, Tel: +420 545 555 305, E-mail: vnovakovazachovalova@cmi.cz
Project website address: http://tracepqm.cmi.cz/</td></tr>
<tr><td>Internal Funded Partners:
1. CMI, Czech Republic
2. BIM, Bulgaria
3. CEM, Spain
4. FER, Croatia
5. IMBiH, Bosnia and Herzegovina
6. INRIM, Italy
7. JV, Norway
8. LNE, France
9. Metrosert, Estonia
10.NSAI, Ireland
11.SIQ, Slovenia
12. RISE, Sweden
13.TUBITAK, Turkey</td><td>External Funded Partners:
-</td><td>Unfunded Partners:
-</td></tr>
<tr><td colspan="3">RMG1: BEV-PTP, Austria (Employing organisation); CMI, Czech Republic (Guestworking organisation)</td></tr>
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