Publishable Summary for 21NRM02 Digital-IT
Metrology for digital substation instrumentation

Overview

Due to the wider use of decentralised renewable energy resources, future electrical power grids require real-time control and monitoring to ensure their stability under more challenging conditions. Digital substation solutions according to IEC 61850 and IEC 61869 are increasingly replacing analogue instrumentation which are approaching the end of their useful lifespan. To support the European electrical power industry, this project will provide the currently missing solutions for the calibration and timing of new types of digital substation instrumentation, e.g. sampled value (SV) enabled equipment such as stand-alone merging units (SAMUs), digital instrument transformers and instrument transformer measuring bridges. The project will also support IEC TC 38 'Instrument Transformers' in their work on the revision of the related standards, with the goal of proposing solutions for more precise measurements of digital substation instrumentation.

Need

The decarbonisation of energy systems has resulted in significant changes in electrical power grids, due to the wide-scale connection of decentralised renewable energy resources. Future electrical power grids need real-time capable control and monitoring systems to ensure stability under increasingly complex conditions, as well as metering systems, to ensure fair trading of electrical energy.

New standards in the IEC 61869 series (on instrument transformers) have helped to address the digital communication of new electronic instrument transformers, as well as SAMUs (which are digitisers for analogue instrument transformers). The IEC 61850 standard series (on communication protocols for intelligent electronic devices at electrical substations) is also under revision and adding new definitions for routable SV data in order to establish a truly real time wide area measurement system. These new standards have helped to boost the transition from traditional analogue instrumentation towards new digital substation instrumentation technology, both on transmission and on distribution level. However, to be able to fully support this change, standardisation bodies need to further develop their standards to include the metrological aspects of digital substation instrumentation.

Currently, there is a lack of calibration methods and metrological infrastructure for new digital substation instrumentation e.g. SV enabled equipment. Therefore, new metrology-level facilities are needed to be able to test and to validate the performance of such intelligent electronic devices (IEDs). Further to this, solutions for higher sampling rates and PTP timing required by the new standards (for digital substation instrumentation) need to be developed.

The importance of this topic and its needs have been highlighted in the European Network of Transmission System Operators for Electricity's (ENTSO-E) new "*Research, Development & Innovation Roadmap 2020 – 2030*", where digitalisation is one of the four structural trends identified as affecting the European power system of which '*digitally-enabled substations of the future*' are a critical part. In addition, IEC TC 38 has recognised digital substations as one of the emerging trends related standardisation in their Strategic Business Plan. Finally, EURAMET's European Metrology Network for Smart Electricity Grids (EMN SEG) has identified digital substations as one of the key priorities in their strategic research agenda.

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The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

Objectives

The overall goal of this project is to develop the metrology infrastructure for the traceable measurement and calibration of digital substation instrumentation (i.e. SV enabled equipment such as SAMUs, digital instrument transformers and instrument transformer measuring bridges).

The specific objectives of the project are:

1. To **develop and calibrate reference systems (hardware) for calibration of SV enabled equipment**, covering the new requirements of recently released IEC standards. To develop new hardware for traceable measurement of new data rates up to 96000 samples per second (SPS), for the related measurement bandwidth up to c. 40 kHz.
2. To **develop software for controlling the setups and handling of SV data streams** and develop new data processing and uncertainty estimation approaches for new data rates up to 96000 SPS.
3. To **develop communication and timing networks**, in participating laboratories, by creating ethernet networks that will transmit SV data and Precision Time Protocol (PTP)-based timing between commercial devices. To **establish a traceable link between PTP timing and 1PPS (One Pulse Per Second) reference pulse** with a target uncertainty of 100 ns.
4. To provide the data, methods, guidelines and recommendations, which are necessary for the calibration of SV enabled equipment, to IEC TC 38. To integrate the plans for future research activities on the European Metrology Network for Smart Electricity Grids (EMN SEG).
5. To contribute to the standards development work of the technical committee IEC TC 38. Outputs will be in a form that can be incorporated into future standards at the earliest opportunity and will be communicated through a variety of media to the standards community and to end users (equipment manufacturers, transmission system operators (TSO), distribution system operators (DSO), and customers).

Progress beyond the state of the art and results

Primary reference systems for calibration of SV enabled equipment

Steps towards developing the capability to calibrate SV enabled equipment were taken in the preceding 17IND06 FutureGrid II project. Basic calibrations of SV based equipment are now possible by some National Metrology Institutes (NMIs) using their SAMUs, however they are only for basic measurements like Root Mean Square (RMS) voltage and RMS current. In addition, traceable measurement services are limited mainly to low sampling rates (4 kSPS) using the 1PPS timing protocol.

