15RPT04 TracePQM

FINAL PUBLISHABLE REPORT

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Coordinator: Věra Nováková Zachovalová, Ph.D., CMI Tel: +420 545 555 305 E-mail: vnovakovazachovalova@cmi.cz Project website address: http://tracepqm.cmi.cz/		
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1 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.

2 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.

3 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.

4 Results

4.1 To design a modular, metrology grade measurement setup for sampled electrical power and power quality (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.

Relevance to the project needs and objective

The first power and PQ sampling systems were developed and implemented by some NMIs, before this project. However, these systems essentially allowed to measure power and only very limited number of PQ parameters. Moreover, the used hardware had several other limitations (such as maximum record length of 3458A, stability, temperature dependence and frequency dependence of input admittance of NI 5922).

To design a new metrology grade measurement setup appropriate for measuring sampled electrical power and PQ parameters, an analysis of existing setups and hardware was undertaken, which included the investigation of the optimum use of equipment available within the NMIs/DIs and extension of traceability for power and PQ measurements up to 1 MHz. The limitations of the used digitizers were investigated and a design to improve their operation was proposed. The new measurement setup and associated software to control the instruments and to post-process the acquired data have a modular arrangement to enable new digitizers or algorithms to be incorporated without the need to rebuild the entire system.

Work undertaken

A review of existing setups

A review of literature and an international survey targeted on European and international NMIs including all project partners were completed by RISE and INRIM and discussed with all project partners. This included existing measurement setups, calibration methods used by NMI/DIs worldwide, and voltage and current transducers for the measurement of power and PQ parameters. The existing measurement setups were categorised based on their measuring principles and/or the hardware used. The review of existing measurement setups identified three candidates for the new low frequency (LF) system based on 3458A multimeter and one candidate for the new wideband (WB) system based on NI 5922 digitizer.

The three candidate LF-systems were:

1) synchronised by external 10 MHz, 3458A external trigger from Arbitrary Waveform Generator (AWG) – both generation of waveforms and measurements are synchronised via a common 10 MHz. When 3458A multimeters are used as samplers, they don’t have 10 MHz synchronisation input so the sampling must be derived from a synchronised pulse generator or AWG;

2) synchronised by software or hardware – the sampling is derived from a trigger synchronisation hardware, either built around a phase-locked loop or a synchronised pair of frequency counter and pulse generator;

3) non/semi-synchronous sampling – Fast Fourier Transform (FFT) can be used if synchronisation is achieved by post-processing of the simultaneous sampled waveforms, e.g. by re-sampling. Or non-FFT data processing can be employed e.g. a Multi frequency sine fit algorithm.

The WB system candidate is based on dual NI 5922 samplers, asynchronous with respect to measured signals, or indirectly synchronous through a common frequency reference. The macro setup based on NI 5922 digitizers has the advantage of being easily adaptable from a single phase to a three phase measurements system. The main features are:

- flexible vertical resolution depending on the sampling frequency;
- several synchronisation and clocking strategies depending on the kind of PQ parameters under investigation;
- reconfigurable digital platforms for traditional, real time measurements and continuous acquisition for long time measurements beyond the capabilities of internal memory;
- Simple synchronisation of single digitizers for a polyphaser digitizer suitable for three-phase PQ measurements.

Calibration methods up to 1 MHz and investigation of the digitizer limitations

The traceability of the modular power system came from the calibration of the measurement components: the resistive voltage dividers, current shunts and digitizers. While methods for low frequency calibration of these components were already in use, the methods for calibration up to 100 kHz or 1 MHz were still immature. Therefore, we improved and verified these methods.

Traceable calibration methods for the transducers (voltage dividers and current shunts) were developed up to 1 MHz in terms of amplitude (ac-dc difference) and phase angle error by CMI and INRIM. The setups for calibration of ac-dc difference are based either on traditional ac-dc difference systems extended up to 1 MHz or on sampling systems using NI 5922 digitizers. The setups for calibration of phase angle error are generally based on sampling systems with NI 5922 digitizers. Two new methods of realising primary standards of ac-dc and phase angle up to 1 MHz were developed. An inter-laboratory comparison of the setups for the calibration of current shunts was performed by four laboratories (CMI, INRIM, RISE and BEV), with good agreement of the results (Figures 1 and 2).

A travelling standard suitable for comparison of Resistive Voltage Dividers (RVD) calibration methods was manufactured by CMI. Three participants (CMI, INRIM, RISE) successfully completed another comparison for calibration setups of resistive voltage dividers.

