EMPIR project TracePQM: Traceability routes for electrical power quality measurements

Věra Nováková Zachovalová[1*], *Antoaneta* Yovcheva[2], *Javier* Diaz de Aguilar[3], *Raul* Caballero Santos[3], *Damir* Ilić[4], *Jasmina* Lončarević[5], *Bruno* Trinchera[6], *Kristian* Ellingsberg[7], *Hervé* Ndilimabaka[8], *Aristo* Philominraj[8], *Andrei* Pokatilov[9], *Oliver* Power[10], *Boštjan* Voljč[11], *Valter* Tarasso[12], and *Hüseyin* Çaycı[13]

[1]Czech Metrology Institute (CMI), Okružní 31, 638 00 Brno, Czech Republic
[2]Bulgarian Institute of Metrology (BIM), Boulevard G.M. Dimitrov 52-B, 1040 Sofia, Bulgaria
[3]Centro Español de Metrología (CEM), C/del Alfar 2, 28760 Tres Cantos, Madrid, Spain
[4]Sveuciliste U Zagrebu Fakultet Elektrotehnike I Racunarstva (HMI-FER/PEL), Unska 3, 10000 Zagreb, Croatia
[5]Institut za mjeriteljstvo Bosne i Hercegovine (IMBIH), Augusta Brauna 2, 71000 Sarajevo, Bosnia and Herzegovina
[6]Istituto Nazionale di Ricerca Metrologica (INRIM), Strada delle Cacce 91, 10135 Torino, Italy
[7]Justervesenet (JV), Fetveien 99, 2007 Kjeller, Norway
[8]Laboratoire national de métrologie et d'essais (LNE), 1 rue Gaston Boissier, 75724 Paris Cedex 15, France
[9]AS Metrosert (Metrosert), Teaduspargi 8, 12618 Tallinn, Estonia
[10]National Standards Authority of Ireland (NSAI), 1 Swift Square, Santry, Dublin 9, Ireland
[11]Slovenski Institut za Kakovost in Meroslovje (SIQ), Tržaška cesta 2, 1000 Ljubljana, Slovenia
[12]RISE Research Institutes of Sweden AB, PO Box 857, E-50115, Borås, Sweden
[13]Turkiye Bilimsel ve Teknolojik Arastirma Kurumu (TUBITAK), Ataturk Bulvari 221, 06100 Ankara, Turkey

Abstract Increasing demand for traceable, accurate measurements of power and power quality (PQ) parameters has resulted in an intensive metrology research effort in this area. This paper describes the objectives and activities of EMPIR project 15RPT04 TracePQM, jointly funded by the European Union and the participating countries. The overall goal of this project is to develop and validate a modular, well documented metrology grade system for the measurement of power and PQ parameters using digital sampling techniques. The first results of the research project, including the description of the system design, the software structure, results of the stability tests on wideband digitizers, and the acquisition of extended waveform records using a digitizing multimeter are presented.

1 Introduction

Electrical energy is a traded product that must be quality assured. Contractual obligations of suppliers to customers, grid design, power factor correction and harmonic mitigation all require reliable measurement of power quality parameters. It is essential that different PQ analyzers yield comparable results. With the diversification of electric power generation to include sources with fluctuating output power such as solar and wind, and the proliferation

*Corresponding Author: vnovakovazachovalova@cmi.cz

of non-linear loads connected to the grid, the measurement of electrical power and power quality (PQ) has become even more important. There is an increasing demand for access to traceable calibrations of PQ measuring instruments and calibrators which has led, in turn, to research and development of reference standards for PQ.

Thirteen categories of measurable parameters relating to power quality are listed in the international standard IEC 61000-4-30 Ed.3 [1]. Many of these parameters are associated with complex waveforms and their measurement is not straightforward. Traditional measuring methods based on thermal converters only provide information about the root mean square value of the measured signal and are not suitable for the task, so alternative measurement techniques are required. At the reference level, a few national metrology institutes (NMIs) have developed metrology grade power and PQ measurement systems based on digital sampling techniques [2-8]. These measurement systems are complex and the resources required to design, build and validate them challenges even larger NMIs.