This project will extend traceable calibration services to both higher sampling rates (14.4 kSPS and 96 kSPS) and to equipment working on the PTP timing protocol, as required by the new standards. Calibration services will also be developed and implemented at metrology beneficiaries that have so far been unable to calibrate digital instrument transformers or SAMUs.

A literature review on requirements for reference SAMUs has been performed.

The modification and extension of the capabilities of an existing reference SAMU calibrator in four alternative ways that vary in the amplitude of the input signals, phases available, bandwidth, and accuracy are under investigation. Tests defining the accuracy on the alternative setups of the modified calibrator are ongoing.

The possibility to lock the reference SAMU to an external 1588 PTP signal has also been investigated. Alternative commercial hardware has been tested to meet the need for higher sampling frequencies.

The first testbed version devoted to the calibration of commercial SAMUs has been designed. In preparation for basic calibration of a SAMU according to the IEC 61869-13, software to analyse the sampled values has been developed. A measurement setup was also realised for the calibration of the absolute phase of a digitiser.

Calibration tests have been started using the modified SAMU calibrator. So far, the capabilities of the SAMU calibrator regarding amplitude and time calibration at 50 Hz have been investigated. There is close cooperation between the laboratories involved in objectives 1 and 3 to improve time calibration capabilities.

The consortium has agreed with different manufactures to have their commercial SAMUs for calibration. In preparing for the calibration campaign, voltage and current sensors that are to work with the SAMU were calibrated using various methods according to its related standards.

One commercial SAMU has already been calibrated on one of the testbeds developed in this project.

Control and analysis software solutions for handling of SV streams

Algorithms for calculating parameters – e.g. RMS value, ratio error or phase displacement – are typically implemented as proprietary solutions in digital substation instrumentation and related test sets. However, their calibration methods have to rely on available SV data streams and separate reference algorithms, which are (i) currently unavailable and not standardised for all parameters under non-synchronous conditions or (ii) are not validated for new data sampling rates up to 96 kSPS.

This project will go beyond the state of the art by developing new data processing schemes and algorithms to accurately characterise the amplitudes, phases, and relevant power quality (PQ) related parameters with complete system-wide uncertainty estimation, thus providing a solid basis for traceable calibrations. All of the project's developed software will be collected and documented in a reference software package that can be used to support a comparison of developed data processing schemes and algorithms. This should enable NMIs and calibration laboratories to better meet end user needs in their transition to digital substations. The comparison results can also be used by standardisation bodies to recommend best validated data processing schemes and algorithms for their intended use.

The software for controlling the setups and handling of SV data streams is under development. Currently it is capable of capturing IEC 61850-9-2 packets from two SV data streams, and it supports real-time reporting RMS and phase for a given SV stream or streams. The implementation of other algorithms is also under consideration.

Static, dynamic, linear, and non-linear parameters that need to be estimated from current transformer (CT) and voltage transformer (VT) SV data streams were identified. Based on the results of the questionnaire sent to stakeholders, it was concluded that the power quality parameters, except DC transient, are not relevant for metrological evaluation of CTs and VTs from SV data streams, as the power quality parameters are related to functional equipment tests and not metrological characterisations.

Two optimisation criteria were defined: (i) accuracy and (ii) speed. As these are often mutually exclusive, the selection and development of data processing schemes can be optimised either for accuracy or speed. The analysis showed that the available data processing is often optimised for accuracy, while a further development would be needed to optimise speed versions, which would enable real-time operation. Hence, further development is mainly focusing on resampling procedures enabling the use of FFT for remaining processing.

Existing SV data processing schemes were reviewed. The open-source software tool TWM SV, developed in the EMPIR project 15RPT04 TracePQM, was chosen to be a good candidate for further use in this project. The TWM SV was further examined to define necessary improvements and modifications which will support communication with reference SAMU and will be able to handle high-rate data streams in "quasi" real time.