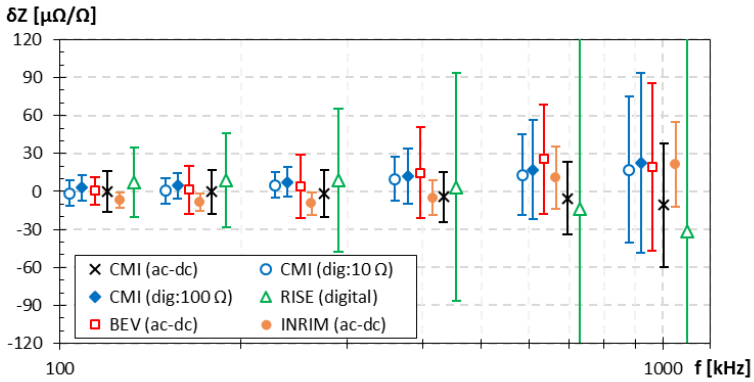

Figure 1: Comparison of ac-dc difference of current shunt 6 Ω up to 1 MHz: CMI (ac-dc) – ac-dc technique; CMI (dig:100 Ω) – digital bridge ratio to 100 Ω calculable resistor; CMI (dig:100 Ω) – digital bridge ratio to 10 Ω calculable resistor; BEV (ac-dc) – ac-dc technique; RISE (digital) – digital sampling setup; INRIM (ac-dc) ac-dc technique.

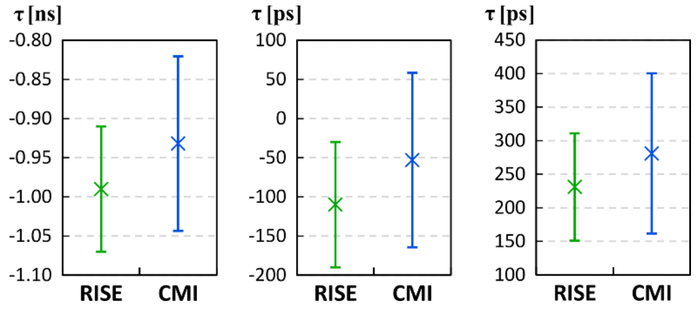

Figure 2: Comparison of time constant of a current shunt (6 Ω, 2 Ω and 0.6 Ω) at 1 MHz between RISE and CMI.

Development of traceable calibration methods for wideband digitizers for the amplitude and phase angle error up to 1 MHz was completed by CMI and INRIM. The inter-channel phase angle calibration is a straightforward method performed by using the same signal in both input channels. The setups for calibration of amplitude, (ac-dc difference), were based on traditional ac-dc difference measurements transferred to NI 5922 digitizers by a transfer standard such as another ac-dc standard or ac voltage measurement standard. These setups were also successfully compared using a micropotentiometer-based travelling standard developed by INRIM as part of the project (see Figure 3).

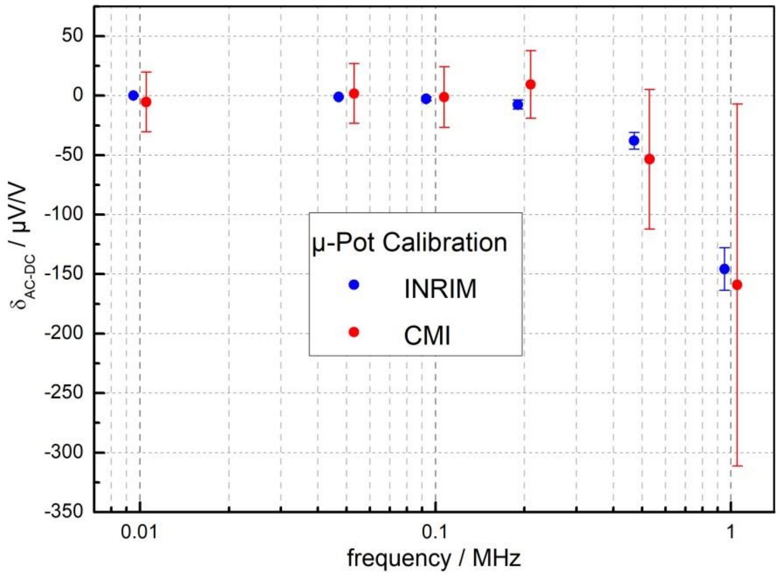

Figure 3: Bilateral comparison of µ-Pot terms of ac-dc voltage transfer difference

Possibilities for extending the record length of the data acquired by 3458A were investigated by SIQ and JV and two solutions were found. These solutions allowed continuous streaming of up to 16 Megasamples at multiple channels: i) a software-based method; ii) an additional hardware (clock box) for synchronisation of two Digital Multimeters (DMMs). The first method, i), was implemented in the developed software (SW) tools.

The short-term stability and temperature dependence were measured by CMI and methods to compensate these effects were suggested. The repeatability of the self-calibration feature of NI 5922 was investigated by CMI, and it was observed that its gain, after self-calibration, exhibited considerable variability with a standard deviation of 20 µV/V and occasional deviations of up to -90 µV/V (red diamonds in Figure 4). A special procedure to reduce the standard deviation of the self-calibration feature was tested and the fluctuation due to the self-calibration routine was reduced by a factor of approximately $1/\sqrt{N}$. This technique can be used to reduce the standard deviation of the NI 5922 whereas the absolute gain is still defined by its internal reference. The method reduced the gain of errors and short-term drifts down to about one half of datasheet values without having an external source of known reference voltage when the method is also combined with correction of the ADC temperature dependence.

