Publishable Summary for 17IND06 FutureGrid II
Metrology for the next-generation digital substation instrumentation

Overview

To support the European electrical power industry, this project provided missing solutions for the calibration and the timing of the new type of substation instrumentation according to IEC 61850 to accomplish the objectives for "establishing calibration methods to support testing of digital instrument transformers", "providing references for instruments with digital input or output", "developing tools for devices that exploit sampled values in digital substations" and for "developing traceable references for the verification of time and synchronisation methods". The project also supported standardisation organisations in their work on new or revised standards that will enable more precise measurements in the future.

Need

The decarbonisation of energy systems has been causing significant and unprecedented changes in electrical power grids, due to the wide-scale introduction of decentralised renewable energy resources. Consequently, future electrical power grids have required real-time capable control and monitoring systems to ensure stability under increasingly complex and challenging conditions. The associated digital high voltage sensors and digital metering systems had to be managed through accurate and reliable time synchronisation in a wide area. This was reflected in project Objective 4.

New standards in the IEC 61869 had previously been published for low power instrument transformers (LPIT) or were expected to be released for the electronic current and voltage transformers in the future, as well as for stand-alone merging units (SAMU) in 2018. Due to the introduction of these new standards, the movement from traditional analogue instrument transformer (IT) technology towards the new digital instrumentation technology was expected to gain speed, both on transmission (>100 kV) and on distribution (<100 kV) level. To support this change, new metrological tools and methodologies were needed. The need to provide test systems for new LPIT and SAMU technology was addressed in this project in Objectives 1 and 2. Also, test systems were needed to prove performance of intelligent electronic devices, like digital energy meters or real-time critical all-digital PMU's. This was addressed in this project in Objective 3. Lastly, to enable industrial uptake and uniformity, active support of standardisation organisations was required, which was addressed in Objective 5.

Objectives

The overall objective of this project is to develop the necessary metrological infrastructure for closing the gap in the traceability chain between measurements made in fully digitally operated substations and the realisation of the relevant units in National Metrology Institutes. This includes characterisation of required industrial products, e.g. digital phasor measurement units, digital instrument transformers and sensors and to provide proposals for implementing time stamping of sampled values according to IEC 61850-9-2 using alternate time dissemination protocols in substation. This is required for the successful transition of the present electricity grid towards a modern future power grid.

The specific objectives of the research were:

1. To establish **calibration methods to support dynamic testing of digital instrument transformers** (IT) for rated voltages up to 400/√3 kV and at least 2 kA. In addition, to support technology integration into digital substations, including real-time monitoring systems associated with power quality (PQ) and synchrophasor measurements with uncertainties from 30 ppm under laboratory conditions and up to 0.1 % under on-site conditions.

2. To develop **reference standards for the calibration of instruments with digital input or output to support the transition to digital substations**. Such devices to be tested are stand-alone merging units, which are disciplined by either GPS or PTP or digital measuring instruments (e.g. energy meters). This includes studies on synchronisation of sampling processes, on increasing sampling rates beyond those specified in IEC standards, and on the accuracy of distributed digital power measurements
3. To develop metrological **tools for the characterisation of devices that exploit sampled values in digital substations**, for the verification of all-digital power and power quality meters and phasor measurement units (PMUs). This includes e.g. studies on limitations due to latency and computation time, and characterisation of error sources in order to provide proposals for an enhanced protocol for sampled values.
4. To develop **traceable reference standards for the verification of UTC time dissemination and synchronisation methods**. This includes study on techniques and algorithms such as PTP and White Rabbit for the synchronisation to a common time reference, both within and between digital substations. In addition, to carry out studies on secure protocols for time dissemination. To develop and validate satellite-independent PMU utilising distributed sensors.
5. To **facilitate the take up of the technology and measurement infrastructure developed in the project.** Target stakeholders included the measurement supply chain (instrument manufacturers), standards developing organisations (IEC TC38 WG 55, IEC TC57 WG 10, IEEE TC39, IEEE P1588) and end users (energy distribution companies).

Progress beyond the state of the art

Substation automation using the IEC 61850 suite of protocols has been extended by the IEC 61869-9 standard, which allows transmitting time stamped sampled values from the high voltage instrument transformers over a local area network within the substation.