To address the need for traceability of PQ measurements, a European wide network of such standards is required and it was with this in mind that the TracePQM project, described below, was conceived. Performing the research in the frame of a joint research project will pool existing knowledge and resources and avoid duplication of research effort and the consequent waste of resources The overall objective of the project is to design, construct, validate and describe a modular, metrology grade measurement system for power quality parameters by building on existing knowledge and expertise in the field. The main features of the measurement set-up will be its modular and flexible design, to cater for commonly used hardware components, to allow new digitizers or PQ algorithms to be easily incorporated, and an open software tool for instrument control, data acquisition and data processing. A good practice guide will assist users to build and validate a PQ measurement system to meet their needs.

The project consortium is introduced in section 2. Section 3 outlines the project objectives and the proposed work programme. In section 4, the first results, including the review of existing reference measurement systems, the system design and software structure and some results on tests on the hardware components are given.

2 Project Consortium

TracePQM is a three year project that was launched in June 2016. It is coordinated by the Czech Metrology Institute and, in total, thirteen EU NMIs from Czech Republic, Bosnia and Herzegovina, Bulgaria, Croatia, Estonia, France, Ireland, Italy, Norway, Slovenia, Spain, Sweden, and Turkey are contributing to the work. In addition, several industrial concerns and universities are involved as collaborators. A stakeholder committee comprising members from distribution service operators, instrument manufacturers, academic research bodies, and test and calibration laboratories has been established to provide guidance and advice. This will ensure that the project outcomes are relevant to the PQ community.

3 Project Objectives and Work Programme

Successful implementation of a reference standard for power and PQ parameters based on digitising techniques requires the development of both hardware and software elements .To meet the project goal, TracePQM has four main technical objectives:

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 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 and at other organisations. The target uncertainties of the modular measurement setup are to be at least four times smaller than the tolerances specified in documentary standards for PQ meters
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.

The work on this project is organised in six work packages (WP), three of which are concerned with technical and scientific matters. The first WP deals with the design, construction and validation of the measurement set-up. In fact, two designs are needed to cover the entire frequency range. Novel features of this WP include: (i) The extension of measurement and calibration capabilities for power and PQ quantities up to a frequency of 1 MHz, (ii) Continuous sample streaming using sampling digital multimeters to enable the capture and processing of extended waveforms, and (iii) improved characterisation of transducers and digitizers up to 1 MHz. In the second WP an open software tool suitable for handling high performance digital sampling systems is being developed. This software tool will: (i) be able to identify the sampling hardware equipment (ii) interact with the experimental modular measurement setup so as to ensure a direct means for the simultaneous sampling of waveforms from voltage and current transducers and (iii) provide fast and transparent calculation of power and PQ parameters and their associated uncertainties. Since the ultimate objective of the project is to assist laboratories to efficiently establish a metrology grade PQ measuring set-up that meets their needs, the production of a comprehensive good practice guide, which is the task of WP 3, is an important one.

4 Results and achievements so far

4.1 Review of existing PQ reference standards

A review of existing measurement setups, calibration methods, and voltage and current transducers for the measurement of power and PQ parameters in use by most NMIs worldwide, and already published in the literature, was conducted to serve as a basis for the design of the new modular setup. Moreover, an international survey of existing methods and their main features has been circulated, targeting European and international NMIs. Answers from 17 NMIs have been collected and analysed.

Several different types of digitizers (i.e. Keysight 3458A, National Instruments 5922/9239/4462) are used in existing setups. The setups use current and voltage transducers to scale input currents and voltages. Most commonly used voltage transducers are resistive voltage dividers, but in some cases inductive voltage dividers or voltage transformers are used. Resistive current shunts are widely used as current transducers. Current transformers were found to be used only occasionally.