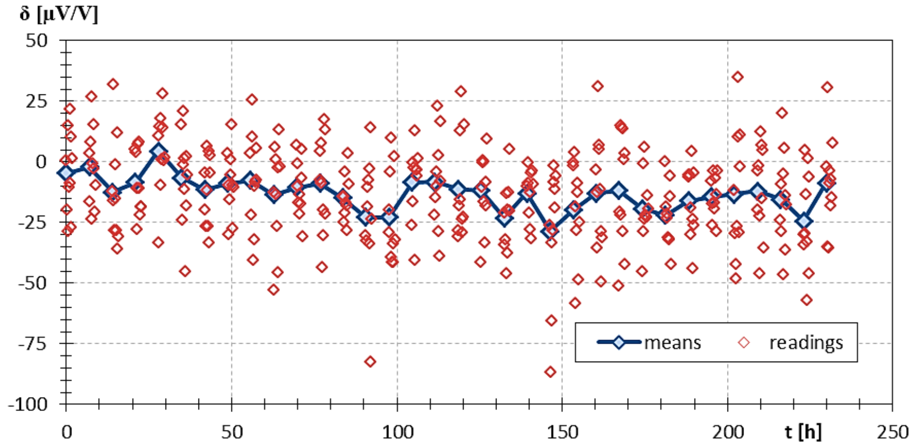

Figure 4: Example of self-calibration repeatability

The input admittance of several NI 5922 units was measured by CMI and a strong frequency dependence of input impedance was identified. The developed SW tools contain a correction mechanism to compensate its effect to the measured quantities.

Design of the new power and PQ setup

The contradictory requirements on 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 required two setups: (i) one for low frequency measurements of the highest accuracy, for which a system based on sampling multimeters 3458A was chosen; and (ii) one for wideband measurements with reduced accuracy, for which the setup is based on NI 5922 digitizers. Both of these digitizers are commercially available and are common at NMIs. Most of these institutes also have coaxial current shunts and resistive voltage dividers, either home built or purchased from another NMI or from an instrument manufacturer. Therefore, most NMIs or even private calibration labs without excessive hardware investments will be able to build these modular setups. The connection schemes and synchronisation methods of both setups were selected in order to enable multichannel, and multiphase measurements which are essential for the PQ analysis.

<u>LF setup:</u> Based on the review of existing setups it was decided to use master – slave topology as the main synchronisation method. The 3458A digitizers were synchronised with the master unit clocked either from internal timer (no additional HW needed) or from an AWG. This way no custom built HW is needed and the setup can achieve coherent sampling without modifications of 3458A. Connection of the transducers is single-ended. The new LF setup was designed by RISE and LNE.

<u>WB setup:</u> Synchronising NI 5922 channels is relatively straightforward. Two channels on the same digitizer card were always synchronised, and for synchronising two or more cards a technique using ni-TClk driver was used. This technique was developed by National Instruments and is implemented in their drivers. Depending on the type of the rack, it may be necessary to connect reference clock inputs of multiple NI 5922 cards externally. However, no external connections were needed unless the cards were mounted in different PXI racks or indifferent computers. The WB setup design was defined by INRIM and RISE.

<u>Summary of the key results and conclusions</u>

This objective was achieved. A review of published literature and an international survey of existing measurement setups, calibration methods and voltage and current transducers for the measurement of power and PQ parameters was undertaken and the most suitable setup designs were identified. Due to contradictory requirements on the setup design (to ensure both the lowest possible uncertainties and the highest possible bandwidth) the design proposal consisted of two setups: one for accurate LF measurement and one for wideband measurement with reduced accuracy.

Calibration methods for calibration of current shunts, voltage dividers and wideband digitizers were investigated with extension up to 1 MHz, developed and validated by a means of comparisons. An investigation of the limited stability and repeatability of the self-calibration routine of NI 5922 was carried out, as well as NI 5922 temperature dependence and frequency dependence of input admittance. Finally, two solutions to extend the data record length of 3458A DMMs were identified and successfully tested.

4.2 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.

Relevance to the project needs and objective

LF and WB setups were developed, verified and validated in order to check if the design meets the stated requirements on i) measurement capabilities of power and PQ with appropriate accuracy and also on ii) modularity of the design. This was required to enable variability of the setup connection and to allow integration of new hardware or algorithms as well as correction of measured data based on calibration of hardware components to keep transparent traceability.

Work undertaken

Development of the setup

Based on the design proposed in section 4.1, the final versions of both the low frequency and wideband setups were developed by CMI and INRIM and the optimal measurement conditions were identified. The LF system setup variants were designed to encompass both internal (non-coherent) sample triggering and external (coherent or not) triggering. Both LF variants were implemented in LabVIEW and LabWindows/CVI. The WB setup was developed based on NI 5922 digitizers to allow the following configurations: (i) Single phase power with single ended channels (two digitiser channels); (ii) Single phase voltage/current and power using differential digitizing; (iii) Multiphase voltage/current with single ended channels. Both setups are accompanied by current shunts and resistive voltage dividers to scale current and voltage channel/channels (Figure 5, 6).