Before the EMRP ENG61 “FutureGrid” project, there was no traceability at NMI level in Europe for the digital type instrument transformers or the devices which make use of the transmitted SV, like metering. In that project, some measuring systems for the non-conventional instrument transformers under steady-state conditions at power frequencies have been established.

This project builds on foundations laid in the previous “FutureGrid” project and extends developments to issues which were not covered before for (i) dynamic characterisation of the instrument transformers, (ii) developing reference standards for calibrating instruments with digital input or output, (iii) metering and PQ monitoring based on sampled value and (iv) traceable references for the verification of UTC time dissemination and synchronisation methods. This project improved on the state of the art regarding these objectives by:

(i) Provide measuring systems and calibration services for digital, time synchronised current- and voltage sensors up to 100 kV and 2 kA. Such systems were not available to this extent.

(ii) Provide reference SAMU with an overall uncertainty of 10 ppm and around 10 µrad including calibration service for commercially available SAMU. Before the project, no such reference existed, and no institute worldwide offered calibration service for one.

(iii) First, new testing tools for energy meters based on timestamped SV data stream (61850-9-2 and 61869-9) were created. Second, PMU algorithms has been implemented for use with the SV protocol in order to demonstrate novel all-digital phasor measurement units.

(iv) Security for time transfer has been advanced by participation in meanwhile published standards (IETF RFC8915 and IEEE 1588 PTP v2.1). Further, a novel satellite-independent PMU measurement system with a synchromerger have been developed, which can handle up to 50 distributed photonic measurement devices over a 50 km radius.

Results

Objective 1: To establish calibration methods to support dynamic testing of digital instrument transformers

First, a novel database of relevant high voltage waveforms associated with power quality measurements, based on real phenomena, was set up. The programmable and time-synchronised high voltage and high-current generation up to 100 kV and 2 kA, capable of producing these PQ relevant waveforms has been integrated in partners measuring systems. Whereas waveform generation of complex low-level signals is not a new field, but the application to, and implementation with the high voltage and high current testing for instrument transformers and sensor can be considered new in Europe.

Second, measuring systems for current- and voltage sensors were set up at different partners. The measurement-related functions for calibrating digital voltage or current transformers and the associated time synchronisation to PPS via either PTP (IEEE 1588), IRIG-B or GPS based time receivers were made ready. In summary, the current sensor calibration system can measure with basic uncertainties of 30 ppm and 60 µrad. The voltage sensor calibration system can handle voltages up to 100 kV with basic uncertainties of 50 ppm and 50 µrad. One existing high voltage facility can handle the extend range 400/√3 kV with the developed measuring systems. Before the *FutureGrid II* project, only some institutes in Europe or even worldwide had been able to offer calibration services in this field at all, and the uncertainties in this field had been higher than 100 ppm (or µrad).

Further, a new (first-in-the-world) universal comparator was finalized, able to compare any type of voltage or current sensor even in the presence of PQ / PMU events within a frequency spectrum up to 9 kHz. Further developments have yielded another device, capable of carrying out a real-time calibration of large digital instrument transformers installed at the substation busbars by comparison to a traceable voltage transformer, and also with the completely new capability of simultaneously analysing tens of different sampled value data streams to obtain a distributed PQ measurement functionality within a smart substation.

Additionally, a multi-purpose calibration system for on-site measurements was built. Each part of the system can be used individually for current or voltage transformer calibrations, including those with digital outputs. The setup including the comparator used for the calibration under current harmonics up to 50^{th} order was characterized with the uncertainty of well below 200 ppm which is quite better than the targeted uncertainty of 0.1%. This substantially improves previous state of the art capabilities in Europe.

Furthermore, several recommendations have been contributed to the new standard developed in IEC TC38 working groups – see impact. Overall, the conclusion of these achievements represents the finalisation of all aspects of Objective 1 by the project consortia.