The review also showed how the voltage/current channel synchronization and subsequent data processing of the waveforms differs depending upon the purpose or required uncertainty. Two main methods were identified: (i) No hardware (HW) modification or external HW are required at the cost of extensive, robust post-processing of the waveforms before any actual parameter calculation can be done, (ii) HW modification and external custom-built HW components with much less signal post-processing.

4.2 Design of the modular PQ measurement setup

The results of a preliminary survey conducted amongst the partners indicated that most laboratories have access to either sampling DMMs such as Keysight 3458A multimeter or to wideband digitizers (mostly National Instruments NI-5922).

The contradictory requirements on the setup design (to ensure both the lowest possible uncertainties and the highest possible bandwidth) cannot be met by a single measurement setup. Therefore the new design needs to consist of two setups, one of which will cater for low frequency (LF) measurements at the best accuracy level and the other for wideband (WB) measurements, but with reduced accuracy.

The review of existing measurement setups identified three candidates for the new LF system based on 3458A multimeter and one candidate for the new WB system based on NI-NI-5922 digitizer.

The three candidate LF-systems are:

1) synchronized by external 10 MHz, 3458A ext trig from Arbitrary Waveform Generator(AWG) – both generation of waveforms and measurements are synchronized via a common 10 MHz. When 3458A multimeters are used as samplers, they have no 10 MHz synchronization input so the sampling must be derived from a synchronized pulse generator or arbitrary waveforem generator;
2) synchronized by software or hardware – the sampling is derived from a trigger synchronization hardware, either built around a phase-locked loop or a synchronized pair of frequency counter and pulse generator;
3) non/semi-synchronous sampling – synchronization is achieved by post-processing the simultaneous waveforms, e.g. re-sampling based on sinc interpolation method and FFT.

Each design has advantages and drawbacks, the final choice depending on which is deemed most important.

The WB system 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. It is applicable not only to emerging research activities conducted in NMIs but also to calibration of the new class of polyphase PQ analyzers, which are designed for power network monitoring and able to reach an accuracy of the order of 0.03%.

With respect to the use of precision digitizers for the design of the WB system, the main features are:

- flexible vertical resolution depending on the sampling frequency;
- several synchronization 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 synchronization of single digitizers for a polyphaser digitizer suitable for three-phase PQ measurements.

4.3 Software structure

Initial discussions has led to the identification of the software requirements and to a proposal for the software structure. The main requirements of the software were considered as follows:

- Simple expandability of the software by means of modular design. This will lead 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 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;
- Uncertainty calculation (accurate but usually slow) or, where possible, estimation based on previous uncertainty analysis (fast estimate for interactive measurements).

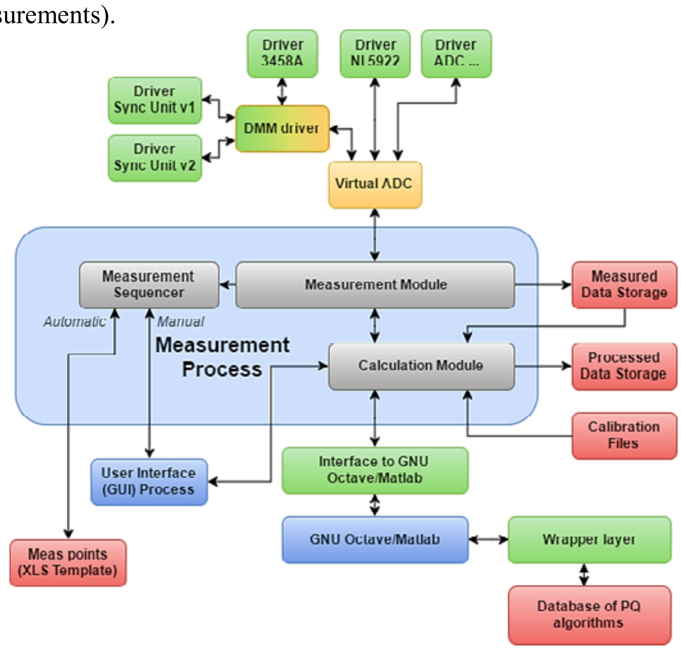

Fig. 1. Proposal for SW structure

The proposed SW structure shown is in Figure 1. The software will consist of several modules: measurement sequence generator; measurement module; hardware control; data storage; results calculation.