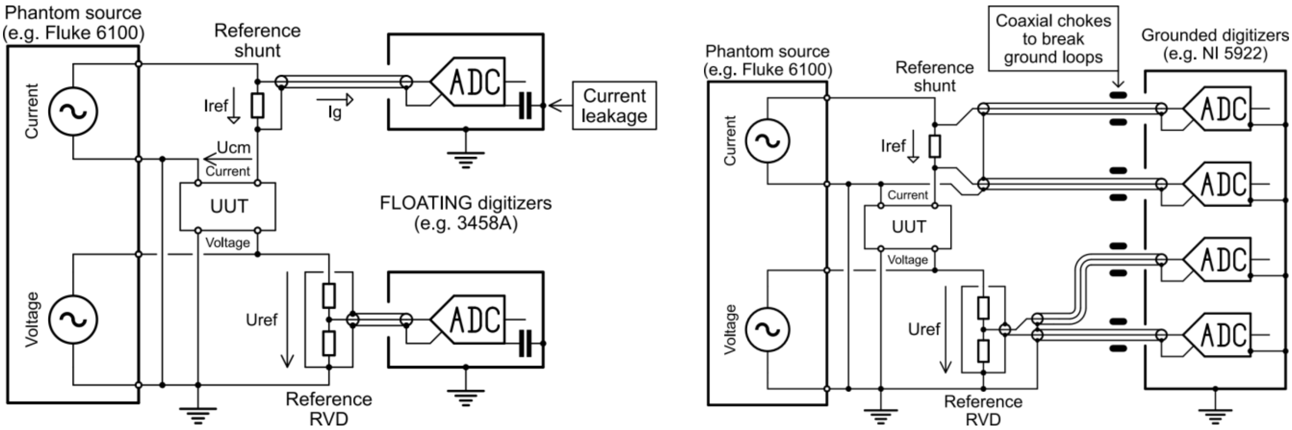

Figure 5: Developed LF setup (left) and WB setup (right). UUT: optional power/PQ analyser to be calibrated.

The setups were successfully integrated with the open SW tools developed within the project and they are described in chapter 4.3. The SW tools were suitable to control the suggested LF and wideband setups in different wiring (and triggering) configurations and to calculate various PQ parameters.

Figure 6: Example of single phase TracePQM measurement setup for calibration of power analyzer: (1) TWM measurement tool;(2) Phantom power calibrator Fluke 6105A (source); (3) Unit under calibration (Yokogawa WT3000); (4) Sampling multimeter Keysight 3458A (voltage channel); (5) Sampling multimeter Keysight 3458A (current channel); (6) External voltage divider; (7) External current shunt.

Verification and validation of the setups

The developed setups allowed for a number of different hardware setup variants, two GUI platforms and more than ten algorithms. A decision was made to verify and validate the setups for a limited number of variants of hardware setups, for the most important of algorithms which revealed eventual fails in the SW tools. Also, the tests of the algorithms and correction capabilities were limited to the LabVIEW platform, since LabWindows/CVI version shares the processing functionality.

The validation was done by BIM, Metrosert, CEM, and RISE to evaluate if the developed system has the intended capabilities such as the possibility to synchronize multiple digitizers, measure is multiphase systems, select correction files for each setup component, etc. The validation of the setups was divided in two sections – hardware and software. The validation of the hardware capabilities showed that both setups can measure normal power and power quality parameters in various synchronisation topologies and connection schemes. The validation of the software showed that both software tools support the necessary hardware and operate by the modular principle allowing to add new hardware drivers, transducer correction files or algorithms in the future. The only difference between the capabilities of the tools is the API (Application Programming Interface) of the TWM tool, which can be used for integrating the TWM tool with a user measurement program, e.g. a sequencer that automatically controls source and Unit Under Test.

The verification tests were made on functionality and accuracy, both for LF and WB setups. Verification measurements of the WB setup (based on NI 5922 digitizers) were done by TUBITAK and IMBIH and were split into four steps including testing LF measurement capability, testing differential current measurement capability, testing single-ended voltage measurement capability, and testing phase measurement capability. The possibility of calibration of resistive voltage dividers and current shunts by using modular setup was investigated. Results were compared to valid calibration certificates. Also, corrections were made for the elements of the setup using TWM tool, which successfully ensured lower relative error. The verification tests of the LF setup (based on DMM 3458A) were performed by CEM and NSAI and included a comparison of the voltage, phase, power, harmonic and flicker measuring functions with that of CEM's reference system. The targeted uncertainties were met by obtaining the target expanded uncertainties for the measurement of the amplitude of voltage harmonics with 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. Tests for the correct application of corrections were done by application real calibration data of the digitizers and transducers. The user friendliness of the test tool was assessed and a number of improvements were suggested without detecting important functionality or accuracy errors.