Objective 2 To develop reference standards for the calibration of instruments with digital input or output to support the transition to digital substations

First, a reference SAMU was built on a collaborative design of a self-built digitizer for the reference SAMU as well as for a distributed digitizer. The partners calibrated the reference SAMU, based on a new method developed for calibrating the delay of the analogue front ends of the internal ADC cards. In the Good Practice Guide, associated to this objective this new method was described. With this setup, an overall uncertainty of 10 ppm and about 28 ns (around 10 µrad) was achieved. Before the *FutureGrid II* project, no such reference SAMU had existed, and no institute worldwide would have been able to offer calibration service for one. This accuracy fully satisfies requirements as a reference standard with respect to the defined error class of commercial SAMUs down to the class 0,05. The reference SAMU and other project-developed references for SAMUs were already used as references for multiple customer calibrations.

A three-phase set of active current clamps for conventional CTs with rated secondary currents of 1A or 5A as an option for the reference SAMU were developed. The calibrated results of three active current clamps were below 0.015 % for the ratio errors and below 0.04 crad for the phase error. The uncertainties of the calibration results are 50 ppm and µrad (k = 2). Another self-built current clamp with a splitable magnetic core and a 3D printer was used for the fabrication of the current clamp case, with much better errors of below 30 ppm and µrad and improved uncertainties could be obtained. All of this constituted an improvement over the state-of-the-art before the project.

Furthermore, asynchronous sampling processes of the Sampled Values have been simulated. Several resampling algorithms have been developed and evaluated. One of these algorithms is enhanced with respect to the known published algorithms and is capable to achieve an uncertainty that is negligible (far below 10^{-6}) in context to the other uncertainty contributions of the system.

Overall, the conclusion of these achievements represents the finalisation of all aspects of Objective 2 by the project consortia.

Objective 3: To develop metrological tools for the characterisation of devices that exploit sampled values in digital substations, for the verification of all-digital power and power quality meters and phasor measurement units (PMUs).

First, to support metering applications based on SV, two platforms for receiving or sending the timestamped SV data stream were created. The first software platform was tested against two commercial devices to demonstrate their functionality. For more time critical applications, where seamless streaming from and to SV based equipment is required, a microcontroller-based SV-Generator and an SV-Receiver were built up and successfully tested with two commercial SAMU's, two instrument transformer bridges and with a commercial digital energy meter. The required software functionality for waveform generation and power meter algorithms was developed. This second platform makes use of the old 61850-9-2 sampled value protocol as well as the enhanced new protocol 61869-9 for higher sampling rates of 14.4kS/s in 50 Hz systems. Furthermore, effects on accuracy of electrical power and energy were simulated for different types of ADCs, number of bits, noise and jitter. Using this platform, an all-digital power and energy meter has been finally tested for the first time in Europe.

Second, for the PMU related aspect, a particular PMU algorithm has been identified and implemented for use with the SV protocol. It allowed to perform accurate measurements of the impact on PMU reporting latency. An open-source library for measuring PMU reporting latency was published and an extension to a Real Time Digital Simulator (64 PMU data streams) was developed. An integrated (Stand Alone Merging Unit) with Phasor Measurement Unit (PMU) functionality has been built and tested, implementing SV based on IEC 61869-9. The synchrophasor estimation algorithm has been optimized for computation performance to minimize delays as well as performance requirements in terms of CPU and RAM. This device is the first one in Europe, that is ready for commercial use.

A further development has taken advantage of the SV extraction feature. A simple and new differential protection algorithm was developed and compared it with strategies involving commercial PMUs and relays. The system was implemented performing the FFT from two different grid points and applying a fault criterium following the typical configuration of 87-L relays allowing the comparison with the other strategies. The developed new SV algorithm showed better tripping time than PMU solution and is near to the tripping time of conventional solutions.

A data compression method for the SV protocol was enhanced and tested under real world conditions. The software package was made publicly available. It was designed for streaming raw measurement data, similar to the IEC 61850-9-2 Sampled Value protocol. It was designed to support high sample rate continuous point on wave (CPOW) voltage and current data and supported other measurement types. The developed data compression is lossless.

Overall, the targeted tools for the characterisation of devices exploiting sampled values in digital substations have been successfully created.

Objective 4: To develop traceable reference standards for the verification of UTC time dissemination and synchronisation methods

Firstly, over the course of the project, PTB continued its established work on security for the Network Time Protocol (NTP) in the Internet Engineering Task Force (IETF). This culminated in the publication of the Network Time Security (NTS) standard as RFC 8915, which marked the first time that users could use NTP in a secured (authenticated) fashion that was both reliable and scaled well (a server can serve large numbers of clients). While the accuracy here is not in line with the goals for smart grids, secure NTP can still be a valuable control tool for other synchronization.