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. Different digitizers are controlled by different commands or communication interfaces however all digitizer have 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. The control and data acquisition part of the software will be developed in environments LabVIEW and LabWindows/CVI.

The virtualization will be also used for algorithms used to calculate power and power quality quantities. Typical inputs into all algorithm for power quality are, for example, sampled data and sampling frequency, although every algorithm use different names for variables. Such virtualization was already achieved in the toolbox QWTB [9]. This toolbox aggregates algorithms required for data processing of sampled measurements. QWTB already contains virtualization interface because it contains data processing algorithms from different sources. QWTB will be directly used in this project. QWTB was developed using high-level interpreted languages Matlab and GNU Octave.

The separation of the data acquisition and data calculation will make the data processing transparent. The same set of calculation scripts will be used for calculation of parameters from the acquired data and for the uncertainty or sensitivity analysis or even simulations. Therefore it will be easy to validate calculations independently of the measurement hardware. All parts of the system, the hardware control, data acquisition, data processing etc., will be integrated so it will appear to the user as one interactive application**.**

4.4 Investigation of the selected digitizers

4.4.1 NI-5922 Digitizer

The short term stability and temperature dependence of the NI-5922 internal reference was analysed. A chassis containing several NI-5922 modules was placed in a thermo-regulated air bath whose temperature was cycled linearly from (23 to 30) C over 3 days. The measured temperature dependence of the gain was linear, repeatable with a relative temperature coefficient in the range (-8 to -14) µV/(V°C).

The repeatability of the self-calibration feature of the NI-5922 was investigated. As shown in figure 2 the NI-5922 gain, after self-calibration, exhibited considerable variability with a standard deviation of 20 µV/V with occasional deviations of up to -90 µV/V (red diamonds in figure 2).

The following procedure to reduce the standard deviation of the self-calibration feature was tested. First, the NI-5922 was connected to an unknown but stable voltage source *U*ref. The self-calibration of the digitizer was performed and the digitizer reading $U_X(n)$ recorded. This sequence of calibration and measurement was repeated *N* times and the average digitizer reading *U*x was calculated (blue diamonds in figure 2). The gain error after the last self-calibration G_E can be evaluated as $G_E=U_X(N)/U_X-1$. Next the digitizer was connected to the device under test and the measurement proceeds. The result was corrected using G_E. Thus the fluctuation due to the self-calibration routine was reduced by a factor of approximately $1/\sqrt{N}$.

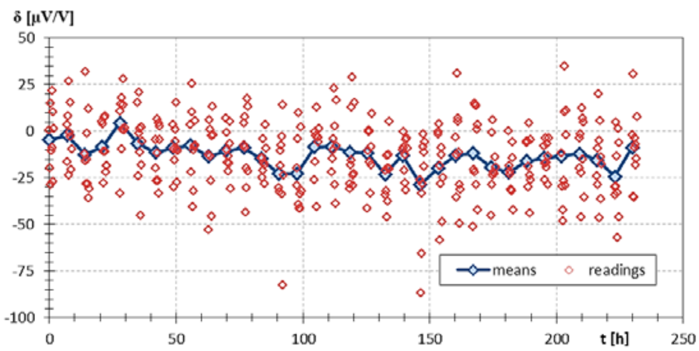

Fig. 2. Example of self-calibration repeatability

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. When combined with correction of the gain by measurement of temperature of the ADC it can reduce gain errors and short term drifts down to about one half of datasheet values without having an external source of known reference voltage. Further investigation of other ADCs is needed in order to validate the conclusions.