Timing networks and calibration method for 1PPS to/from PTP time protocol conversion

Recently, some NMIs (including project beneficiaries VSL and VTT) have developed calibration setups, where the device under calibration uses 1PPS as a timing source and the phase encoded into its SV stream can be compared to the 1PPS pulse front. These reference calibration systems rely on determining the latency of the reference device front-end electronics and compensating for it to produce a 1PPS aligned SV data stream. Similar, commercial devices are required to do the same, as per IEC 61869-9 (Digital interface for instrument transformers) Annex 9B. Several methods for determining the required compensation parameters, and a robust implementation of reference and commercial systems already exist.

The 1PPS timing has been replaced by PTP timing protocol in the new versions of related standards. Therefore, this project will go beyond the current state of the art by developing best practices for the calibration of PTP slave device timing and for verifying leap second insertion in the timing networks. As the PTP timing quality will ultimately depend on all networking components relaying timing packets, the project's focus will not only be on slave devices, but also on master clocks and network switches.

The beneficiaries have studied the technical requirements of devices needed for establishing reliable PTP and SV networking in their institutes and in general use. Inventories of commercially available PTPv2 grandmaster clocks and PTPv2 supporting Ethernet switches were prepared. While the inventories of devices are non-exhaustive, it serves as a good starting point for selecting the equipment needed for the networks. It was noted that practical experience equipment is often required, as manufacturers do not always provide complete product information that may be relevant for the selection of a particular device.

Details of various commercially available network Traffic Access Points (TAPs) for optical networks have been studied. It was found that none of them meet the requirements of this project's objective. Fortunately, the custom device built in the EMPIR project 17IND14 WRITE was found to be a good solution after some modifications. The device is now working correctly and has been calibrated.

PTP trigger devices have been designed and are currently under construction at two beneficiaries' institutes. The solutions for the PTP trigger devices are based on commercially available networking chips and on an embedded software development board.

Finally, a report was prepared specifying the proposed "golden calibrator pair" calibration procedures. The selection of equipment for the proposed method is complete and the building will start once all parts have been received.

Outcomes and impact

The outcomes of this project will benefit the electrical power industry including digital substation instrument manufacturers and grid operators. The project will also contribute to standards especially those associated with IEC TC 38.

Outcomes for industrial and other user communities

This project will improve, and extend, the current electrical power and energy metrology infrastructure to cover digital substation instrumentation to support the development and improvement of electrical distribution and transmission grids. Industrial end-users and stakeholders such as TSOs, DSOs and digital substation instrumentation manufacturers will benefit from project outcomes, such as

(i) enhanced measurement capabilities for the dynamic characterisation of instrument transformers for PQ measurements,

(ii) a metrological infrastructure for the calibration of SAMUs,

(iii) reliable time synchronisation (e.g., transmission of SV data and PTP-based timing) between commercial devices, and

(iv) new test systems for measuring SV-enabled instruments based on IEC 61850-9-2 (Communication networks and systems for power utility automation - 9-2: Specific communication service mapping (SCSM) - Sampled values over ISO/IEC 8802-3), such as energy meters and digital Phasor Measurement Units (PMU).

This project liaises with industrial stakeholders via the formation of a stakeholder committee, which has been set-up and so far has 26 members from 21 organisations. This group includes representatives from TSOs and DSOs, test and calibration service providers, digital substation instrument manufacturers and standardisation organisations, and will help the project's results to directly impact such representatives.

In addition, this project will also produce and publish 2 good practice guides for end-users (such as digital substation instrument manufacturers, TSOs, DSOs):

- Good practice guide on the calibration of commercial SV enabled instrumentation with sampling rates up to 96 kSPS
- Good practice guide for the calibration of substation instrumentation using PTP timing, including a traceable link between PTP timing and 1PPS reference pulse with a target uncertainty of 100 ns.

Further to this, the consortium has produced and sent an e-newsletter to stakeholders on the project (need, objectives, beyond state of the art, consortium). This e-newsletter was sent to stakeholders in December 2022 and the next e-newsletter is in preparation. The e-newsletters will be used to communicated with and disseminated information on the project to stakeholders and to inform them of important outcomes and upcoming events such as the Good Practice Guides and project workshops.

Outcomes for the metrology and scientific communities

The project will develop new and demanding measuring techniques including several important additions and extensions to CMC statements. The power systems scientific community will benefit from these new or enhanced measurement capabilities in areas where scientific information has been scant or lacking. Major scientific impact will be provided via the publication of the key project results in peer review journals and via presentations at key conferences. To date, the project has been presented at 3 conferences ITSF2022 Düsseldorf, Germany, CPEM 2022 Wellington, New Zealand and SMAGRIMET 2023 Cavtat, Croatia.