Based on the experience gathered from NTP related work, PTB conducted research on security and self-assessment measures for PTP. Results were constantly transferred to the IEEE 1588 WG developing and maintaining the PTP standard, to facilitate improved PTP security. Some of this input was reflected in version 2.1 of the PTP standard (IEEE 1588-2019), which details about 20 main changes, three of which were related to PTB's input to the working group: adding security data, options for monitoring, and a high-accuracy profile oriented on White Rabbit. Transferability of PTP security methods to White Rabbit was found to be high.

Further, work on satellite-independent PMU measurement using distributed photonic sensors was completed. A synchromerger was finished, intended for up to 50 distributed photonic measurement devices over a 50 km radius. The PMU algorithm can be executed externally (cloud-based) using SV measurements or can be executed directly on the measurement device for real-time applications. This yielded a completely new technology for conducting wide area monitoring measurements without the need of time transfer to remote locations. The proof-of-concept setup was operated by a central interrogation unit, which by necessity required a calibrated time link. However, the far ends consisted of passive fiber links, with distances up to and beyond 30 km. This way, a measurement system covering a geographically significant area could be established, with only modest requirements for timing infrastructure.

In the Good Practice Guide, associated to this objective a collected overview was presented on how to assess both the accuracy and reliability levels and relate them to the required effort, for different digital methods of synchronizing clocks (such as PTP and White Rabbit, but also NTP or GNSS). The novel presented process enabled end users to judge the three aspects for (existing or future) possible technologies used to realize required time synchronization, all illustrated with numerous examples.

Overall, work on the targeted traceable reference standards, security methods and distributed PMU validation has been successfully finished.

Impact

To ensure that the power systems scientific community benefited from these new or enhanced measurement capabilities, the following ways of disseminating project results were pursued:

- Peer reviewed open access scientific publications (39) some of which are highly cited
- Conference presentations or posters (33)
- Two stakeholder workshops were organised. The project members regularly reported to meetings of IEC TC 38 WG 47 to reach a wider audience and in particular the scientific community.
- Due to the projects partner structure, a close cooperation between the partners from universities and NMIs also supported the transfer of knowledge between the metrological and scientific community.
- The project published 7 datasets, five of these are datasets were required for publications, another one is a dataset of measured 3-phase medium voltage and current waveforms from a MV grid, and the last is a Software Library with a method for lossless compression of power system data.
- Two Good Practice guide have been compiled and made publicly available via the project's ZENODO community
- Articles published in a trade/professional press (11). One of them is not open access. Another is accepted for publication in the CIGRE ELECTRA #319 WG A3.31 Report on "Accuracy and Calibration of Instrument Transformers with Digital Output". The remaining articles are open access.

Impact on industrial and other user communities

The project has improved, and extended, electrical power and energy metrology infrastructure at the level of NMIs, universities, research centres and two SME's providing solutions for the control, protection, and monitoring of power networks. This covered calibration facilities for the instrumentation with SV (such as instrument transformers, SAMUs, energy meters and all-digital PMUs) and enhanced capabilities for time dissemination. The stakeholder committee included 29 members at the end of the project and has received regular newsletters. Stakeholder-supplied digital instrumentation has been successfully used for testing plausibility of project-developed measuring systems. Two industrial stakeholder workshops were held. At least 5 calibrations were carried out with respect to SAMU's, a digital energy meter and a high voltage digital instrument transformer. Associated companies were European companies. 5 follow-on collaborations with European companies were realised. One of this is a common IP exploitation on the development of commercial PMU/Merging Unit device.

Impact on the metrology and scientific communities

The project developed new and demanding measuring techniques and capabilities with claimed near future additions or extensions to CMC statements. Further knowledge dissemination to the metrology and scientific communities. The project and its objectives were presented in several meetings and workshops e.g. the Power and Energy Experts Meeting, Satellite Meeting CPEM 2018, and to a workshop of a transmission system operator.

Impact on relevant standards

This project generated results valuable to standardisation work within e.g. IEC, CENELEC and IETF/IEEE. Liaisons were accomplished by members of the project, who were active within the respective committees. The partners who were members of corresponding technical committees have been informing them about the results of this project and endeavouring to ensure they were incorporated in any updates to the standards.