The input admittance of several NI-5922 units has been measured and a strong frequency dependence of input impedance was identified. This is very important for HF measurements where the current shunt or voltage divider will be loaded by the frequency-dependent input admittance of the NI-5922. Further investigation of the stability of the input admittance is in progress.

4.4.2 Keysight 3458A Multimeter

3458A multimeters are usually equipped with internal memory so that the samples are stored in memory in real time even at the highest sampling frequencies. When sampling is terminated, the stored values can be read from memory. However, the size of the internal memory is limited and, at the highest sampling frequency, only a few seconds of the sampled waveform can be captured. This relatively short time interval is insufficient for some power and power quality measurements so a different approach is required.

In our approach, we directly connected the 3458A to a PC via NI USB-GPIB controller. The 3458A is initialized, i.e. we define the aperture, number of readings (NRDGS), sampling frequency, and voltage range, set DVC digitizing and read the scaling factor (ISCALE). The triggering is set to AUTO (TRIG AUTO) and arming to SYN (TARM SYN). This configuration starts sampling immediately after the USB port is ready to receive the data. The samples are then transferred from DMM to internal PC's memory one by one until the predefined total number of samples is read. However, the maximal NRDGS supported by the 3458 is limited to a maximum of 16777 512. If a higher number of samples is required the reading loop needs to be repeated. This approach is compatible for different generations of 3458A models and allows continuous sampling even at the highest supported sampling frequencies (i.e. 100 kHz for SINT and 50 kHz for DINT memory format) since the USB bus allows smooth data transfer in real time. Additionally, the total number of samples is virtually limited only by the memory size of the PC. One major drawback of the approach is the missing samples between the loops (about 40 ms) when another reading loop to be reinitiated.

If PQ measurements need sampling of more waveforms (i.e. voltage and current, voltage in three phases etc.), the approach described above should be modified to allow connection and sampling of at least two (or several) multimeters. A few solutions might be possible:

- development of specially designed external hardware (memory) which would allow simultaneous writing of the data received from the GPIB and simultaneous reading from the PC (this solution is currently under investigation),
- two (or more) 3458A multimeters connected through two (or more) NI GPIB-USB controllers connected to one PC (the solution might not be appropriate especially when high sampling frequencies are needed),
- two (or more) 3458A multimeters, connected through two (or more) NI GPIB-PCI cards inserted in one PC (this solution is currently under investigation),
- two (or more) 3458A multimeters, connected through two (or more) NI GPIB-USB controllers connected to a master and slave PC.

The last solution was successfully tested and is currently fully operational. In this case, we need to connect the external output of the master 3458A to the trigger input of the slave 3458A and set the multimeters accordingly. Most settings (TARM, aperture, sampling frequency, NRDGs and number of loops) are the same but the master multimeter is set to EXTOUT, APER, NEG and slave to TRIG EXT. In this configuration, the software for the slave is started first. The slave multimeter is initialized and waits for an external trigger from the master in order to start the first loop. Then the software for the master is started. After initialization of the master, it triggers the slave and afterwards both multimeters synchronously sample the waveforms. The measured delay between the master and slave due to triggering and non-synchronized internal clock is of the order of 1 μs.

5 Conclusion

The objectives and planned work programme of TracePQM, "Traceability Routes for Power Quality Measurements", a joint research project to develop a modular metrology grade measurement system for PQ parameters, has been described. Based on a comprehensive review of existing PQ measurement systems, three candidates for an LF measurement set-up based on Keysight 3458A multimeter, and one for a HF system based on an NI-5922 digitizer have been identified. A software structure has been outlined which is flexible and can be readily adapted to incorporate hardware changes or the addition of new algorithms. Performance tests on the NI-5922 digitizer have shown a relative temperature coefficient in the range (-8 to -14) μV/(V°C). The variability of the digitizer gain due to repeated operation of its self-calibration feature has been studied and a method of improving its performance is suggested. A method of overcoming the limited size of the Keysight 3458A multimeter's internal memory has been implemented so that extended waveforms can be sampled at the multimeter's highest sampling frequency.

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