The project will also host two workshops which are targeted to standardisation bodies (IEC, CENELEC) as well as industrial stakeholders (e.g., digital substation instrument manufacturers and TSOs), to foster uptake in these communities. The first workshop will summarise the progress during the first half of the project and will be used to gain feedback from stakeholders to guide the work on the second half of the project. The second workshop will present the results from the project and will highlight the 2 good practise guides developed.

Close cooperation between the project's different types of beneficiaries i.e., from research institutes, digital substation instrument manufacturers and NMIs will also support the dissemination and uptake of its outcomes. The project outcomes will also be shared with the NMI community through the EURAMET Technical Committee for electricity and magnetism (TC-EM), in particular the EURAMET TC-EM "Power and Energy" subcommittee.

Finally, the project will provide output to the metrology and scientific communities, via the plans for future research activities in the EMN SEG strategic research agenda. Indeed, the consortium has already engaged with EMN-SEG at its general meeting in April 2023. The beneficiaries VSL, RISE and VTT will also contribute to via their participation in the associated 18NET03 SEG-Net project.

Outcomes for relevant standards

This project will generate important results on the development of a metrology infrastructure for the traceable measurement and calibration of digital substation instrumentation that will be very valuable to standardisation work within IEC TC 38, CENELEC TC 38, IEC TC 13, IEC TC 57, IEC TC 77A WG1, WG2 and WG9, IEC TC 38 WG37 and JWG 55, IEC TC 42, CIPM CCEM, EURAMET TC-EM and CIGRE JWG B5/D2.67. Liaison will be accomplished by members of the project, who are active within the respective committees. The beneficiaries who are members of corresponding technical committees will inform them about the results of this project and will endeavour to ensure they are incorporated in any updates to the standards or guidelines. So far, the consortium has participated in and disseminated information to EURAMET TC-EM (Electricity and Magnetism) and BIPM CCEM (Electricity and Magnetism).

Longer-term economic, social and environmental impacts

This project supports the long-term transition of the European power grid from analogue to digital control. The use of next-generation instrument transformers and PMU equipped substations is the prerequisite for successful integration of wide-scale connection of decentralised renewable energy sources in the High Voltage (HV) distribution and transmission grid. These next generation digital substations will also help to ensure the stability of the European power grid. European power grids are under increasingly complex and challenging conditions due to the societal desire for the large-scale introduction of renewable energy sources. By supporting the stability of the grid, more electricity supplied by renewable energy sources can enter into Europe's energy supplies, meaning that less conventional carbon-rich electricity generation (i.e., coal), is required and less CO_2 emitted.

Reliable electrical delivery is also one of the key needs in modern society e.g., even our water supply depends on the supply of electricity. This means that when black-outs and brown-outs occur, they result in major costs and disruptions to society. HV transmission grids are crucial for the electricity grid infrastructure; however, the current electricity grid infrastructure is aging. The ageing of the first generation of instrumentation is already stressing the network and impacting the reliability of our daily electricity supply. This project will help support the reliability of Europe's electricity supply by through the implementation of new digital substation instrumentation and HV transmission grids.

The project's outcomes will also support the long-term competitiveness of the European electrical industry, in particular digital substation instrumentation manufacturers, by providing them with the metrology tools to unambiguously prove the quality of their equipment. High quality equipment is one of the prime selling points for European industry and should provide a decisive competitive advantage with respect to other lower-cost but lower-quality equipment.

List of publications

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

<table>
<tr><td colspan="2">Project start date and duration:</td><td>1 September 2022, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Jari Hällström, VTT Tel: +358 50 382 2127 E-mail: jari.hallstrom@vtt.fi
Project website address: https://www.ri.se/en/digital-it</td></tr>
<tr><td colspan="2">Chief Stakeholder Organisation: IEC TC 38</td><td>Chief Stakeholder Contact: Volker Leitloff</td></tr>
<tr><td>Internal Beneficiaries:
1. VTT, Finland
2. CMI, Czechia
3. GUM, Poland
4. JV, Norway
5. Metrosert, Estonia
6. RISE, Sweden
7. SIQ, Slovenia
8. VSL, Netherlands</td><td>External Beneficiaries:
9. CIRCE, Spain
10. LeftRight, Slovenia
11. Lukasiewicz-ITR, Poland</td><td>Unfunded Beneficiaries:
12. OMICRON, Austria
13. Statnett, Norway</td></tr>
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