Summary of the key results and conclusions

This objective was achieved. The verification and validation of the developed setups were successfully completed. No major fails were identified. Only minor problems were found in regard to user friendliness of the user interface and corrective actions suggested. Those problems will be considered when new versions of the SW tool are issued. 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.

4.3 To develop an open software tool for instrumentation control, data acquisition and the calculation of electrical power and PQ parameters with full uncertainty estimation.

Relevance to the project needs and objective

The traceable measurement of PQ parameters required the establishment of an appropriate measurement setup software to control the instrumentation and collect data, and the use of algorithms to process the data and calculate the PQ parameters and their associated uncertainties. Therefore, the aim of this objective was to develop an open software tool suitable for handling the sampling systems designed for power and PQ measurements in the previous objectives, and to embrace also the data processing.

Work undertaken

A concept for the software tool was proposed by CMI, SIQ, FER and INRIM and discussed with project partners. It was based on the low frequency and wideband setup designs and experience of the partners with sampling measurement techniques and processing of the acquired data including uncertainty calculation. 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) and GNU Octave and Matlab were selected for the data processing within the software tools as users are familiar with the m-code and the scripts are directly visible to users. Based on the concept, the TWM and TPQA tools were developed with consideration of special requirements of selected software environments (LabVIEW and LabWindows/CVI, Matlab, GNU Octave). The TWM tool was developed by CMI with support from Metrosert and SIQ; the TPQA tool was developed by INRIM with support from CMI and SIQ. Power and PQ algorithms for data processing were developed by CMI, SIQ, JV TUBITAK and LNE, and validated by JV, RISE, SIQ and CMI. The algorithms were implemented into both tools including uncertainty estimators developed by CMI and SIQ.

Concept of the open software tool

It has been defined that the software tools should have the following requirements to allow transparent operation and future expandability:

- Simple expandability of the software by means of modular design. This leads to flexible addition of new types of digitizers and algorithms for data processing;
- Fast identification of the hardware and initialisation of the ADC acquiring parameters;
- Storage of data and results in unified, transparent and human readable (where possible) format;
- Separated modules for hardware control, data processing and graphical user interface;
- Estimation of power and power quality quantities;
- Monte Carlo uncertainty calculation (accurate but usually slow) or, where possible, estimation based on previous uncertainty analysis (fast estimate for interactive measurements).

The concept of a new software tool was proposed to include two parts: (i) a user interface (GUI) and instrument control module that acquires and stores the digitized waveforms (developed in LabVIEW and/or CVI); (ii) A calculation module in MATLAB or GNU Octave for data processing and uncertainty evaluation (Figure 7).

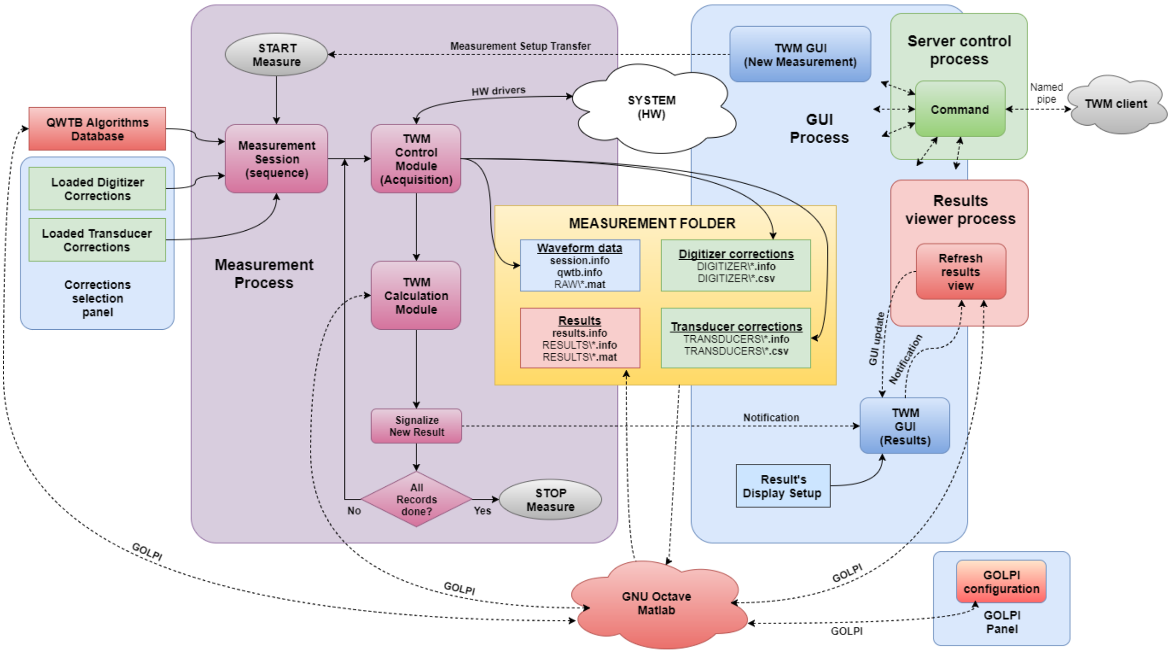

Figure 7: Concept of the software tool.