- Workshops or informational meetings with standardisation bodies. The project, its activities and early research results were presented during several standards related meetings, e.g. IEC TC 38 and CENELEC TC 38. This led to more in-depth presentations and discussions with e.g. IEC TC38 / WG 47.
- Input to new or updated standard documents. Project partners actively participated in various concrete working groups in Standardisation Bodies by either face-to-face meetings or web meetings.
    - JWG 55 of IEC TC 38 “Uncertainty evaluation in the calibration of Instrument Transformers”. The key output was the Technical Report IEC/IEEE TR 61869-105, which is now in the committee draft status. The forecasted publication date is November 2022. This stands as a common viewpoint of the evaluation of uncertainty in calibration and its application in testing procedures for ITs.
    - WG 47 of IEC TC 38 “Evolution of Instrument transformer requirements for the modern market”. The partners worked on some preliminary documents relevant to uncertainty requirements of digital instrument transformers for PQ measurements and about the implementation of PMUs, which were circulated in IEC TC 38.
    - WG ntp of area “Internet” (int) of IETF “Network Time Protocol”. Input to various drafts was given to the draft “draft-ietf-ntp-using-nts-for-ntp”, which was made into a standards track RFC document in September of 2020. Project partners plan to continue to be involved in the WG, especially aiming at taking influence on the upcoming NTP version 5.
    - Subcommittee “Security” of WG PNCS “Precise Networked Clock Synchronization” of IEEE. Input was given for revision 2.1 of the standard document P1588 “Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems”. Project partners continue to be involved in the WG, with a specific interest of White Rabbit security.
    - Involvement in the activity of the IEC TC38 WG37 of the new IEC 61869-7 (Low Power Electronic Voltage Transformer) and IEC 61869-8 (Low Power Electronic Current Transformer) has led to tangible progression in the development of standards. Both Standards include Analog and Digital output of Low Power Instrument Transformers were already sent to TC38 Secretary for circulation and the IEC 61869-8 is now in the committee draft status. Both are forecasted for publication in December 2022. Project partners plan to continue to be involved in these activities.

Longer-term economic, social and environmental impacts

This project is supporting the transition of the grid from analogue to digital control, which may take decades as large-scale replacement of equipment is necessary. The use of such new next-generation ITs and PMUs in digital equipped substations is the prerequisite for successful integration of wide-scale connection of decentralised renewable energy sources in the high voltage distribution and transmission grid and for ensuring stability of the highly vulnerable European power grid under these increasingly complex and challenging conditions. The project facilitates this by providing test and calibration systems for these digital instrumentations. The project results are directly impacting the competitiveness of European industry in their endeavours on the international market for electricity supply, by providing them with the metrology tools to unambiguously prove the quality of their equipment. This quality is one of their prime selling arguments giving European industry a decisive global competitive advantage. To meet the requirements for a substantial impact in the long-term, the following project outputs provide benefits to industrial end-users and stakeholders:

- Many new or enhanced measurement capabilities are ready for digital or non-conventional instrument transformers, stand-alone merging units, digital energy and PQ meters as well as all-digital phasor measurement units by the NMIs, universities and research centres. This now largely support the procurement of new systems or components for the digital instrumentation in high-voltage substations. Target beneficiary groups are transmission and distribution system operators (TSO, DSO) and major equipment manufacturers.
- A metrological infrastructure for steady state and dynamic measurements on digital instrument transformers by providing proper calibration services including scheduled CMC submissions from three partners. Beneficiaries are manufacturers and purchasers of such equipment.
- Reference measuring systems for stand-alone merging units with time synchronisation by providing proper calibration services including scheduled CMC submissions from two partners. Further Test

systems for digital energy and PQ meters are available from two partners. Target beneficiary groups are transmission and distribution system operators (TSO, DSO) and major equipment manufacturers.

- Improved standardisation by providing input or recommendations to several standards related to instrument transformer technology (IEC TC38) and related to time synchronization (IETF, IEEE)
- Improved knowledge and expertise in the European Metrology landscape in the field of testing new digital substation instrumentation technology.

List of publications

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Project start date and duration:	01 June 2018, 36 + 4 months = 40 months	
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