The key methods to reach modular structure relies on virtualization of digitizers and virtualization of calculation algorithms. The virtualization of digitizer provides the translation of device specific hardware commands to a generalized form (Figure 8). Different digitizers are controlled by different commands or communication interfaces. However, all digitizers have the same types of properties (e.g. sampling frequency, range etc.) and methods (e.g. start sampling, acquire sampled data, etc.). Virtualization will simplify any future addition of new digitizers to the software and ensure simple extensibility and higher usability for users outside the consortium.

Virtualization was also used for algorithms calculating power and power quality quantities. Typical inputs into all algorithms for power quality were, for example, sampled data and sampling frequency, although every algorithm used different names for variables. Such virtualization was already achieved in the toolbox QWTB developed in a previous EMRP project, SIB59 Q-WAVE. This toolbox, developed for Matlab and GNU Octave, aggregates algorithms required for data processing of sampled measurements. QWTB already contains virtualization interface because it contains data processing algorithms from different sources. Thus, the developed SW tools added another layer to interface it with the measured data and correction files.

The separation of data acquisition and data calculation makes the data processing transparent as the m-code of the scripts is directly visible to users. The same set of calculation scripts is used for calculation of parameters from the acquired data and for the uncertainty or sensitivity analysis or even simulations. Therefore, it is easy to validate calculations independently of the measurement hardware. All parts of the system, the hardware control, data acquisition, data processing etc., are integrated as one interactive application.

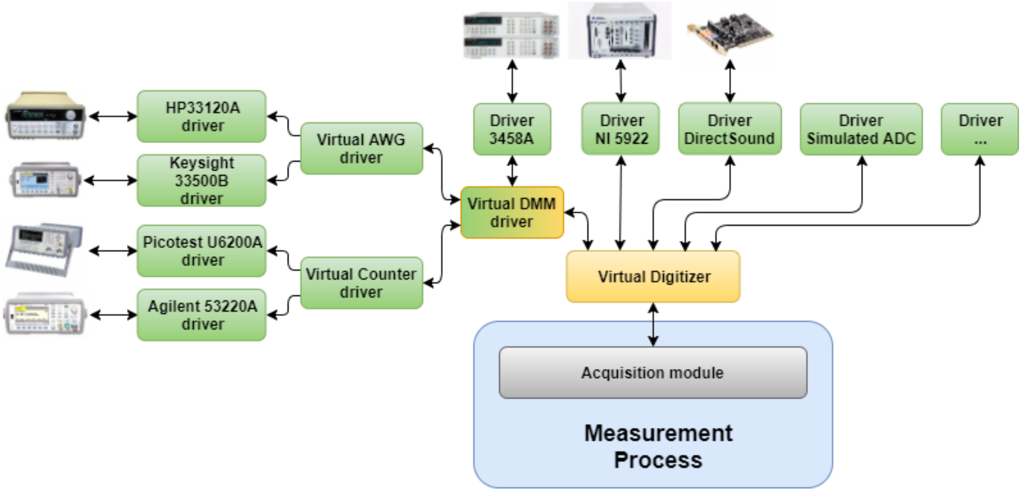

Figure 8: Concept of the virtual instrument drivers.

Development of TWM and TPQA tools

The developed TWM software tool can: (i) Digitize with the sampling multimeters 3458A, the digitizers NI 5922, or with 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 used HW 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 to TWM tool.

Algorithms and uncertainty evaluation

A total of 12 algorithms were developed during the TracePQM project (Table 1).

Table 1: Implemented power and PQ algorithms.

Name	**Uncertainty**	**Verification**	**Description**
TWM-PSFE	GUF	Yes	Single-harmonic estimation (amplitude, frequency and phase)
TWM-FPNLSF	GUF	Yes	Single-harmonic estimation (offset, amplitude, frequency and phase)
TWM-MFSF	GUF, MCM	Yes	Multi-harmonic estimation (offset, amplitudes, phases, frequency)
TWM-WRMS	GUF, MCM	Yes	RMS level calculation in time-domain
TWM-WFFT	GUF	Yes	Multi-harmonic estimation (offset, amplitudes, phases)
TWM-PWRTDI	GUF, MCM	Yes	Power parameters estimation in time-domain
TWM-PWRFFT	GUF	Yes	Power parameters estimation in frequency domain
TWM-Flicker	GUF	Yes	Flicker measurement following IEC 61000-4-15
TWM-MODTDPS	GUF	Yes	Amplitude modulation estimator
TWM-HCRMS	GUF	Yes	Half-cycle RMS detector following IEC 62586
TWM-InDiSwell	GUF	Yes	Events detector IEC 61000-4-30
TWM-THDWFFT	GUF	Yes	Harmonics and THD estimator
TWM-InpZ	None	No	Estimation of digitizer input impedance

The algorithms can be divided into several groups:

1) Single harmonic estimators – providing frequency, amplitude and phase of the single harmonic
2) Multiharmonic estimators – providing estimates of multiple harmonics at once
3) Power and RMS algorithms – providing RMS levels, power P, Q, S, PF, etc.
4) Special algorithms – Flicker, modulation, events, etc.

The developed algorithms are unique due to the ability to apply complex corrections to the errors of the setups and its components. The algorithms can apply frequency dependent corrections of digitizer and transducer errors (Figure 9). They can also apply correction for the cables used to interconnect the components based on the impedance models, which makes high frequency measurements possible with reduced uncertainty (Figure 10). Furthermore, all the algorithms are open source, so they can be further improved, debugged and reused in future measurement systems.

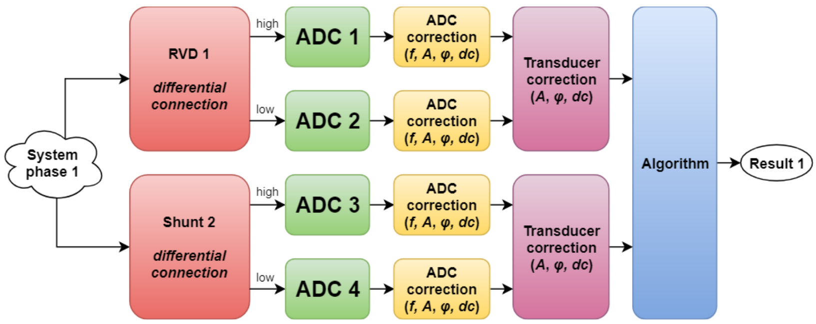

Figure 9: Example of correction scheme for power algorithm having differential inputs.

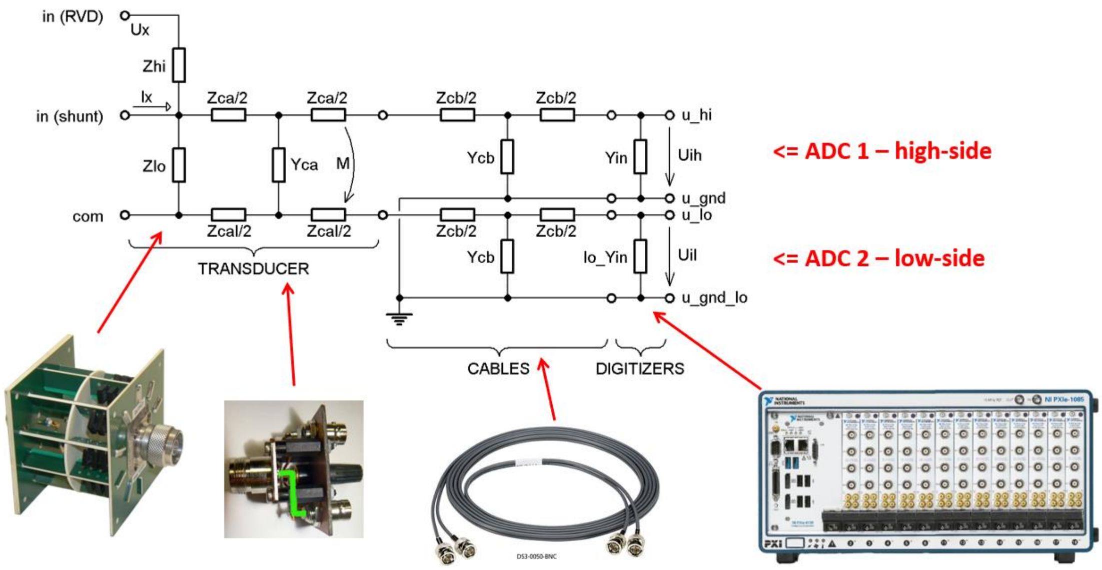

Figure 10: Example of cable correction scheme used in the algorithms.

Each of the algorithms developed was equipped by an uncertainty estimator (GUF) or Monte Carlo calculator (MCM) which considers the errors of the algorithm itself as well as all correction uncertainties. All algorithms were validated using numeric simulation under typical operating conditions. For each algorithm at least thousands of different signals and correction combinations were tested in order to discover possible failing conditions. In a second stage, the algorithms were tested on real sampled signals and the results were compared to other algorithms and/or measurement setups.

Summary of the key results and conclusions

This objective was achieved. Both the TWM tool and TPQA tool were released as open-sources and they are accessible through the project website.

The TWM software tool is being tested in several institutes both within and outside the consortium. Moreover, the TWM tool is being investigated for possible application in EMPIR project 17RPT04 VersICaL and has been already used in other EMPIR projects (such as 17IND10 LiBforSecUse or 15SIB04 QuADC).

4.4 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.

Relevance to the project needs and objective

A Good Practice Guide (GPG) was necessary to support the propagation of developed power and PQ sampling measurement setups. This guide aims to support NMIs and laboratories who intend to invest in the development of power and PQ standard based on sampling measurement techniques. This Guide provides detailed description of the components required to design and develop a practical system with full traceability to SI as well as information on measurement techniques, software tools, data processing and uncertainty estimation, supported by a comprehensive list of references to material already published in scientific literature. The document was successfully drafted, integrated, checked and validated with contribution from the project partners, LNE, BIM, CEM, CMI, FER, INRIM, JV, Metrosert, SIQ, RISE, and TUBITAK.

Work undertaken

The GPG was organised in three sections: i) instrumentation and setup designs, ii) calibration methods of the hardware components used in the setup, and iii) software tools.

I. Designs for a low frequency, high accuracy setup and a high frequency setup with reduced uncertainty were described as developed in objectives 1 and 2. The commonly used hardware components, such as digitizers, voltage dividers and current shunts were introduced, and their performance outlined. Schemes for interference free connections were also studied and described. Methods of evaluating the measurement uncertainties were provided together with some examples for commonly measured quantities. This part of the Guide was completed by LNE, INRIM, and CMI.

II. The characterisation of the hardware components played a vital role in the establishment of the achievable uncertainty of the measuring system and full traceability to the SI. Calibration methods for various components (digitizers, current and voltage transducers) were studied and described including an extension to high frequencies (up to 1 MHz where appropriate) which was developed within the project and validated by comparisons. Moreover, a system channel calibration was also described as an alternative calibration to single components. This part of the Guide was completed by JV, RISE, INRIM, CMI, LNE, BIM, TUBITAK, CEM, SIQ, and Metrosert.

III. As part of the present project, two open software tools which handle the control of the instrumentation, the data acquisition and the data processing were developed. Section 3 of the guide contains full instructions for installing, configuring, and operating the tools. This part of the Guide was completed by INRIM, CMI, and Metrosert.

Summary of the key results and conclusions

This objective was achieved. A GPG on the assembly and operation of the modular measurement setup was successfully completed and made available on the project website (www.tracepqm.cmi.cz).

4.5 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.

Relevance to the project needs and objective

The EURAMET "Strategic Research Agenda for Metrology in Europe" established that considerable metrology research is necessary to support the Energy Grand Challenge. At the beginning of the project there were only nine institutes worldwide with published CMCs for PQ measurements, of which four were from EURAMET. To further support the advance of metrology capabilities in the field of energy, including power and PQ, it was necessary that the NMIs establish their individual strategic plans for the development of electrical power and power quality standards.

Work undertaken

As a result of the activities carried out within the project, all 13 partners prepared individual strategies for the long-term operation of the capacity developed in the field of electrical power and power quality measurements covering at least the next five years. CEM prepared a draft, whereas all other partners filled in the strategy plans.

Each individual plan included: i) identification of current and future user needs for power and PQ measurements in its country; ii) priorities for collaborations with the research community in the NMI country or with neighbouring NMIs/DIs for the establishment of the required power and PQ standard; iii) future applications of power and PQ standard and possibilities for research co-operations; iv) the power and PQ measurement system to be modified or implemented v) development of a comprehensive long term plan, including economic justification, to develop the power and PQ standard based on the good practice guide; vi) establishment of appropriate quality schemes and accreditation to ensure a coordinated development of traceability for this field in Europe; vii) Gantt chart presenting the planning of the individual strategy implementation: purchase, setup, applications, CMCs improvement, etc.

These individual strategies were revised from the beginning by the most experienced NMIs in the project and the revised strategies were discussed and agreed within the consortium. This was done to ensure a coordinated and cooperative approach to the development of traceability for this field in Europe.

A report incorporating the agreed individual strategies was written and presented to the EURAMET TC-EM SC Power and Energy for comments and suggestions. The feedback is still pending at the time of this report.

Summary of the key results and conclusions

This objective was achieved. All partners prepared long-term strategies for the development of measurement capabilities in the area of power and PQ metrology. In accordance with these strategies NMIs will have, in few years, power and PQ standards, providing full traceability to the SI.

4.6 Research Mobility Grant (RMG) results

One RMG from BEV-PTP supported the project by focusing on the influence of ground currents in WB power measurement system based on NI PXI-5922 sampling cards.

Different grounding situation of the WB setup and methods to reduce the influence of ground currents were investigated by the RMG researcher. It was shown that: i) the individual ground situation of the laboratory has to be analysed, ii) the cables should be kept as short as possible, iii) the setup hardware components need to be grounded in star configuration, iv) battery operated PXI rack should be used, if possible and v) special care must be put on the ground connections due to power cord, GPIB lines and 10 MHz clock. It was also recommended to use chokes to separate ground sections where additional ground connections are necessary.

The RMG conclusions were incorporated in the GPG (objective 4), under section 1.1 "Methods for proper interference-free connections".

5 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.

6 List of publications

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[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

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7 Contact details

Work package leaders:

Stefan Svensson, RISE, stefan.svensson@ri.se

Bruno Ottavio Trinchera, INRIM, b.trinchera@inrim.it

Soccalingame Soureche, LNE soureche.soccalingame@lne.fr

Javier Diaz De Aguilar Rois, CEM, jdiaz@cem.es

Oliver Power, NSAI, oliver.power@nsai.ie